WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945
DOI: 10.24425/ace.2021.138501
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVII ISSUE 4 2021

pp. 303 – 316

Research paper

Thermal and acoustic behavior of energy saving wall panel

M. Yasir Khan[1], Abdul Baqi[2], Rehan Sadique[3]

Abstract: Research and development of energy-efficient materials have been essential for sustainable infrastructure growth. A considerable amount of money is being spent on various energy stabilization techniques worldwide to attain thermal comfort in buildings. Thus, lowering the energy demand through green materials is vital to save energy and the environment. In this paper, a new form of Structural Insulated Panel (SIP) has been developed and referred to as Ferro Cellular Lightweight Concrete Insulated Panel (FCIP). Comparative thermal efficiency and acoustic performance of FCIP and brick masonry walls have been tested experimentally. The thermal results show that FCIP allows just 2°C rise in the internal temperature of the room chamber in two hours, whereas the brick masonry allows 9.5°C rise in the internal temperature of the room chamber for the same period. Similarly, the acoustic results show that FCIP has 0.85 sound absorption coefficient compared to 0.2 for brick masonry wall. Further, the cost-benefit analysis was conducted based on the electricity consumption results of a building produced by the eQuest energy simulation program. The outcome shows that the building's lifetime running cost gets reduced to 50% when FCIP replaces the concrete/brick masonry envelope.

Keywords: sustainable building, sandwich structures, structural insulated panels, building thermal performance, acoustic absorption

[1]PhD., Eng., Dept. of Civil Engineering, Aligarh Muslim University, Aligarh, India, e-mail: yasirkhan2808@gmail.com, ORCID: 0000-0003-3628-2903

[2]Professor, Dept. of Civil Engineering, Aligarh Muslim University, Aligarh, India, e-mail: baqiamu@rediffmail.com, ORCID: 0000-0002-1192-7130

[3]Associate Professor, Dept. of Civil Engineering, Aligarh Muslim University, Aligarh, India, e-mail: rehan.sadique@gmail.com, ORCID: 0000-0002-9570-6801

1. Introduction

Protection of residential and commercial buildings from extreme weather and temperature conditions is one of the basic requirements of a human being. In this aspect, countries worldwide spend a lot of money yearly on thermal comfort, which increases the electrical energy consumption in buildings [1]. More energy consumption leads to an increase in coal and gas burning, polluting the environment, and rising global warming [2]. Further, due to the continuous rise in population, building energy use is expected to rise in the future [3]. It can be observed from Figure 1 that the usage of electricity in the USA in the year 2014 is maximum in the air conditioning of buildings, i.e., 30% of the total energy consumption. Researchers have suggested several factors that help to minimize energy consumption in buildings, such as the building's orientation and the type of glass used for doors and windows [4–6].

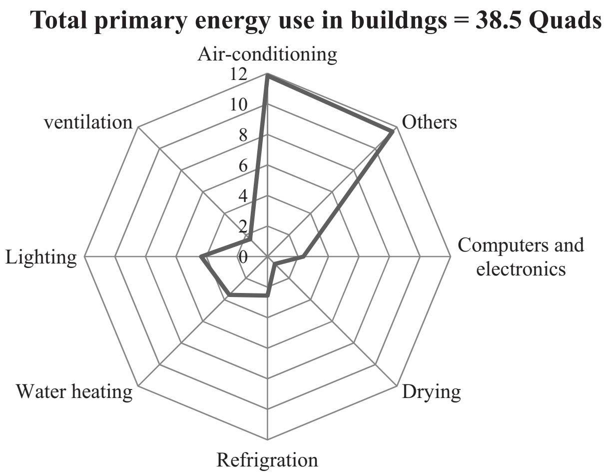

Fig. 1. Total primary energy consumption by residential and commercial buildings in the U.S. in 2014 [9]

However, the most significant one is the insertion of the insulation layer within the building's walls and roof, which reduces the electrical load up to a large degree [7]. This technique significantly enhances the whole building's thermal performance as the heat flow through the building envelope is reduced effectively. Hence, making the environment significantly cleaner by lowering electrical energy consumption [8].

Hence, proper insulation of the walls and the roof of the building is a more natural and sustainable way to reduce cooling/heating load over the building's lifetime. The first building insulated with mineral wool was reported in the USA in 1880. From the 1970s onwards, more efficient insulation materials have been discovered and used in building construction worldwide [10]. Several insulation materials are commercially available, such as Rice hulls, fiberglass–urethane, polyurethane-rigid panels, PUR (polyurethane), expanded perlite, XPS(extruded polystyrene), cork, foam, EPS(expanded polystyrene), PIR (polyisocyanurate). However, it is a part of research investigating to find out a material that is best in cost-effectiveness, structural stability, and thermal performance.Various energy stabilization techniques were studied previously to minimize the building's lifetime running cost. Still, these techniques add an extra cost and effort to the structure [6, 10, 11].

On the other hand, the Structural Insulated Panels (SIP)are more energy-efficient, durable, and made with low construction costs. The primary purpose of the SIP is to provide a thermally insulated and structurally strong wall support system. The core of SIP having low thermal conductivity mainly offers thermal insulation. The facesheets on both the faces of the core carry bending stresses while the core contributes towards the shear load and stabilizes the faces against buckling and wrinkling [12]. SIPs have many advantages over conventional insulation methods used in wall systems [13]. It delivers lower total construction costs and lesser wastage due to prefabrication, higher seismic resistance due to lower weight [14], and less project duration [15]. Also, SIP use in residential buildings reduces electricity consumption and makes it thermally efficient [16]. SIP also gives an increased R-value compared to a brick masonry wall, and they also form an uninterrupted air barrier within it in the form of vapor. Many other problems related to conventional buildings, such as untimely deliveries, placement difficulties, poor quality control, can easily be eliminated with this technique [17]. However, even with so many advantages, the lightweight SIPs are not commonly used as an external wall of single/multi-story buildings due to their limited structural applications, as reported in the literature [18–21]. In comparison, the concrete SIPs have high load-bearing capacities but are bulky, hence, less feasible and uneconomical in pre-cast construction work. On the other hand, the traditional construction with brick masonry does not provide the temperature control insulated homes.

Hence, to further improve the structural, thermal, and acoustic performance of outer walls of the building, a new form of SIP referred as Ferro Cellular Lightweight Concrete Insulated Panel (FCIP) is developed and tested for its thermal and acoustic behavior in the present study. Its initial structural behavior has been reported in Khan et al. [22]. Whereas, its thermal and acoustic behaviors has been reported in details here. It has been observed that the FCIP performed thermally efficient and acoustically absorbing building panel compared to brick masonry wall. Also, the lower weight of the FCIP reduces the overall dead load of the structure that ultimately reduces the size of the foundation. Hence, FCIP can efficiently replace the present forms of SIPs in terms of structural, thermal and acoustic features, which will be a giant leap in SIPs.

2. Testing and selection of different layers for FCIP

The traditional form of SIPs consisting of three-layer assembly (a core sandwiched between two inner and outer facesheets). Similarly, the proposed FCIP was supposed to be composed of an insulation core sandwiched between two dissimilar inner and outer facesheet. The materials for core and facesheets for FCIP were selected by some laboratory experimentation.

The core is a base material responsible for providing insulation to all the SIPs [3]. It also needs high strength; otherwise, the whole panel's performance gets affected [23]. Hence, to make FCIP a structurally stable building panel, stiff foam like EPS, XPS, and PUR were considered in the present study. In terms of shear resistance, flexural strength, and compressive strength, the XPS is approximately twice as good as EPS. WhereasPUR is more water & fire resistant than XPS and EPS and produces a strong bond between the sandwich core and external facesheet [16]. Comparatively, XPS and EPS are cheaper than PUR and readily available in the market. Therefore, considering all the constraints, XPS is chosen as the core material for the proposed FCIP. The XPS foams of 35 kg/m3 of density were supplied by supreme petrochem Ltd, India, to the testing laboratory.

The selection of suitable external facing is important for the whole panel's stability. It has to be robust against compressive load, accidental load. Also, durable to both fire and environmental impact and should be lightweight. Therefore, a cellular lightweight foam concrete (CLC) is produced in the laboratory by using CLC foaming agent. The compressive strength test was performed on the CLC, in the form of a cube of each side 76 mm. Initially, different trial mixes were cast and tested for different mix ratios. The required compressive strength of 10 MPaat the density of 1100 kg/m^3 was found on a ratio of 1.0:1.0:0.1:0.01 of cement, fly ash, silica fume, and fiber of polypropylene, respectively.The addition of finer silica particles and polypropylene fiber was found to be favorable to achieve the desired compressive strength of CLC. The author's complete study to developed this new material (CLC) is under communication [24]. Finally, the produced CLC was incorporated as an external layer of FCIP (see **section 3**).

The key measures considered for selecting the internal-facing of FCIP were strength, durability, cost, and aesthetics. To test its strength and deformability criteria, a series of different sandwich panels of size (300 mm *times* 600 mm) were tested in axial compression through a hydraulic jack of capacity up to 500 kN fitted ina heavy steel frame in the laboratory. These panels were fabricated with a common XPS core of thickness 50 mm, sandwiched between different types of facings commonly used in SIPs industries. The ultimate axial compressive load sustained by each panel is given in Table 1.

Table 1. Ultimate axial compressive load sustained by different SIPs

Facesheet	Panel Size (mm)	Ultimate axial comp load (kN)	Failure type
Oriented strand board (OSB) – 11 mm	600 × 300 × 72	35	Buckling & debonding
Plyboard – 11 mm	600 × 300 × 72	40	Buckling & debonding
Fiber cement board (FCB) – 11 mm	600 × 300 × 72	56	Buckling & debonding
Magnesium oxide board (MgO) – 11 mm	600 × 300 × 72	49	Buckling & debonding
Low density Aerated Concrete – 50 mm	600 × 300 × 50	20	Crushing & splitting
GI sheet – 1 mm	600 × 300 × 52	8	Deformation

It can be seen in Table 1 that the load sustained by a sandwich panel made up of FCB as facesheets is highest (56 kN). Also, FCB is lightweight and resistant to fire, water, and termite [25]. Therefore, considering all parameters, the FCB was chosen as an internal-facing for FCIP. The 10 mm thick prefabricated board (FCB) was supplied by Everest Industries limited. These boards were manufactured from a mixture of Portland cement, cellulose fiber, finely ground silica quartz, and other selected mineral fillers. On behalf of the above results, the FCB, XPS, and CLC were chosen as an inner, sandwich, and outer layer of FCIP, respectively.

3. Fabrication of FCIP

FCIP consists of three layers, as discussed in Section 2. A layer of 10 mm thick internal facesheet (FCB) connected to 50 mm core (XPS) with thermally insulated fiber-reinforced polymer fasteners. The layers were glued by Araldite epoxy adhesive to provide a strong bond between the internal and sandwich layers of FCIP. These two layers (inner and sandwich) were placed in wooden moldings. The CLC was produced separately and then poured into each mold up to 30 mm in depth, as shown in Figure 2a. To further improve the flexural rigidity of the CLC, a 1 mm thick chicken wire mesh is incorporated inside the CLC facing at the time of casting. After 24 hours, each panel was removed from the molds, and proper water curing is provided to the outer layer (CLC) for 28 days to achieve full structural strength. Afterward, all the panels were dried in sunlight before the laboratory testing, as shown in Figure 2b. The cross-section of the FCIP specimen is shown in a schematic diagram of Figure 2c.

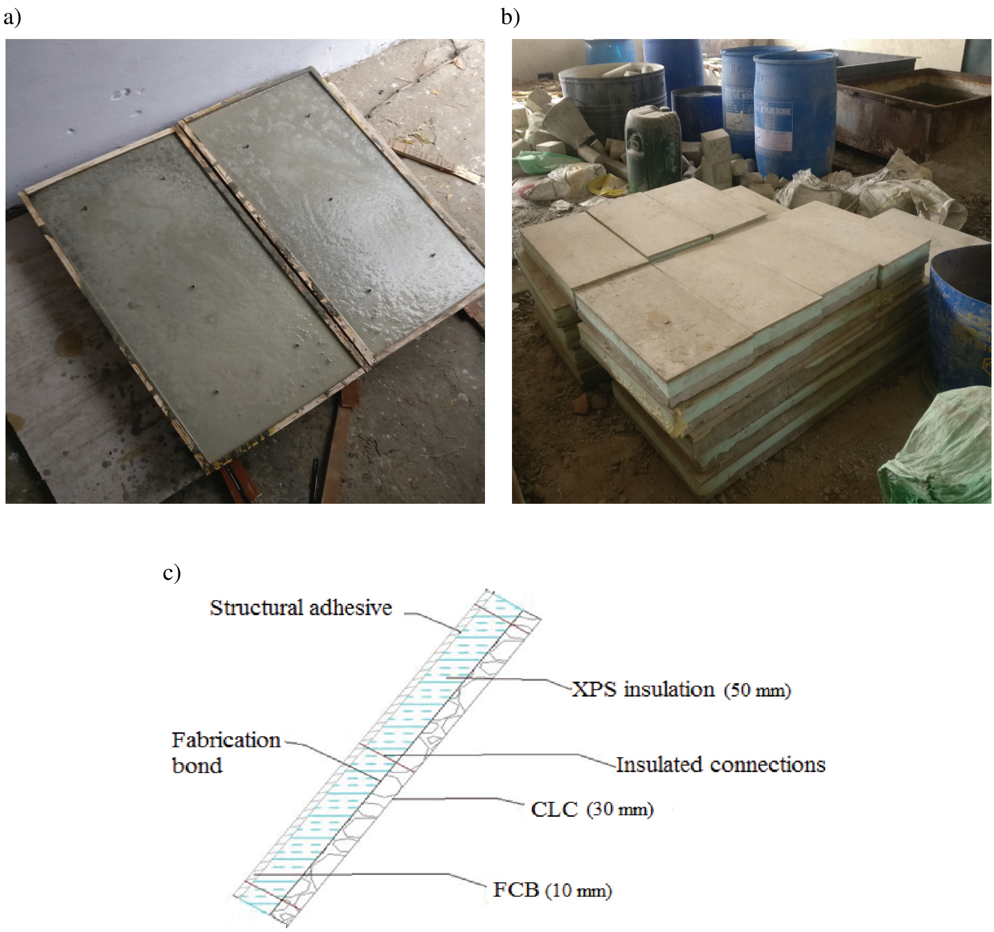

Fig. 2. FCIP in different phases (a) Casting (b) Drying (c) Cross-section

4. Experimental setup and testing

FCIP is designed to be used as an outer wall member of framed structures. It helps to resist heat and sound transfer from the outer space to inner spaces and makes a building energy efficient and acoustically absorbing. Hence, it has been tested experimentally to determine its temperature and sound resistance behavior.

4.1. Thermal test

In most of the previous studies, the thermal behavior of different outer envelopes of the buildings was analyzed experimentally. Small-scale cubicles were constructed in an open atmosphere to determine the thermal efficiency of the different outer envelopes [10, 26]. This method does not provide data about the influence of solar radiation, the effect of thickness, and the panel's size. Still, it helps to determine the overall thermal behavior of FCIP in comparison to brick masonry. Similarly, in the present study, a small chamber was constructed in the university laboratory to analyze and compare the thermal efficiency of a brick masonry wall and FCIP in practical conditions, as shown in Figure 3.

a) b)

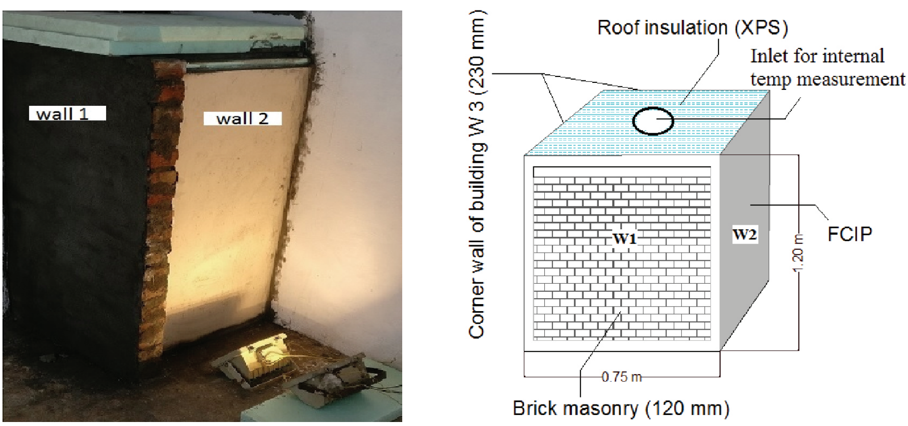

Fig. 3. Testing chamber for thermal study (a) Experimental setup (b) Schematic diagram

The chamber consists of three different walls, 1.2×0.75 m each. Wall 1 was constructed with brick masonry (110 mm). In contrast, Wall 2 was constructed by FCIP (90 mm). The other two corner walls (wall 3) of the chamber were pre-constructed brick masonry walls (220 mm). The chamber was airtight and sealed with the XPS insulation and cement plaster to prevent the airflow from inside to outside. First, the heat was applied using two 500 wattage mercury lights focused at Wall 1 for a fixed period of two-hours. Then, after neutralizing the chamber's inside temperature, the same process was repeated on Wall 2 for the same time. The temperature has been recorded on the front face and rear face of heat facing walls and also at the center of the chamber through an infrared thermometer and thermocouple.

4.2. Acoustic test

To study the acoustic behavior of FCIP, a laboratory test was conducted with the help of a Microflown Acoustic In-situ Absorption Setup. It supports non-destructive testing of material samples. Furthermore, sound absorption can be measured at any angle of incidence, and it can also measure the acoustic behavior of assembled parts such as SIPs.

The setup has a small handled impedance gun that measures acoustic absorption reflection or impedance. The source object was placed 5 mm apart from the in-situ sound absorption facility, and different frequency sounds were produced at a 90-degree angle of the object. The acoustic particle velocity and sound pressure were measured directly on the surface of the material. The absorption was obtained from the measured impedance, i.e., the complex ratio of sound pressure and particle velocity. The complete test setup is shown in Figure 4. The experimental readings for FCIP (90 mm) and brick masonry wall (120 mm) were noted in terms of sound absorption coefficient of the body.

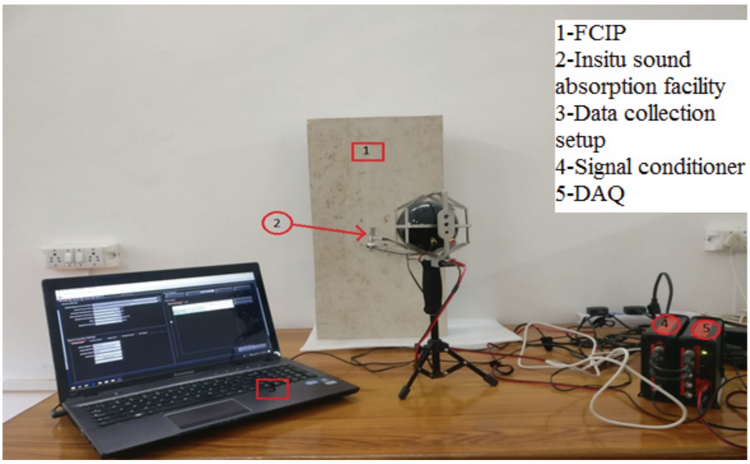

Fig. 4. Acoustic test setup for FCIP

5. Results and discussions

5.1. Thermal behavior

The thermal test results on brick masonry wall and FCIP are given in Figure 5 & Figure 6, respectively. When the heat was applied from the external source for two hours on the brick masonry wall, it increased the outer surface temperature (T_o) from 22°C to 91°C. While the inner face temperature (T_I) of the same wall (Wall 1) exceeded rapidly up to 45°C. Correspondingly, the chamber's inside temperature (T_c) moves from 21.5°C to 32°C within this period. In the second study, when the external heat was applied to the outer face of Wall 2 (FCIP) for two hours, a little change in the inner face temperature of FCIP was recorded, as shown in Figure 6.

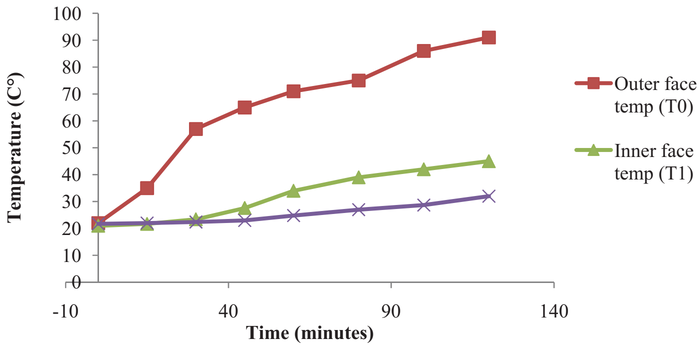

Fig. 5. Effect of temperature on 120 mm thick brick masonry wall

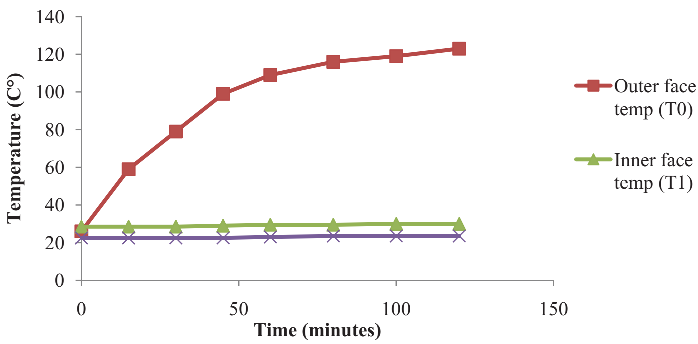

Fig. 6. Effect of temperature on 90 mm thick FCIP

In this case, T_o was increased from 26°C to 123°C. Its due to high surface absorbance on Fibre Cement Board (facesheet of FCIP). However, the inner face temperature (T_I) recorded an increase of 5°C only, which is 78% lesser than the previous study. Similarly, The T_c was changed by just 2°C and reached from 22.5°C to 24.5°C. This small difference in temperature T_I and T_c shows the thermal resistive tendency of FCIP compared to the brick masonry wall. FCIP's lower thermal conductivity decreases the thermal transmittance (U value) of the whole assembly up to a large extent, which leads to a slow rate of heat flow through its body that ultimately reduces the electricity need to cool and heat the building's interior spaces.

5.2. Acoustic behavior

The experimental test data has been drawn between the 200–4000 frequency (υ), as the testing device can calibrate accurately in this frequency range. It is the range of horns and whistles of general vehicles and locomotives. The results of the tests are presented in a graphical form, as shown in Figure 7.

It can be seen from Figure 7 that, at a lower frequency range (υ < 300 Hz), the absorption capacity of brick masonry and FCIP is almost equal. On the other hand, at υ = 1000 Hz, the FCIP absorbs 70% of incoming sounds compared to 10% by brick masonry. Hence, FCIP

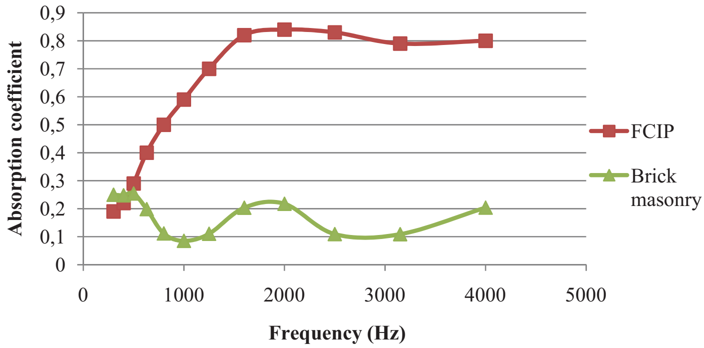

Fig. 7. Acoustic sound absorption coefficient of FCIP and brick masonry at different sound frequencies

behaves as an acoustically absorbing material for the most common frequency range of sound. At last, after υ = 1000 Hz, FCIP sound absorption capacity continues to increase up to 85% while brick masonry shows the highest 0.2 sound absorption coefficient value. Hence, FCIP will efficiently work as a sound barrier in the external wall application of the buildings.

6. Cost & benefit analysis

An energy consumption analysis has been conducted through the eQUEST-an energy simulation program to determine the cost-effectiveness and energy-saving capacity of FCIP fora full-scale building model. The eQUEST is a building energy analysis computer program for building envelope and HVAC. It provides energy simulation for the public building that uses actual weather data and can be operated by professionals [27]. A 3D geometry of a two-story building with a walls area (254.5 m^2) and roof area (88 m^2) has been developed in the software shown in Figure 8.

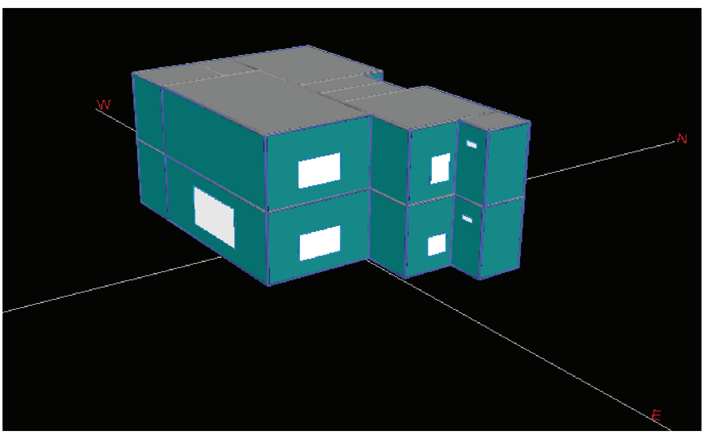

Fig. 8. 3-D diagram of building produced by eQuest

The emphasis has been given to comparing the thermal efficiency of FCIP with different traditional building materials used in the construction of walls and roofs. The thermal conductivity and thickness of each layer of FCIP, plaster finished brick masonry wall, and RCC wall were incorporated in the building envelope. The eQuest program calculated the resultant thermal transmittance (U-value) based on the data of Table 2.

Table 2. Properties of different wall support systems

Walls	FCIP			Brick masonry	RCC
	CLC	XPS	FCB		
Density (kg/m^3)	1100	35	1300	1900	2400
Thickness (mm)	30	50	10	120	120
Thermal conductivity (W/mk)	0.44 [27]	0.028	0.086 [28]	0.7	1.4 [27]

Results of the theoretical simulation produce by eQuest are shown in Figure 9. It can be seen that in the case of the RCC envelope, the energy consumption was 4789 kWh per year, while for the brick masonry envelope, the yearly consumption of electrical energy was reduced to 4173 kWh.

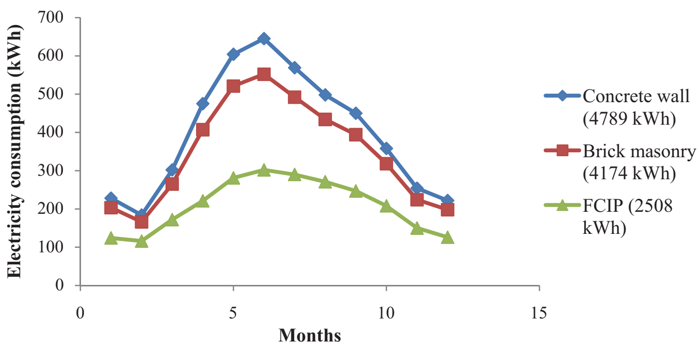

Fig. 9. Energy consumption by RCC, brick masonry, and FCIP envelope

On the other hand, a sudden drop was observed in the energy consumption of the FCIP envelope as it falls to just 2508 kWh/year. From Figure 9, it can also be observed that the FCIP building envelope consumes less electricity than that of the brick masonry and RCC envelope throughout the year. Also, between April to September, when the weather becomes hot, and the temperature rises, the FCIP envelope proves incredibly thermally efficient, as less electricity is required to cool the building during summer. The difference in the total construction cost of walls and roof of the two-story residential building was calculated to estimate the construction and energy saving cost of brick masonry and FCIP envelope. The results are presented in Table 3.

The cost of the brick masonry wall construction was given as per the Indian market rate. In comparison, the FCIP envelope cost includes the individual cost of each layer of the FCIP, its fabrication, and installation cost. On behalf of the results of Table 3, the total cost of the

Table 3. Probable cost of brick masonry and FCIP envelope

Parameters	FCIP	Brick masonry
Walls area (m^2)	254.5	
Roof area (m^2)	88	
Cost/m^2 of the plastered finished wall	1177 (Indian Rupees)	749 (Indian Rupees)
Cost/m^2 of roof surface	760 (RCC slab with XPS insulation layer)	434 (RCC slab without insulation)
Total Cost	INR 367700 = $5252	INR 229720 = $3281
Wall thickness (mm)	90	120
hline Weight (1.85 m^2)	82 kg	245 kg

analyzed building was increased by 1.60 times when FCIP replaced the brick masonry envelope. Consequently, a mathematical calculation was performed to obtain the payback periods based on the monthly electricity consumption of Figure 9 and presented in Table 4. The monthly electricity unit consumption was multiplied with their respective electricity charges in New Delhi, India, per the year 2019.

Table 4. Yearly consumption of electricity by brick masonry and FCIP envelope

Months	Electricity consumption (Brick masonry)			Electricity consumption (FCIP)		
	Units (kWh)	Rate (INR)	Total	Units (kWh)	Rate (INR)	Total
January	203	4.5	913.5	124	3	372
February	166	3	498	116	3	345
March	265	3	795	172	3	516
April	407	6.5	2645.5	221	4.5	994.5
May	521	6.5	3386.5	281	4.5	1264.5
June	552	6.5	3588	302	4.5	1359
July	492	6.5	3198	290	4.5	1305
August	434	6.5	2821	271	4.5	1219.5
September	394	4.5	1773	247	4.5	1111.5
October	318	4.5	1431	208	4.5	936
November	224	4.5	1008	150	3	450
December	198	3	594	126	3	378
	Grand Total		= INR 22651.5 = $323	Grand Total		=INR 10251.5 =$146.5

Electricity charges in of New Delhi were as: Rs 3/unit < 200, 200 > Rs 4.5/unit > 400, and 400 < Rs 4.5/unit > 800.

Following the results of Table 4, the yearly difference in the electricity consumption cost of brick masonry and FCIP envelope was12400 (INR). Therefore it will take about 11 years to recover the cost of the whole building. The payback period may be further reduced to low for high occupancy/energy use buildings. Moreover, the three times lower weight of FCIP reduced the overall dead load of the structure. Thus, it will ultimately reduce the size of the column, beam, and foundation of the framed structure, which minimizes the total cost of the building.

7. Conclusions

In the present work, an innovative form of the sandwich wall panel is proposed and referred as Ferro Cellular Insulated Panel (FCIP). FCIP has been tested experimentally to analyzed its thermal and acoustic behavior. The following conclusions have been made:

– The presence of low thermal conductivity sandwich layer (XPS) in FCIP makes it highly resistive towards heat flow comparison to brick masonry wall. Hence, the heat supply on brick masonry surface for two hours period resulting in the rise of in the internal temperature from 21.5°C to 32°C of the hollow chamber, i.e an increased of 49%. Whereas, the effect of the same heat for this period on the surface of FCIP resulting the 2°C rise in the internal temperature of the chamber, i.e. an increase of 8% only. Hence, FCIP has up to 6 times more temperature resistive tendency than conventional brick masonry wall and will prove to be an energy efficient exterior wall panel for buildings.
– The acoustic test data also give prolific results as at initial frequency range ($\upsilon < 300$ Hz), the FCIP behaves acoustically similar to brick masonry wall and absorb about 20–30% sound radiation. Whereas, at higher frequency ($\upsilon = 1000$ Hz), the sound absorptionco-efficient of FCIP increases from 0.2 to 0.8. Hence, FCIP absorbs almost 50–60% more incoming sound compared to half brick thick masonry wall. Hence, FCIP can be used as an acoustic panel in residential and commercial types of buildings.
– The cost-benefit analysis shows that the initial cost of the FCIP envelope is more than that of the brick masonry envelope by 1.6 times. But the lifetime running cost is low due to the high thermal efficient nature of FCIP. FCIP envelope for a two-story residential building may act nearly 66% and 90% more energy efficient than that of the brick masonry and RCC building envelope, respectively. In the present case of low occupancy, the building's payback period was nearly 11 years, which can be further reduced to fewer years for high occupancy buildings. Additionally, the lower weight of FCIP reduced a dead load of a framed structure. Thus, it will ultimately reduce the column, beam, and foundation size, which reduced the building's total cost.

Acknowledgments

We want to acknowledge Dr. Yasser Rafat of Sustainable Energy and Acoustic Research Lab (SEARL), Mechanical Engineering Department of Aligarh Muslim University, to provide acoustic test set up; their lab was funded by DST grant ECR/2016/002030.

References

[1] N.A. Kurekci, "Determination of optimum insulation thickness for building walls by using heating and cooling degree-day values of all Turkey's provincial centers", Energy and Buildings, pp. 197–213, 2016, DOI: 10.1016/j.enbuild.2016.03.004.

[2] "Green building", www.usgbc.org/articles/green-building-101-why-energy-efficiency-important (accessed 12 Jan 2021).

[3] M. Mohamed et al., "Manufacturing and evaluation of polyurethane composite structural insulated panels", Journal of Sandwich Structures and Materials, pp. 769–789, 2016, DOI: 10.1177/1099636215626597.

[4] S. Chaiyapinunt and N. Khamporn, "Selecting glass window with film for buildings in a hot climate", Engineering Joutnal, pp. 29–42, 2009, DOI: 10.4186/ej.2009.13.1.29.

[5] M.S. Sodha, J. Kaur, and R.L. Sawhney, "Effect of orientation on thermal performance of the building", pp. 709–715, 1992, DOI: 10.1002/er.4440160806.

[6] T. Pekdogan and T. Basaran, "Thermal performance of different exterior wall structures based on wall orientation", Applied Thermal Engineering, pp. 15–24, 2017, DOI: 10.1016/j.applthermaleng.2016.10.068.

[7] G. Kirankumar, S. Saboor, and T.P. Ashok Babu, "Thermal analysis of wall and window glass materials for cooling load reduction in green energy building design", Matererials Today: Proceedings, pp. 9514–9518, 2017, DOI: 10.1016/j.matpr.2017.06.215.

[8] H.T. Rakotondramiarana, T.F. Ranaivoarisoa, and D. Morau, "Dynamic simulation of the green roofs impact on building energy performance", Case Study of Antananarivo, Madagascar, pp. 497–520, 2015, DOI: 10.3390/buildings5020497.

[9] Q.T. Review, "Quadrennial Technology Review", An assessment of energy technologies and research. Chapter 5 : Increasing Efficiency of Building, 2015.

[10] H.U. Rehman, "Steady state experimental analysis of various solar insulation materials and techniques for buildings in climatic condition of ras al khaimah", ARE, Energy Procedia, pp. 1419–1424, 2015, DOI: 10.1016/j.egypro.2015.07.241.

[11] N.C. Balaji, "Thermal performance of the building walls", Building Simulation Applications (BSA 2013), 1^{st}. IBPSA Italy conference Bozen – Bolzano, pp. 151–160, 1998.

[12] M.A. Mousa and N. Uddin, "Global buckling of composite structural insulated wall panels", Mater. Des., pp. 766–772, 2011, DOI: 10.1016/j.matdes.2010.07.026.

[13] M.A Medina., J.B. King, M. Zhang, "On the heat transfer rate reduction of structural insulated panels (SIPs) outfitted with phase change materials (PCMs)", Energy, pp. 667–678, 2008, DOI: 10.1016/j.energy.2007.11.003.

[14] B Yeh., T. Williamson, and E Keith., "Development of structural insulated panel standards", vol. 314, 2008, DOI: 10.1061/41016(314)232.

[15] M. Panjehpour, A.A.A. Ali, and Y.L. Voo, "Structural Insulated Panels: Past, Present, and Future", Journal of Enineering, Project and Production Management, pp. 2–8, 2013, DOI: 10.32738/JEPPM.201301.0002.

[16] SIPs and CSIPs, www.generalpanel.com/downloads/whataresips.pdf (accessed 8 Nov 2020).

[17] "Precast febrication, www.financialexpress.com/opinion/precast-prefabrication-can-help-construct-houses-in-lesser-time-and-at-lower-cost/1242735/ (accessed 10 Dec 2020).

[18] T. Sharaf, W. Shawkat, A. Fam, "Structural performance of sandwich wall panels with different foam core densities in one-way bending", Journal of Composite Materials, pp. 2249–2263, 2010, DOI: 10.1177/0021998310369577.

[19] M.A. Mousa and N. Uddin, "Structural behavior and modeling of full-scale composite structural insulated wall panels", Engineering Structures, pp. 320–334, 2012, DOI: 10.1016/j.engstruct.2012.03.028.

[20] A. Vaidya, N. Uddin, and U. Vaidya, "Structural characterization of composite structural insulated panels for exterior wall applications", Journal of Composites and Construction, pp. 464–469, 2010, DOI: 10.1061/(ASCE)CC.1943-5614.0000037.

[21] T. Smakosz and J. Tejchman, "Evaluation of strength, deformability and failure mode of composite structural insulated panels", Materials and Design, pp. 1068–1082, 2014, DOI: 10.1016/j.matdes.2013.09.032.

[22] M.Y. Khan, A. Baqi, and A. Talib, "Energy efficiency analysis of a building envelope", Springer Proceedings in Energy, pp. 1691–1702, 2021, DOI: 10.1007/978-981-15-5955-6_160.

[23] G.C. Saha, A.L. Kalamkarov, and A.V. Georgiades, "Effective elastic characteristics of honeycomb sandwich composite shells made of generally orthotropic materials", Composites: Part A Applied Science and Manufacturing, pp. 1533–1546, 2007, DOI: 10.1016/j.compositesa.2007.01.002.

[24] M.Y. Khan, A. Baqi, and R.A. Khan, "Development of an improved quality cellular lightweight foamed concrete with low cement content", Journal of Engineering Research (under communication).

[25] "Structural Insulated Panels, www.wbdg.org/resources/structural-insulated-panels-sips (accessed 15 Nov 2020).

[26] L.F Cabeza et al., "Experimental study of using PCM in brick constructive solutions for passive cooling", Energy Build., pp. 534–540, 2010, DOI: 10.1016/j.enbuild.2009.10.022.

[27] B. Birdsall et al., "Overview of the DOE-2 building energy analysis program", version 2.1 D, 1990.

[28] "Thermal conductivity", www.fao.org/3/y5013e/y5013e08.htm (accessed 15 Nov 2020).

[29] Heavy Duty Fibre Cement Board – Technical Data Sheet, www.everestind.com/boards-panels/fibre-cement-boards (accessed 19 Jan 2020).

[30] "Electricity rate", www.economictimes.indiatimes.com/industry/energy/power/budget-emphasises-on-renewables-evs-for-indias-energy-security/articleshow/67797090.cms (accessed 5 Jan 2020).

Received: 2021-03-18, Revised: 2021-07-15