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Numerical Evaluation of Structural Concrete Insulated Panels for Thermal Energy Efficient Buildings

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ABSTRACT

This study is focused on thermal evaluation of Structural Concrete Insulation Panels (SCIPs) as building material. In Pakistan energy shortage is one of major issues since the last decade. As buildings consume more than 40 % of total production of electrical energy, it is necessary to innovate, analyse and apply various energy saving and optimization techniques for constructing thermal energy efficient buildings. SCIPs consist of three layers, in which a central polystyrene foam is sandwiched between two concrete layers. SCIPs are available in flexible sizes ranging from 0.3-1.2 m in width and 2.4-3.0 m in length. Owing to their light weight and easy fabrication, they are suitable for remote areas and severe weather conditions. In this study, numerical approach is used to compare the thermal performances of SCIPs and ordinary concrete incorporated walls in a school building system. Hourly recorded data of dry-bulb and dew-point temperatures of surface, humidity and mean air temperatures are used in simulation. Data for one typical year are used to compare the energy requirements of building made of ordinary concrete and SCIPs walls with expanded polystyrene as insulation material. Simulation results were acquired by means of EnergyPlus software and are presented to evaluate the heating and cooling demands of energy for a year. Study reveals that the SCIP walls incorporated buildings have a greater energy efficiency, reduce energy demand by 25% and HVAC systems by 20 % for assigned thermal zone.

Keywords: Structural Concrete Insulation Panels (SCIPs); ordinary concrete; buildings; EnergyPlus software; energy demand; HVAC system size

INTRODUCTION

Pakistan is a country with extreme weather conditions; the Southern regions are extremely hot during the summer, while Northern regions are extremely cold during the winter season. A high electricity demand for heating and cooling during the extreme weather conditions is the major cause of load-shedding. While, classical building materials like concrete, mortars, bricks and stones are good options for conventional load and non-load bearing applications, they have proved inefficient in providing thermal comfort to the occupants (Khitab & Anwar 2016). On the other hand, many sustainable materials are also developed, using industrial and agricultural wastes (Ahmed et al. 2020; Jalil et al. 2019; Riaz et al. 2019): While they are thermally efficient, they greatly reduce the materials strength, owing to their porous nature. Using efficient construction materials, the energy demands of the buildings can be reduced. Many energy efficient materials and techniques have been developed within the past few decades like light-weight plasters (Corinaldesi et al. 2015), wood-composites (Li et al. 2016), Building Envelopes using Phase Changing Materials (Cheng et al. 2014), and aerogel glazing (Gao et al. 2016), etc. Structural Concrete Insulation Panels (SCIPs) are low-weight earthquake resistant materials, suitable for earthquake prone regions of Pakistan, located in seismic zones 3 and 4 (Bhatti 2016; Khitab 2020). They comprise of three layers, two of which are of concrete having varying thicknesses on outer sides, sandwiched by a layer of polyurethane or polystyrene foam. Concrete and insulating layers are connected with steel wire mesh. Various studies are available, narrating the benefits of SCIPs against dynamic loads (wind and earthquake): Some past findings are described as follows.

Bhatti analysed the performance of a single story school building made of SCIPs (with varying thicknesses of polystyrene insulation layers) situated in seismic zone 4, using SAP2000 software (Bhatti 2016): According to his numerical findings, SCIP walls can carry loads from 584 to 1752 kN per linear meter of wall, can withstand up-to 320 km/h wind load and an earthquake of 7.5 magnitude on Rictor-scale. Khitab et al. carried out the numerical analysis of a double story school building made of SCIPs (Khitab 2020): They have reported that SCIP walls can sustain loads from 660 KN/m to 1800 KN/m of the wall (depending on the thickness), 90 Km/h wind speed and 7.5 magnitude earthquake. Tomlinson et al. performed flexural tests on SCIPs incorporating Glass Fibre Reinforced Polymer (GFRP) connectors and floating concrete studs (Tomlinson & Fam 2016): They have reported high structural strength, and resistance against fire. Ascoine et.al. experimentally investigated and numerically evaluated multi-layered walls with vacuum insulation panels for buildings in typical Mediterranean climate (Ascione et al. 2017): Their SCIPs consist of 8-13 cm thick concrete layer with 5-10 cm expanded polystyrene in between the outer concrete layers. They have reported 10.7 kWh/m^2 as energy demand for buildings incorporating SCIP in typical Mediterranean climate [3]. Woltman et.al. experimentally and numerically investigated the thermal properties of concrete sandwich insulation panels with shear connectors using fibre glass material (Woltman et al. 2017): They have reported the experimental thermal resistance (R-value) from 2.84 to 4.68 m^{2}K/W for their designed SCIPs against 2.74 m^{2}K/W for the steel-reinforced control panels.

In different climate conditions and with different constituent materials; the thermal behaviour of SCIP wall panels significantly changes. The main focus of this study is to analyse the thermal performance of SCIPs as well as to predict the energy requirement of the buildings incorporating these panels. A two-storey school building made of SCIPs is investigated to check the energy performance of these panels and predict the energy demand of the building. A comparison between the thermal behaviour of SCIPs and ordinary concrete wall system is numerically drawn to demonstrate the energy efficiency and cost effectiveness of SCIP system over the conventional reinforced concrete. SCIP is a new material and it comprises of three layers. The insulation layer is sandwiched between the reinforced concrete layers connected by GI wire mesh. Fabrication of SCIPs is time and cost effective. While, the dynamic analysis of the SCIP system has been reported by several researchers, its evaluation as a thermal energy efficient material is still missing: With that intent, this study is aimed to highlight the use of SCIPS for constructing thermal energy efficient buildings.

MATERIALS AND METHODS

In this study, SCIP is composed of three layer of materials; one layer of polystyrene insulating material is sandwiched between two layers of structural concrete connected by Galvanized Iron (GI) steel wire mesh. The wall panel consisting of 5 cm thick polystyrene rubber is sandwiched between two layers of 8 cm thick structural concrete. The properties of SCIP constituent materials is given in Table 1.

SIMULATIONS

EnergyPlus simulation engine is used in this study to measure the thermal energy performance of the school building incorporating SCIP and concrete walls. EnergyPlus is a fully integrated building and HVAC simulation software (EnergyPlus 9.2.0, 2020). EnergyPlus software is developed by GARD Analytics, United States of America. For analysis of energy gain and requirement of different systems of a building, an Input Data File (IDF) is generated in which geometry, materials, thermal zones and heating and cooling systems are defined.

SketchUp Pro software can generate IDF file using OpenStudio extension software. The weather data file (.epw) is incorporated with building location, time zone and hourly temperature values of the surface. The simulation engine runs IDF and Weather Data File to calculate the energy cost and sizing of HVAC systems of the building. EnergyPlus runs building thermal simulation through EP-Launch in combination with IDF and weather file. Figure 1 shows the interface of EP-Launch. Input Data File (IDF) is user input file containing information about geometry, materials and energy systems of the building.

The information provided in IDF is described in Table 2.

IDF can be edited by using the text editor or the IDF editor.

Figure 2 and Figure 3 display the interface of the IDF editor and the text editor, respectively.

BUILDING MODEL

A two-storey school building was modelled to perform energy analysis. It is a double story building, 9.4 m long and 20.2 m wide. Architectural details of the ground floor and first floor are shown in Figure 4 and Figure 5, respectively.

THERMAL ZONES

Thermal Zone is defined as group of surfaces that can interact with each other thermally and have a common air mass at roughly the same temperature. There are seven thermal zones in the building, in accordance with the ASHRAE 189.1-2009 thermal zones standards (ASHRAE 189.1-2009 2009). Each class room is defined as Thermal Zone ASHRAE-189.1-PriSchl-Classroom, while store room and offices are defined as Thermal Zone ASHRAE-189.1-Office-ClosedOffice.

SURFACES

One or more surfaces make up a zone. The walls, slab, windows and doors etc. are the unique surfaces that make up a thermal zone. Surface gives the complete geometrical and thermal envelope hierarchy of the building. Surfaces are of two types, opaque and fenestration. Walls, roofs, floors, ceilings etc. are termed as opaque surface. These surfaces do not allow direct passing of sunlight through them however, thermal energy can be transmitted, depending upon the thermal properties of the construction assigned to them. Fenestration surface are sub-surface components of the building. Windows or glazing doors are assigned as fenestration surfaces. These surfaces allow direct sunlight to pass through them.

CONSTRUCTION

Construction defines the properties of a surface. A construction is a group of layered materials ranging from

TABLE 1. Thermal Properties of SCIP Components

Layers	Thickness (cm)	Thermal Conductivity λ (W/m K)	Density ρ (kg/m³)	Specific Heat c (J/kg K)
Reinforced Concrete	8	0.850	2400	1000
Expanded Polystyrene Foam	5	0.035	25	1200

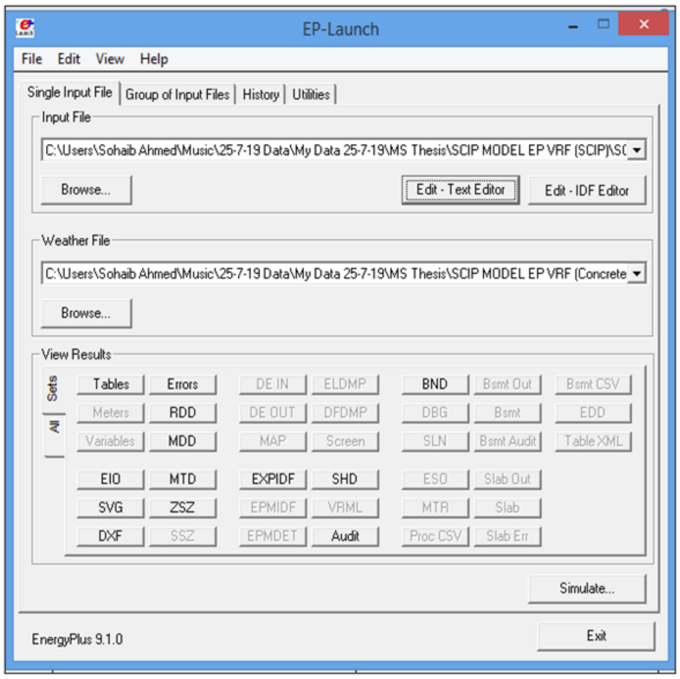

FIGURE 1. EP-Launch Interface

TABLE 2. Input Data for School Building

Version of EnergyPlus	EnergyPlus 9.1.0
Location of Building	Karachi Pakistan 24.8214° N, 66.8711° E
Time zone of Building	GMT+5.0
Elevation	22m
Time steps	6 per hour
Daylight Saving Period	N/A
Analysis Run Period	From Jan-01-2019 to Dec-31-2019 (365 Days)
Analysis Run Controls	Simulation run for zone sizing, system sizing, sizing periods and weather file run periods
Ground Temperatures	18 °C

outer to inner side. List of construction used is given in Table 3.

MATERIALS

Materials are the fundamental unit of building thermal envelope hierarchy. The thermal properties of the materials, used in the construction of the building are given in Table 4.

BUILDING THERMAL SCHEDULES

Thermal schedules represent a series of activities in the defined thermal zones. These activities include usage of electricity equipment, lights, HVAC system etc. EnergyPlus uses a series of schedule units to develop specific schedules. Schedules are the critical part of EnergyPlus analysis methodology and play a substantial role in the design and explanation of many components of thermal simulation model. Table 5 shows the various schedules assigned to the building. The schedules are divided into sub-units; Day Schedule, Week Schedule and Year Schedule.

HVAC SYSTEMS

HVAC systems are designed to attain a temperature between the defined thermal comfort control limits for building thermal zones. The design specifications for various types of internal HVAC systems are defined by ASHRAE Handbook for HVAC Application (Ashrae 2019), while specifications for inspection and maintenance are defined by ASHRAE

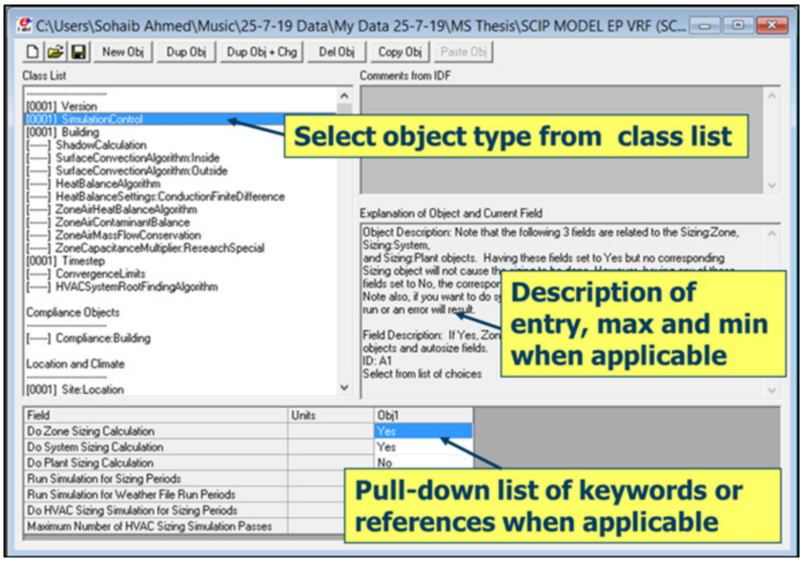

FIGURE 2. IDF Editor Interface

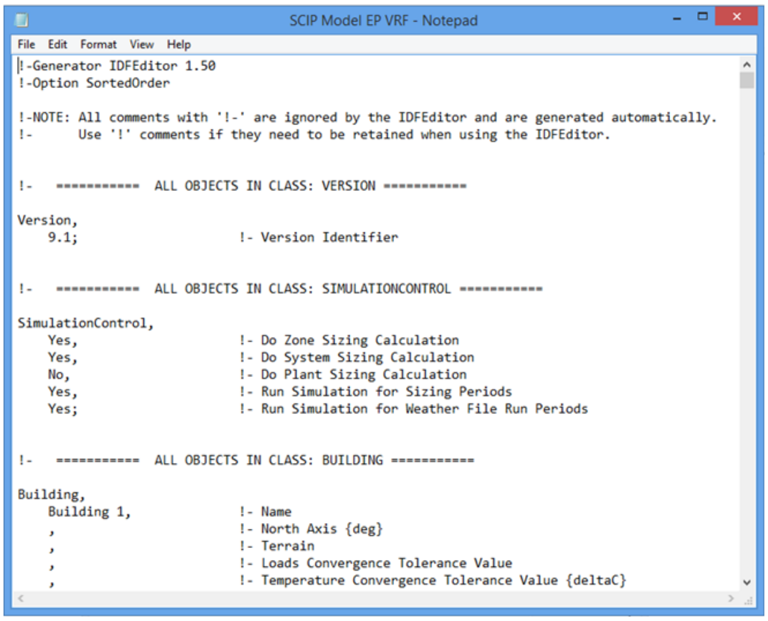

FIGURE 3. Text Editor Interface

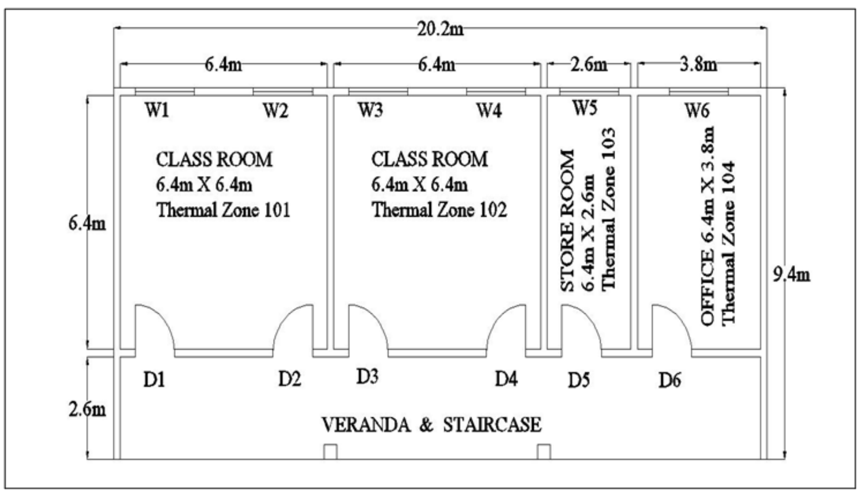

FIGURE 4. Ground Floor Plan

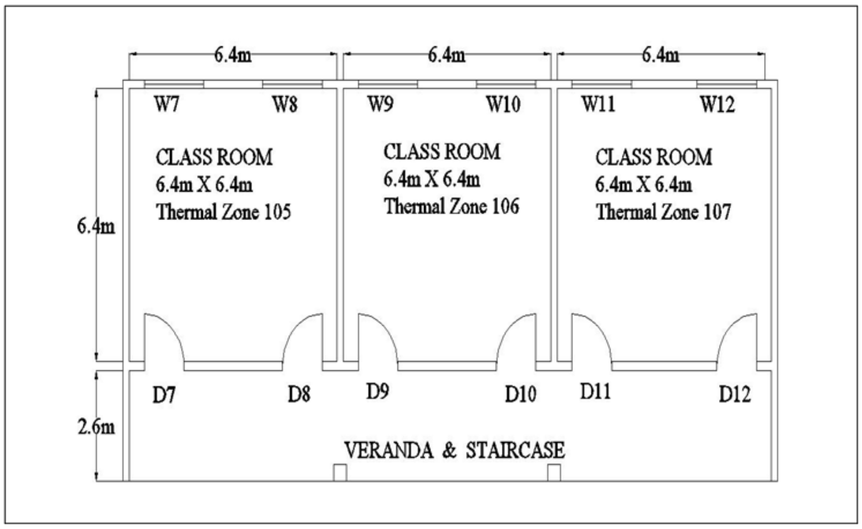

FIGURE 5. First Floor Plan

TABLE 3. Construction details of building

Construction	Materials		
Interior Wall SCIP	Reinforced Concrete 80mm	Polystyrene Rubber Foam 50mm	Reinforced Concrete 80mm
Exterior Wall SCIP	Reinforced Concrete 80mm	Polystyrene Rubber Foam 50mm	Reinforced Concrete 80mm
Slab Concrete	Plaster 12mm	Reinforced Concrete 150mm	-
Floor & Finishes	Stucco 25mm	Lightweight Concrete 50mm	-
Window	Clear 3mm Glass	-	-
Door	Insulation Board 25mm	Door Wood 25mm	-

TABLE 4. Thermal Properties of Materials

Material	Thickness (m)	Thermal Conductivity λ (W/m K)	Density ρ (kg/m^3)	Specific Heat c (J/kg K)
Reinforced Concrete SCIP	0.080	0.850	2400	1000
Expanded Polystyrene Foam	0.050	0.035	25	1200
Reinforced Concrete Slabs/Walls	0.150	0.850	2400	1000
Plaster	0.012	0.720	1860	1000
Lightweight Concrete	0.050	0.530	1280	840
Stucco	0.025	0.692	1858	837
Clear 3mm Glass	0.003	0.900	2500	840
Insulation Board	0.025	0.030	43	1210
Door Wood	0.025	0.150	608	1630

Standard 180 (Ashrae 2018). A unique Variable refrigerant flow (VRF) HVAC system is assigned to each thermal zone of the building. Properties of VRF system components include thermostat, HVAC Template VRF system and HVAC Template zones. Each zone is assigned a unique thermostat with heating set-point of 15 ^{o}C and cooling set-point 25 ^{o}C, a unique VRF system template with auto design of sizing the system and a unique VRF Zone Template with auto design of sizing the zone template.

INTERNAL GAINS

Thermal activities and energy gains within the defined zones depend upon population density, lighting and electrical equipment energy demand per unit time and area. The estimates were decided as per ASHRAE standards 62 (ANSI/ASHRAE 2019) and ASHRAE handbook of fundamentals (Ashrae 2017). Internal gains associated to the building model are given in Table 6.

RESULTS AND DISCUSSION

By using concrete and SCIP walls, the thermal performance of the building, energy demand of different systems and thermal properties of different wall panel systems are compared. A two-storey school building with independent HVAC systems for all rooms is analysed under different

TABLE 5. Schedules

Schedule	Power Consumption W/ person	Day Schedule	Week Schedule	Year Schedule
Primary School Activity Default Schedule	30	8:00 to 16:00	Monday to Sunday	Jan-01 to Dec-31
Primary School Building Equipment Schedule	0.35 to 0.95 varies	8:00 to 16:00	Monday to Sunday	Jan-01 to Dec-31
Primary School Building Lighting Schedule	0.18 to 0.90 varies	8:00 to 16:00	Monday to Sunday	Jan-01 to Dec-31
Primary School Building Occupancy Schedule	0 to 0.75 varies	8:00 to 16:00	Monday to Sunday	Jan-01 to Dec-31
Small Office Activity Default Schedule	30	8:00 to 16:00	Monday to Sunday	Jan-01 to Dec-31
Small Office Building Equipment Schedule	0.4 to 0.9 varies	8:00 to 16:00	Monday to Sunday	Jan-01 to Dec-31
Small Office Building Occupancy Schedule	0 to 0.95 varies	8:00 to 16:00	Monday to Sunday	Jan-01 to Dec-31

TABLE 6. Internal Gains

	Thermal Zones	Schedule	People per zone area (Persons/m²)
People	189.1-2009 Office-ClosedOffice	Small Office Building Occupancy Schedule	0.25
	ASHRAE-189.1-PriSchl Classroom	Primary School Building Occupancy Schedule	0.8
Lights	Thermal Zones	Schedule	Watts per zone floor are W/m²
	189.1-2009 Office-ClosedOffice	Small Office Building Lighting Schedule	5.0
	ASHRAE-189.1-PriSchl Classroom	Primary School Building Lighting Schedule	5.0
Electric Equipment	Thermal Zones	Schedule	Watts per zone floor are W/m²
	189.1-2009 Office-ClosedOffice	Small Office Building Equipment Schedule	2.0
	ASHRAE-189.1-PriSchl-Classroom	Primary School Building Equipment Schedule	2.0

weather conditions for the whole year. The main objective is to find the suitability of SCIP system for better thermal performance, energy conservation and cost effectiveness of the building. The measures of thermal properties were conducted in accordance with AHSRAE Standard 55 (ANSI/ASHRAE 2017).

THERMAL TRANSMITTANCE (U-FACTOR)

Thermal transmittance is the rate of transfer of heat energy through materials. It is represented as U-factor and is an important characteristic of thermal insulation materials, such as concrete or insulation boards. Thermal transmittance is opposite of thermal resistance (R-value). For a layered material such as SCIP, it is calculated by dividing thickness (D) of material to its thermal conductivity (λ).

$$R_1 = D_1 / \lambda_1 \quad (1)$$

$$R = R_{IS} + R_1 + R_2 + \ldots + R_N + R_{OS} \quad (2)$$

R_{IS} = Interior Surface thermal resistance
R_{OS} = Outer Surface thermal resistance

$$U = 1 / R \quad (3)$$

Thermal properties of various surfaces of buildings shown in Table 7.

Thermal comfort of building greatly depends upon the thermal transmittance of building surfaces. Thermal properties of SCIP in comparison with other construction materials shows a great difference (Table 7). The thermal transmittance (U-factor) of SCIP is significantly lower than the other material surfaces, indicating a better thermal performance and comfort to the building environment. The maximum U-factor value (to provide a better thermal comfort) for a wall of an energy efficient building is 0.70 W/m^2K according to BS EN ISO 6946 (BS EN ISO 6946:2017 2017), and that of SCIP is well below this limit.

ENERGY REQUIREMENTS OF BUILDING

The buildings energy requirements are determined using the EnergyPlus simulation and results are based on simulating a typical weather year. The energy demand is based on the weather data of Karachi Pakistan. The building end-user energy requirements with Reinforced Concrete walls and SCIP walls are listed in Table 8 and Table 9, respectively.

In comparison to the reinforced concrete, SCIP wall panels have a significantly lesser demand of electrical energy. Building, using SCIP panels requires 22% less amount of energy, while cooling load is 25% reduced. The electricity demand for lighting and electric equipment is independent of the material used in the buildings. The comparison between Reinforced concrete walls and SCIP panels is shown in Figure 6 below.

TABLE 7. Thermal Properties of Wall Surfaces

Surface	Reflectance	U-factor (W/m^{2}K)
SCIP Wall Panel	0.35	0.566
RCC Wall	0.30	2.782
Floor & Finishes	0.08	2.585
RCC Slab	0.30	3.026
Window	-	5.906
Door	-	0.87

TABLE 8. Building energy requirements using RCC walls.

System	Electricity [kWh]
Lighting	4137.18
Electric Equipment	2026.71
Cooling	38356.76
Fans	800.38
Total End Uses	45321.03

TABLE 9. Building energy requirements using SCIP walls.

System	Electricity [kWh]
Lighting	4137.18
Electric Equipment	2026.71
Cooling	28704.95
Fans	568.78
Total End Uses	35437.62

ENERGY DEMAND OF BUILDING SYSTEMS

In this section, energy demand of different building systems obtained by EnergyPlus simulation is discussed and a comparison is drawn between SCIP and RCC buildings. The energy demand of building systems for the building using RCC walls is given in Table 10 and for SCIP building in Table 11, respectively.

The SCIP systems have considerably lower demand of electricity for building systems than that of RCC. The comparison of energy demand of building systems for RCC and SCIP is shown in Figure 7.

DESIGN AND SIZING OF HVAC SYSTEM

The HVAC system was designed for providing an indoor thermal comfort in accordance with the specification for ventilation and acceptable indoor air quality given in ASHRAE Standard 62.2 (ANSI/ASHRAE 2019; Ashrae 2019). The sizing of HVAC system depends on outdoor surface temperature, building activity schedules and thermal comfort control limits. The sizes and electricity demand of HVAC systems for thermal zones of the building are given in Table 12 for RCC walls incorporated building and in Table 13 for SCIP walls incorporated buildings.

In comparison with the reinforced concrete, SCIP wall panels have significantly small size HVAC systems requirements 21, 33, 19, 15 and 19 % less for thermal zone spaces 103, 104, 105, 106 and 107; respectively.

DESIGN OF HVAC SYSTEMS

HVAC systems are designed according to requirements of design size cooling supply air flow rate and design size gross rated total cooling capacity. The proposed design of HVAC systems is given in Table 14.

INTERNAL THERMAL ENERGY GAINS OF BUILDING

Internal thermal energy gains of building are important parameters to understand thermal comfort of indoor environment of thermal zones. These parameters include adequate indoor lighting level and ventilation rate, which are assessed with reference to ASHRAE Standard 55. Human occupancy releases thermal energy as well as increases carbon dioxide content within the thermal zone. According to ASHRAE 55, carbon dioxide generation rate must not be greater than 5 (10^6) m^3/s (ANSI/ASHRAE 2017; Persily & de Jonge 2017). The internal thermal energy gains for different thermal zones of building are given in Table 15, which clearly indicate that the values are within the limits; hence building behaviour for thermal comfort control is good.

TABLE 10. Building Systems Energy Demand for RCC

Utility System	Electricity Intensity (kWh/m^2)
Lighting	15.73
HVAC	148.87
Other	7.71
Total	172.31

TABLE 11. Building Systems Energy Demand for SCIP

Utility System	Electricity Intensity (kWh/m^2)
Lighting	15.73
HVAC	111.29
Other	7.71
Total	134.73

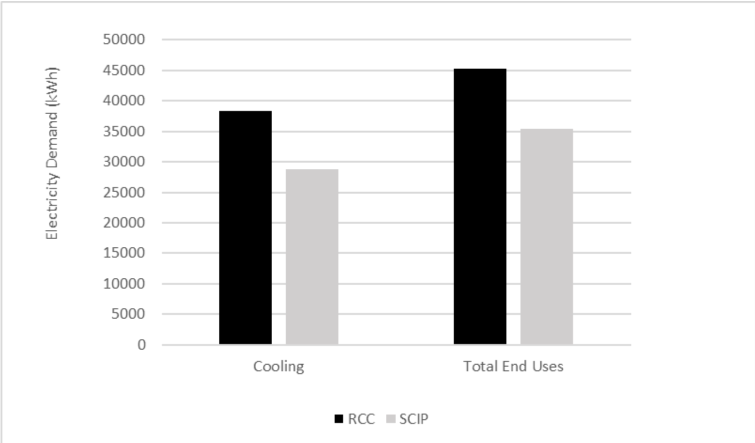

FIGURE 7. Comparison of Building Systems Energy Demand for RCC with SCIP

TABLE 12. Sizing of HVAC system for RCC walls incorporated building

Thermal Zone	Type of Room	Design Size Cooling Supply Air Flow Rate (m^3/s)	Design Size Gross Rated Total Cooling Capacity (W)
Space 101	Class Room	0.319	7910
Space 102	Class Room	0.333	8264
Space 103	Small Office	0.042	1044
Space 104	Small Office	0.110	2721
Space 105	Class Room	0.396	9824
Space 106	Class Room	0.389	9670
Space 107	Class Room	0.422	10481

TABLE 13. Sizing of HVAC system for SCIP walls incorporated building

Thermal Zone	Type of Room	Design Size Cooling Supply Air Flow Rate (m3/s)	Design Size Gross Rated Total Cooling Capacity (W)
Space 101	Class Room	0.319	7910
Space 102	Class Room	0.333	8264
Space 103	Small Office	0.033	828
Space 104	Small Office	0.073	1825
Space 105	Class Room	0.319	7910
Space 106	Class Room	0.333	8264
Space 107	Class Room	0.342	8491

TABLE 14. Proposed design of HVAC systems

Thermal Zone	Type of Room	No of 1-Ton ACs	Cooling Supply Air Flow Rate (m^3/s)	Gross Rated Total Cooling Capacity (W)
Space 101	Class Room	2	0.3	7000
Space 102	Class Room	2	0.3	7000
Space 103	Small Office	1	0.15	3500
Space 104	Small Office	1	0.15	3500
Space 105	Class Room	2	0.3	7000
Space 106	Class Room	2	0.3	7000
Space 107	Class Room	2	0.3	7000

TABLE 15. Internal Thermal Energy Gains

Thermal Zone	Type of Room	Maximum Number of People	Carbon Dioxide Generation Rate (10^6)	Maximum Lighting Level (Watts)	ASHRAE 55 Warning
Space 101	Class Room	3	0.0382	63.595	No
Space 102	Class Room	7	0.0382	140.142	No
Space 103	Small Office	25	0.0382	189.804	No
Space 104	Small Office	26	0.0382	198.289	No
Space 105	Class Room	25	0.0382	189.804	No
Space 106	Class Room	26	0.0382	198.289	No
Space 107	Class Room	27	0.0382	203.738	No

CONCLUSIONS

The building presented in this study is a research-based model for energy efficient design of a typical double storey school building in Pakistan. The SCIP walls for a building under seismic loadings have been evaluated by many researchers in Pakistan (Bhatti 2016; Khitab 2020). In this research an effort is made to determine the thermal performance and energy efficiency of the building structure for weather conditions over a whole year. By using EnergyPlus simulation software, the thermal behaviour of the building constructed with SCIP walls is evaluated under the weather conditions for a typical year. From results it can be concluded that:

1. Keeping in view the increasing energy demands in Pakistan, SCIP is a better approach towards energy efficient design of the buildings. SCIP walls, having a very low value of thermal transmittance (U-factor value 0.566 W/m^2K) provide better solution to avoid energy losses.
2. Building incorporating SCIP walls, have shown a significant drop in energy demand for cooling load; hence they reduce the size of HVAC system and its operational electricity cost.
3. SCIP is a built thermal insulating material, and therefore, does not need additional thermal insulation for the walls that are mostly exposed to outer environment and sun.
4. In comparison with the reinforced concrete walls, SCIP walls incorporated building have a substantially lesser demand for electrical energy. Building using SCIP panels demands 22 % lesser amount of electrical energy, while HVAC system load is 25 % reduced. The electricity demand for electric equipment and interior lighting is independent of the material used in the construction of buildings. SCIP wall panels have a significantly small-sized HVAC systems requirements; almost 20 % lesser than that of reinforced concrete walls building.
5. SCIP walls can have better thermal performance in regions with extreme weather conditions. This technique provides significant thermal energy savings, better thermal comfort and operational cost reduction for HVAC systems in a building.
6. SCIP walls can be readily available to reduce the cost and time for construction. The brick masonry, block masonry, wood framing and RCC structure requires a lot of time in preparation, construction and gain strength after a long time to bear the super structure loads.
7. Traffic noise is also a major problem in large cities and urban areas. SCIP is an insulating material, and helps to control noise within the perimeter of building.

DECLARATION OF COMPETING INTEREST

None.

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