Proceedings of 10th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2021 Month: October Volume: 10

Effect of Structural Lightweight Concrete on Energy Performance of a Residential Building

Bivek Joshi [a], Sanjaya Uprety [b]

[a, b] *Department of Architecture, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
Corresponding Email: [a] joshibivek10@gmail.com, [b] suprety@ioe.edu.np,

Abstract
In this modern world, everything is linked with efficiency in terms of energy, economics, or comfort. The inclusion of energy efficiency measures in construction industry could bring significant decrease in energy consumption. The materials used in the construction of building envelope can vary the consumption based on their thermal properties and thus contribute in overall life cycle cost of the building. The usage of materials having low thermal conductivity can substantially reduce the energy consumption in a building. To find the effect, a study was carried out on structural lightweight concrete (SLWC) with low thermal conductivity compared to normal weight concrete (NWC). A residential building on a warm and temperate climate of Dhangadhi was considered to find out the influence of SLWC replacing NWC on roof. The thermal properties; density, specific heat and thermal conductivity coefficients of the concrete types were extracted from literatures. The energy consumption of the building for heating and cooling periods for both NWC and SLWC were calculated using the Ecotect simulation. The results showed the decrement in energy consumption using the SLWC mix. All heating energy of the building marked the energy saving by 11.2 percent and total annual energy consumption by 4.7 percent using SLWC over NWC to maintain the indoor environment.

Keywords
Energy efficiency, structural lightweight concrete, normal weight concrete, thermal conductivity, thermal comfort

1. Introduction

The developments in prominent areas like construction industry and technology result in swift increment in energy demand. The inevitable increase in this energy demand brings imbalance to the environment causing climate change and many more adverse impacts. To minimize these kinds of problems a series of mandatory and encouraging policies have been implementing in many sectors especially in developed and developing countries [1]. With time, the advancement and improved lifestyles, people are in search of higher performance and efficiencies in every aspects. The construction sector consumes a significant amount of energy i.e. around 40 percent of the total energy consumption [2] and in Nepal it is even more in case of residential buildings [3].

The lightweight concrete provides variation in designs as it allows thermal properties as well as compressive strength alteration. It improves the building in terms of cost reducing the dead load, sizing of structural elements and energy consumption of the building during its life cycle. It also has better cyclic loading structural response and fire ratings [4].

The amount of energy consumed in a building is substantial and the operating energy has a major share compared to that of embodied energy. The materials used and operational energy in a building during their life cycle is an important parameter in determining the energy efficiency of the building and results in saving a considerable amount of energy and maintaining the comfort level [5]. The consideration of structural stability is substantially high with the people in comparison with other aspects of energy performance. As learnt from the key informants, the practice of using normal weight concrete for construction has led to considerable thermal discomfort in the region (Dhangadhi) and thus resulted in higher consumption of energy for maintaining the optimum environment. Considering this aspect, the change in construction material i.e., structural lightweight concrete as an alternative for normal concrete could be beneficial due to its superior performance thermally.

This paper aims to investigate the effects of structural lightweight concrete with lower thermal conductivity, its behavior on the energy performance of residential building in a warm and temperate climate and compare that with of NWC having higher thermal conductivity coefficient.

2. Methodology

Basically, the study followed some steps as guide lines for achieving the objectives. The review of various relevant literatures gave the ideas about the historical development, the impacts and effects that structural lightweight concrete make in a residential building in a certain climatic zone. The parameters like density, thermal conductivity coefficients of the concrete mixes were acquired through international research papers to put a step forward in this research. The thermal conductivity of NWC used is 2.5W/m-K and the unit weight is 2400kg/m3 and that of 450-FA/MK5 is 0.55W/m-K and 1884kg/m3 respectively. 450-FA/MK5 used fly ash and metakaolin as mineral additives in a proportion with cement and have a water cement ratio of 0.40 which used pumice as a coarse lightweight aggregate.

A recently constructed residential building at Chatakpur, Dhangadhi was selected for the analysis and as learnt from the key informant they feel significant thermal discomfort for which the building was further taken into consideration for study. The meteorological data of Dhangadhi was obtained from Department of Hydrology and Meteorology and a reliable weather file was extracted. Using the climatic analysis tool, the comfort zone for the region was noted from bioclimatic chart. The obtained data were used for energy simulation of the case residential building using Autodesk Ecotect software for NWC and SLWC scenarios. The modelling of the building was based on the site condition and divided into various zones. The zones were divided based on its purpose as bedroom, living and circulation space, kitchen, toilet and bathroom, and staircase and verandah. Staircase and verandah were not considered for the simulation. The data's for energy consumption and internal gains of those zones based on their operation schedule and occupancy were calculated. The location along with the software compatible ".wea" weather file of Dhangadhi, internal gains, comfort range and material properties were input for the analysis.

At first the simulation was run for the existing building conditions with normal weight concrete and the relevant results were obtained. Then SLWC was used for the new scenario in roof without altering the other parameters of the building. The results for heating and cooling loads are extracted for the new condition of SLWC and was compared to that of the base case roof with normal weight concrete.

3. Literature Review

3.1 Structural Lightweight Concrete

Lightweight concretes are classified based on their compressive strengths and densities and SWLC is one of the lightweight concretes based upon such classification. SLWCs are used as structural elements in buildings (column, roof elements, slabs and roofs).

According to the ACI 213R-14 standard, a minimum compressive strength of 21 MPa is recommended for SLWC [6]. According to the TS 2511 standard, SLWC are defined as concretes with a unit volume weight of 1400-2000 kg/m3, with a compressive strength of at least 17.2 MPa and suitable for use as a structural element in structures [7]. According to TS EN 206 standard, concretes with an oven dry unit volume weight of 800-2000 kg/m3 are defined as SLWC [8].

A concrete with a bulk density less than 1950 kg/m3 and compressive strength of 17 MPa or more is called structural Lightweight concrete. A lightweight aggregate is used to make the lightweight concrete. In present time, structural lightweight concrete is made around 25percent lighter than the concrete with normal weight without compromising its compressive strength, which is up to 60 Mpa. Structural lightweight concrete is durable with enhanced chemical, frost and fire resistance as compared to the normal weight concrete. This concrete also has permeability reduction. Similarly, the coefficient of thermal expansion of structural lightweight concrete is $7 \times 10^{-6}/\circ$ C, which is about one third of normal weight concrete. Therefore, its insulating thermal conductivity is reduced to 25 percent or more. The history of structural lightweight concrete date back to 1920s where it was generally used in the infrastructural construction in Europe, United States and China. Because of lower expansion coefficient and lower reduction of strength at elevated temperature, it has improved fire resistance [9].

3.2 Thermal Conductivity

Every material has its own capacity to conduct heat. The ability of a material to conduct/transfer heat is its thermal conductivity. It is generally denoted by the symbol 'k' but can also be denoted by 'λ' and 'κ'. Thermal resistivity is the reciprocal of thermal conductivity. Materials with high thermal conductivity are used in heat sinks whereas materials with low values of λ are used as thermal insulators. The concrete with low thermal conductivity restricts the transfer of heat efficiently than the concrete with higher thermal conductivity. The unit of measurement is W/m.K.

3.3 U-value of material

Thermal transmittance, also known as U-value, is the rate of transfer of heat through a structure (which can be a single material or a composite), divided by the difference in temperature across that structure. The units of measurement are W/m^{2}K. The better-insulated a structure is, the lower the U-value will be.

3.4 Previous Research Findings

Nayir et al. [10] carried out a research in Ankara (40.12°N, 33.00°E, altitude 949m), in Climate region III, representing the cold climate of Turkey, to find the effects of structural lightweight concrete on energy performance and life cycle cost in residential buildings. The study showed all the mixes of experimented SLWCs provided energy saving by about 18-25 percent on average compared to NWC. Also it is mentioned that in a similar study conducted in European countries, it was stated that approximately 15 percent reduction in heating energy was observed in apartments as compared to NWC. The results clearly showed the effectiveness of using SLWCs in cold climate during the heating period but during the cooling period (summer months) there was no significant difference observed using the SLWCs instead of NWC.

The energy performance of SLWAC in residential buildings was studied in Lisbon, Portugal. All SLWAC demonstrated the ability for providing higher thermal insulation than NWC. The results indicated that, depending on the type of LWA, the portion of the calculated energy attributed for an intermediate floor apartment in Lisbon was 11–19 percent lower for the case with SLWAC elements than for the case with NWC elements. The results also showed that SLWAC has the ability to contribute to the reduction of the heating energy needs anywhere in Europe, independently of the outdoor conditions. Percentage-wise, the greatest heating energy needs difference between apartments with SLWAC elements and apartments with NWC elements reached 15 percent, with the cooling energy needs not experiencing significant variation with the type of concrete [11].

In a structural or building envelope, there is limited data on the thermal properties of materials with lightweight aggregates. In this study, building materials with lightweight aggregate were tested to determine the thermal properties of the bulk materials, providing more accurate inputs to building energy simulation. These materials were tested in several commercial structures and in a simple model, use of sand lightweight concrete resulted in prediction of 15–17 percent heating energy savings and 10 percent cooling energy savings, while use of all lightweight concrete resulted in prediction of approximately 35–40 percent heating energy savings and 30 percent cooling energy savings. In more complex models, results showed superior thermal performance of lightweight aggregate building materials in 48 of 50 building energy simulations. Predicted energy savings for the five models ranged from 0.2 percent to 6.4 percent [12].

De Souza, 2014 [13] analyzed the thermal performance of the building envelope in lightweight concrete. Depending on the climate conditions, on the location of buildings and composition of concrete (water/cement ratio of mixtures), the replacement of lightweight aggregates lead to a reductions of 0.7 to 4.4 percent in the energy needs of summer and 3.7 to 19.4 percent in the energy needs of winter. The introduction of lightweight sand lead to reductions of the energy needs of up to 6.4 percent in summer and 40.0 percent in winter. It was verified in all locations a reduction of heat exchanges of the opaque envelope, as can be expected, almost exclusively through structural elements and can minimize the thickness of thermal insulation to comply with the minimum requirements of thermal quality of the external opaque envelope. The structural lightweight concretes provide better constructive solutions for improving thermal performance and to minimize the heat exchanges and also save energy necessary to guarantee the intended comfort levels.

4. Case Study and Research Context

For energy performance analysis, a building for a family of 4 was used in the reference residential building project with different concrete types. The building is located in Dhangadhi, in a warm and temperate climate. The floor plan of the building with zones is shown in Figure 1.

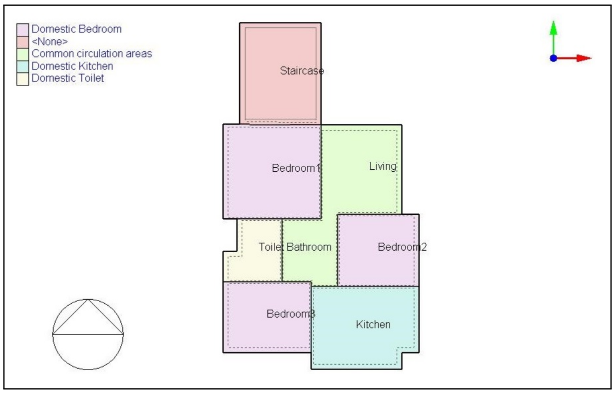

Figure 1: Floor Plan and Zones

The building, with a total floor area of 117.8 m2, has a living room + kitchen, 3 bedrooms, 2 bathrooms, staircase space and verandah. The height of the reference flat is 3.2m. This building is oriented in north-south direction. The building has both exterior and partition walls. The exterior wall is 225mm thick made up of solid brick wall and the interior wall is 105mm thick of same material which are both way plastered. The staircase and verandah spaces are not considered for energy analysis, so a floor area of 89.930 m2 is only analyzed excluding those spaces. The roof of the building is a flat roof and is composed of a 100mm reinforced concrete with internal plaster and cement screed and plaster on the outside.

Figure 2: Case building

This building can be classified as Group A i.e., residential building based upon the NBC classification. The windows use 6mm clear glass and the main door is of hardwood whereas the internal doors use wooden flush panel door. The roof element is one of the most vulnerable components for energy transfer.

5. Simulation and Analysis

5.1 Meteorological data

The building model was located in Dhangadhi, Far-West of Nepal (28.8° North, 80.55° East, altitude 187m). The climate in Dhangadhi is warm and temperate and the summers here have a good deal of rainfall, while the winters have very little. This location is classified as Cwa by Köppen and Geiger. The average temperature in Dhangadhi is 23.1 °C — 73.6 °F. About 1563 mm — 61.5 inch of precipitation falls annually. Meteorological data for Dhangadhi is given in Figure 3.

Dhangadhi Atariya	SE	NPL										
month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dry Bulb	12.7	16.8	20.4	25.7	28.7	29.6	28.3	28.4	27.4	24	18.7	14
Dew Point	10.7	13.3	16	14.7	19.1	23.6	25.6	25.8	24.8	20.6	15.6	11.2
Rel. Humidity	88.9	81.5	78	54.2	57.8	72.4	86.3	86.3	86.2	82.9	84.1	85.2
Global Hor Rad	265.4	418	480.5	556.2	561.2	495.6	400.1	421.5	424.5	425.1	366.3	311.3
Direct Norm Rad(Wh/m2)	221.6	489.5	498.3	565.7	539.6	393.6	214.4	245.4	294.2	424.6	448.6	381.1
Diffuse Rad(Wh/m2)	150.5	132.2	144	144.5	147.7	183.7	226	226.8	210.4	151.4	120.8	118.3
Wind Speed(m/s)	0.05	0.16	0.2	1.03	1	0.58	0.28	0.19	0.05	0.1	0.01	0.03

Figure 3: Meteorological Data of Dhangadhi

5.2 Climatic Analysis

Climatic analysis for Dhangadhi was carried out to obtain the comfort zone of the region. Using the ecotect weather tool, a psychrometric chart was developed from a weather file with climatic data of fourteen years, from 2004 to 2018, and an average comfort range of 22.8 to 27.7°C was obtained.

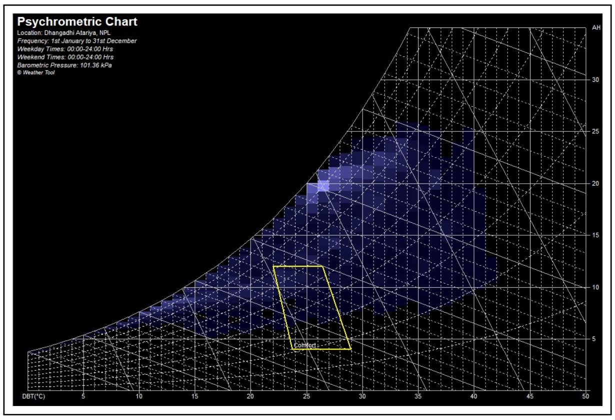

Figure 4: Bioclimatic Chart of Dhangadhi

Analysis shows that there is significant discomfort hours throughout the year and a minimal of time falls under comfort range. Summer months are hot with average monthly temperature as high as 29.6°C.

5.3 Simulation

Autodesk Ecotect Analysis software version 2011 is used to carry out the simulation. This software allows to perform the analysis from the earliest stages of conceptual design. It combines analysis functions with an interactive display that presents analytical results directly within the context of the building model. It calculates building's energy consumption by simulating its context within given environment. The compatible weather file of the region to be analyzed is input to perform the thermal analysis and other energy performance of a building. The monthly discomfort loads were calculated for NWC and alternative SLWC scenarios on roof element to project the discrepancies in energy performance. The other construction parameters were not varied and also the internal gains were kept constant.

5.3.1 Base Case Scenario:

Base case model is considered to be existing site condition. The base model was divided into different zones in Ecotect analysis modeling were depending upon its purpose, and parameters like material properties, comfort range, operational schedules, and internal gains were set as obtained from the existing scenario. As the zones were differentiated for their purposes, their internal gains, number of occupants and the activity of occupants varied.

5.3.2 Alternate Scenario

Alternate scenario was set for energy performance comparison. The alternate scenario comprises of a different roof material as SLWC (450-FA/MK5) keeping all other parameters of materials and gains unchanged. The properties of NWC and SLWC is listed below in Figure 5.

	NWC	SLWC (450-FA/MK5)
Thermal conductivity	2.5W/m-K	0.55W/m-K
Density	2400kg/m3	1884kg/m3
U-value with internal and external layers (Roof)	3.68W/m2K	2.41W/m2K

Figure 5: Base and Alternate scenario

6. Results and Discussion

After the simulation for energy performance using Ecotect, monthly heating and cooling loads for normal weight concrete and structural lightweight concrete for a residential building in Dhangadhi were obtained, as shown in Figure 6.

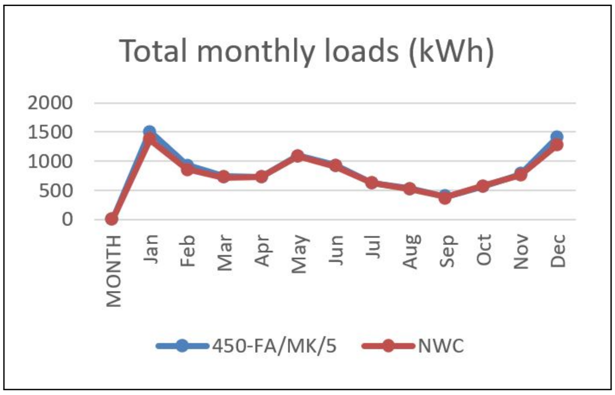

Figure 6: Total monthly loads in Dhangadhi

From the analysis, for all visible thermal zones for base case scenario, the results show the maximum heating of 84.33 kW at 04:00 on 16th January whereas the maximum cooling load of 95.12 kW at 21:00 on 4th June. The total annual heating load of the building is 5276.94 kWh and annual cooling load is 4999.72 kWh. The total monthly loads for the base case are shown in Figure 7.

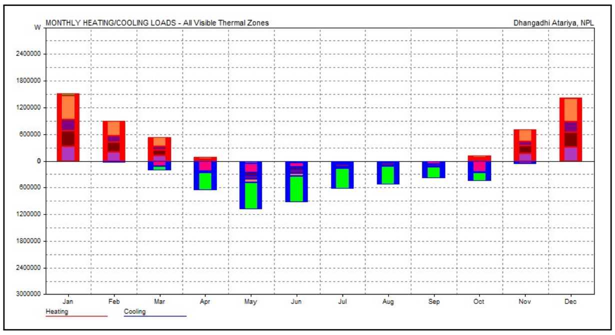

Figure 7: Monthly load/discomforts for all visible thermal zones NWC

Similarly, after varying the roof material by SLWC for alternate scenario, the maximum heating load is 77.34 kW at 04:00 on 16th January and the maximum cooling load is 89.60 kW at 21:00 on 4th June. The total annual heating load of the building is 4687.88 kWh and annual cooling load is 5110.03 kWh. The total monthly loads for the SLWC are shown in Figure 8.

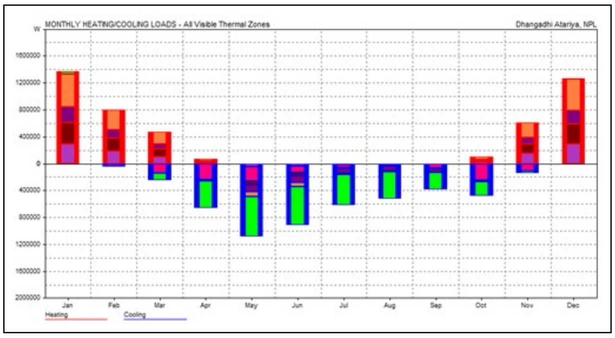

Figure 8: Monthly load/discomforts for all visible thermal zones SLWC

According to the obtained results, it can be observed that SWLC consume less total annual energy as compared to the base case. 450-FA/MK5 has lower total annual loads by 4.7 percent. The total annual energy consumption for NWC and 450-FA/MK5 is in Figure 9.

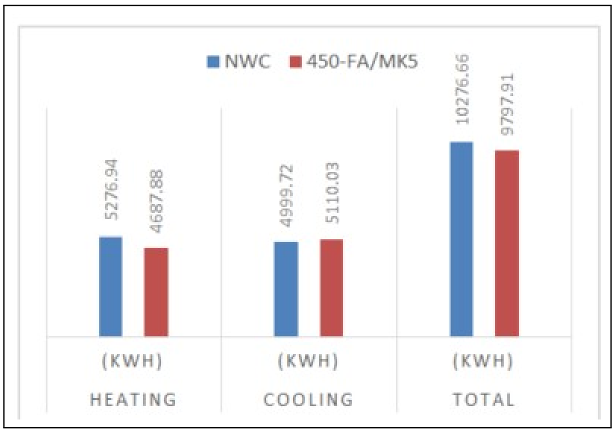

Figure 9: Total (Heating/Cooling) loads

The Figure 9 shows SLWC is better in terms of annual energy consumption. During winter months the alternate material was found to be efficient and can save heating load by 11.2 percent annually. The cooling load annually somehow contrast the result. NWC has 2.2 percent less cooling energy consumption throughout the year. Overall evaluation of the total loads shows that SLWC can be beneficial over a longer period of time.

7. Conclusion

In this study, the energy performance of SLWC and NWC were investigated based on the simulation results for warm and temperate climate region. For simulation, a residential building with 3 bedrooms, living and kitchen, 2 bathrooms, staircase and verandah was used. The thermal properties of concretes were obtained from the research papers and used during simulation in Ecotect software. The annual heating and cooling loads within the building were calculated based on the thermal properties and also the gains in the building. The results showed the use of structural lightweight concrete over normal weight concrete; other parameters kept unchanged; can save 478.75 kWh i.e. 4.7 percent of total energy load annually. During the heating period, 450-FA/MK5 contributed to 589.06 kWh less energy consumption than NWC. The practice of using structural lightweight concrete can be beneficial in energy as well as structural aspects. The use of such concretes can be efficient and lessen the energy demand in long run. Further study can be carried out to incorporate phase change materials that can enhance the properties of SLWC and analyze the effects on energy performance of the building.

References

[1] Ü Bahadır, X Thomollari, and V Toğan. Evaluation of energy-cost efficient design alternatives for residential buildings. *Journal of Construction Engineering, Management & Innovation*, 1(1):43–54, 2018.

[2] José V Martí, Tatiana García-Segura, and Víctor Yepes. Structural design of precast-prestressed concrete u-beam road bridges based on embodied energy. *Journal of Cleaner Production*, 120:231–240, 2016.

[3] Water WECS. Energy commission secretariat. *Energy Synopsis Report," Government of Nepal*, 2010.

[4] P Sundar Kumar, MJ Ratna Kanth Babu, K Sundara Kumar, and K Satish Kumar. Experimental study on lightweight aggregate concrete. *Int. J. Civ. Eng. Res.*, 1(1):65–74, 2010.

[5] Íizzet Yüksek. The evaluation of building materials in terms of energy efficiency. *Periodica Polytechnica Civil Engineering*, 59(1):45–58, 2015.

[6] ACI Committee 213. Guide for structural lightweight-aggregate concrete. American Concrete Institute, 2014.

[7] TS-2511. Mix design for structural lightweight aggregate concrete, 1977.

[8] TS EN 206: 2013+ A1. Concrete-specification, performance, production and conformity, 2017.

[9] Z Li. Advanced concrete technology; hoboken john wiley & sons. *Inc.: Hoboken, NJ, USA*, 2011.

[10] Safa Nayır, Ümit Bahadır, Şakir Erdoğdu, and Vedat Toğan. The effects of structural lightweight concrete on energy performance and life cycle cost in residential buildings. *Periodica Polytechnica Civil Engineering*, 65(2):500–509, 2021.

[11] Sofia Real, M Glória Gomes, A Moret Rodrigues, and J Alexandre Bogas. Contribution of structural lightweight aggregate concrete to the reduction of thermal bridging effect in buildings. *Construction and Building Materials*, 121:460–470, 2016.

[12] Tara L Cavalline, Jorge Gallegos, Reid W Castrodale, Charles Freeman, Jerry Liner, and Jody Wall. Influence of lightweight aggregate concrete materials on building energy performance. *Buildings*, 11(3):94, 2021.

[13] Diego Júnior de Souza. Thermal performance analysis of the building envelope in lightweight concrete. 2014.