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Design and Application of Cellular Concrete on a Mexican Residential Building and Its Influence on Energy Savings in Hot Climates: Projections to 2050

Ana C. Borbon-Almada ¹, Jorge Lucero-Alvarez ², Norma A. Rodriguez-Muñoz ^{3,*} ,
Manuel Ramirez-Celaya ¹, Samuel Castro-Brockman ¹, Nicolas Sau-Soto ¹  and
Mario Najera-Trejo ⁴

¹ Departamento de Ingeniería Civil y Minas, Universidad de Sonora, Blvd. Luis Encinas y Rosales, Centro, Hermosillo 83000, Mexico; ana.borbon@unison.mx (A.C.B.-A.); manuel.ramirez@unison.mx (M.R.-C.); samuel.castro@unison.mx (S.C.-B.); nicolas.sau@unison.mx (N.S.-S.)

² Facultad de Zootecnia y Ecología, Universidad Autónoma de Chihuahua, Periférico Francisco R. Almada, km 1, Chihuahua 31453, Mexico; jluceroa@uach.mx

³ Cátedras CONACYT, Centro de Investigación en Materiales Avanzados, Calle CIMAV 110, Ejido Arroyo Seco, Durango 34147, Mexico

⁴ Departamento de Ingeniería Sustentable, Centro de Investigación en Materiales Avanzados, Calle CIMAV 110, Ejido Arroyo Seco, Durango 34147, Mexico; mario.najera@cimav.edu.mx

* Correspondence: norma.rodriguez@cimav.edu.mx; Tel.: +52-614-439-4898

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Featured Application: A cellular concrete design for building walls to promote the reduction of heat transfer on the envelope and the energy-related CO₂ emissions without compromising the mechanical performance of the material.

Abstract: The thermal performance of economical housing located in hot climates remains a pending subject, especially in emerging economies. A cellular concrete mixture was designed, considering its thermophysical properties, to apply the new material into building envelopes. The proposed materials have low density and thermal conductivity to be used as a nonstructural lightweight construction element. From the design stage, a series of wall systems based on cellular concrete was proposed. Whereas in the second phase, the materials were analyzed to obtain the potential energy savings using dynamic simulations. It is foreseen that the energy consumption in buildings located in these climates will continue to increase critically due to the temperature increase associated with climate change. The temperatures predicted mean vote (PMV), electric energy consumption, and CO₂ emissions were calculated for three IPCC scenarios. These results will help to identify the impact of climate change on the energy use of the houses built under these weather conditions. The results show that if the conventional concrete blocks continue to be used, the air conditioning energy requirements will increase to 49% for 2030 and 61% by 2050. The proposed cellular concrete could reduce energy consumption between 15% and 28%, and these saving rates would remain in the future. The results indicate that it is necessary to drive the adoption of lightweight materials, so the impact of energy use on climate change can be reduced.

Keywords: cellular concrete; lightweight materials; thermal conductivity; electricity; dynamic simulation; housing; climate change

1. Introduction

The climate change effects over the different areas of life are considered one of the most critical and urgent aspects to attend, especially in the urban areas related to the use and consumption of material goods [1–3]. However, it is known that the Mexican industry builds and uses materials that are not in compliance with the precept of habitability and keeping the buildings within the thermal comfort zone, especially in hot climates [4,5]. The situation means that in order to reach thermal comfort, heating, ventilation, and air conditioning systems (HVAC) are intensively used, generating high electric energy demands affecting the seasonal electricity production and damaging the environment due to the intensive use of fossil fuels [6,7].

Nowadays, construction materials in Mexico present low capacity to prevent heat transfer into the buildings' interior. Most of the materials used in urban construction in Mexico are manufactured from mixtures with cementitious high-density materials and a very high thermal conductivity [8], leading to the need to establish a comparison between conventional and lightweight materials to determine their effects on energy savings in buildings. There are different dynamic simulation techniques to obtain quantitative information to assess the impact and propose improvements in the construction envelopes. An essential part of this work is that it will enable us to determine with high precision the thermophysical properties of the materials through reliable measuring techniques and specialized equipment and, as a result, obtain the thermal performance of the building.

Studies have been carried out that show the benefits of using lighter materials, which reduce dead loads in buildings, handling, and packaging costs. Another advantage is the resultant thermophysical properties that these materials present, which are advantageous because they reduce heat fluxes between the envelope and the exterior environment [9–11]. These materials are lightened with additives, mineral and synthetic substances, and some of natural origin [12,13]. There are materials on the market made from lightweight concrete created using additives (without gravel nor reinforcing steel). Those materials offer a change in their properties, basically as a function of the density and low thermal conductivity, such as cellular concrete. This type of concrete has properties that place them as materials with insulating properties and mechanical resistance to support loads.

These materials are manufactured through processes that, in addition to modifying their density and thermal conductivity with the inclusion of a foaming additive, are cured in an autoclave process (AAC: autoclaved aerated concrete) that consists of subjecting the material to high temperatures and pressure to achieve adequate mechanical resistance. These blocks are made of sand, gypsum, cement, lime, aluminum powder, and water to achieve a chemical reaction that generates hydrogen gas, achieved from the calcium hydroxide in the presence of water and aluminum powder. These materials can reach a nominal density of 500 kg/m^3 and an average compression strength of 40.8 kg/cm^2 with thermal conductivities of up to $0.09 \text{ W/m}\cdot\text{K}$ [14].

Lastly, commercial cellular concrete has a wide range of thermal conductivity values depending on the density. The thermal conductivity of lightweight concrete varies from 0.09 to $0.22 \text{ W/m}\cdot\text{K}$ and compared against other commonly used materials, and it has reductions of up to 90%.

1.1. Lightweight Construction Materials

Construction materials are generally dense elements; among the most common are concrete, mortar, and all kinds of water-based mixtures, cementitious and additives. The densities for the heavier materials have values above 2000 kg/m^3 , depending on the composition. These materials can become lighter if the composition changes, modifying the supplies to prepare the mixtures, either by changing their proportions or replacing some of the heavier elements for lighter ones or by including additives in the mixtures when it is still fresh.

A recent review of lightweight concrete explored and categorized investigations that contribute to the state-of-the-art in this field [15]. The incorporation of different types of waste materials into foamed concrete was analyzed. It was found that incorporating a maximum of 75% of waste material can be used as an additive in concretes, noticing that a high replacement can interfere with the hydration

process. However, the thermal conductivity can be lowered to the range of 0.1–0.7 W/m·K, which is low compared to conventional construction materials. Finally, while incorporating waste materials in foamed concrete will decrease the compression strength, fairly attractive materials can be achieved.

The structural performance of lightweight EPS-foam (LEPSF) concrete was studied for its application in slab systems [16]. The analyzed LEPSF concrete had a 35 MPa at a 1980 kg/m³ density, and it revealed excellent structural behavior. In another investigation [17], recycled concrete was developed to mitigate aggregate depletion and help with concrete waste disposal. Industrial waste was used to obtain a material of 1733 kg/m³ density and good mechanical properties. A new cellular concrete with densities of 500, 700, 800, and 1000 kg/m³ was created using a synthetic polymer foaming agent [18]. The new mixture properties' evaluation showed a compression resistance of over 60 kg/cm².

Wagh et al. experimentally investigated cellular concrete of three different densities (700, 1000, and 1400 kg/m³) using various additives [19]. The conclusions point out that an attractive thermal conductivity value was achieved; nonetheless, the mechanical properties were not studied. Font et al. investigated ecological alternatives to cellular concrete technology to contribute to a necessary shift in the circular economy [20]. One-part alkali materials (AAM-OP) and new alkali-activated materials (AACC) were combined with cement, aluminum powder, and residues to propose novel mixtures. Densities of 660 kg/m³ showed a compression resistance of 64 kg/cm² and a thermal conductivity value of 0.20 W/m·K. The experimental work was complemented with a life cycle analysis finding reductions of 96% on the kgCO₂eq per cubic meter of material compared against traditional materials.

Sodangi and Kazmi carried out a comprehensive analysis of coconut palm wood (CPW) for sustainable construction processes [21]. In the study, 13 impediments were listed and evaluated, which are pointed out as a key factor in the slow adoption of the material. Among the main obstacles were the high processing costs, low market demand, and reluctance to use the CPW due to the perceived low social status. Negro et al. explored various interventions for the application of novel sustainable materials in energy and seismic retrofits [22]. An easy to apply biocomposite was analyzed within the study, demonstrating an improvement in seismic performance and reducing the energy requirements of historical Italian buildings. In the investigation, laboratory tests and noninvasive methods such as thermography were used to understand the capabilities to improve the energy performance concerning the seismic retrofits without compromising the integrity of the building.

One of the main characteristics of the lightened materials is the decrease in their density. Thus their thermal conductivity [23] makes the lightened materials, as they have less weight, are workable, and demand less stress to the structures, generating benefits in logistics and costs in the construction sites. In addition to reducing weight, a low thermal conductivity is critical for the material's thermal performance. Additionally, a reduction in the heat flux through the building envelope will reach adequate thermal comfort and less energy demand due to HVAC.

This work will refer to cellular concrete as a lightened material which consists of a mixture of cement, water, and sand with a significant volume of voids through the incorporation of air with the use of foam, that generally is used to manufacture panels and to divide walls with or without mechanical load. The recommended foam density to achieve good stability is 60 kg/m³ [24]. It is generated using an additive and an instrument that converts the additive into foam using pressurized air. Its proportion is vital to consider the absolute volume that the foam will occupy within the mixture and adjust through laboratory tests.

Cellular concrete can be an environmentally friendly material with excellent insulation and low-density properties (300–1800 kg/m³) that yields moderate mechanical performance [25]. Cellular concretes are increasingly used in applications in the construction industry [26]. According to Chica and Alzate [27], there are two methods of manufacturing the cellular concrete depending on the origin of the material that generates the mixture's voids. The first is based on the chemical reaction, and the second is based on the manufacturing of foam, which is a generalized and commonly used method. However, it requires the appropriate equipment or machinery to ensure a dry foam, which is well integrated into the concrete mixtures.

Measurements of mortar and concrete mixtures' mechanical properties, both fresh and hardened, are common in construction materials laboratories. However, measures related to thermal performance are different, such as the case of thermal conductivity [28], since it requires specialized equipment if measurements are to be carried out with a low error. This work presents the resulting thermophysical values of the designed materials with high certainty levels, which allows estimating the building's thermal performance through dynamic simulations with a closer approach to reality.

1.2. Impact of Lightened Materials on the Thermal Performance of Buildings

The thermal performance of buildings, whether residential or nonresidential, depends on several factors; among others is the conformation of the thermal envelope that consists of walls, roofs, floors, doors, and windows. The crystal envelope consists of glazing elements such as windows, domes, and skylights, whereas the opaque envelope is the elements that include walls, floors, and roofs. When talking about lightened materials, this study refers to opaque materials for the construction of walls. Walls can be composed of several materials and layers. To calculate the global thermal resistance, it is crucial to know all materials' thermal conductivity, thickness, and geometric configuration. When buildings are located in extreme climates, whether due to cold or heat, these building systems' thermal responses are significant for achieving thermal comfort and reducing energy consumption.

There are studies of thermophysical properties of various materials that provide information for the design of opaque elements in buildings; one of the investigations worked with materials from agricultural residues to replace cement and fine aggregates [29]. Eiras et al. [30] studied the incorporation of granulated rubber to prepare lightened mortars, resulting in lightening the mixtures and good mechanical properties.

In Mexico, conventional construction systems are based on hard materials such as simple concrete, reinforced concrete, sand-based masonry, and mixtures with binders such as cement and plaster combined with additives. The insulation of construction systems is carried out mainly by adding industrialized insulation materials whose technical specifications are determined in the existing market. However, the lightening of the aforementioned massive systems is not common due to the lack of technology or knowledge in the construction sector. This work proposes designing a series of lightened mixtures using foam and fabricating nonindustrialized cellular concrete on-site, without going through the autoclaving procedure.

The Mexican codes related to the production and testing of concrete mixtures used in this investigation refer to lightweight concrete in general, with a particular subsection for cellular concrete. Complimentary international codes as ASTM C1693-11 [31] for autoclaved aerated concrete (AAC) and ACI-523.3R-14 [32] for cellular concrete were also considered. ASTM-C-1693-11 refers to the characteristics of cementitious products with the inclusion of a foaming agent in steel molds. Whereas in ACI-523.3R-14, critical aspects of cement-based materials proportions, curing, and physical properties of the mixtures are described.

In México, the standard NOM-018-ENER-2011 has the objective to establish the testing methodology for thermal resistance evaluation of national materials with insulating properties [33]. NMX-C-460-ONNCCE-2009 regulates the thermal resistance specifications that apply to residential buildings [34]. Its purpose is to improve the housing habitability and reduce the energy demand related to heating and cooling systems considering the corresponding thermal zone; this code is in concordance with ISO-10456 [35]. All of the mentioned codes are related to the design and production of lightweight materials characterized to have low density and low thermal conductivity. Correspondingly, the regulations help to classify the materials as insulating.

On the other hand, two codes that focus on the envelope and are intended to limit the heat gains in buildings are NOM-020-ENER-2011 [36] and NOM-008-ENER-2001 [37]. Their primary purpose is to reduce the energy demand for cooling; the first code has applications in residential buildings, whereas the second in nonresidential buildings.

1.3. Hot Climate Energy Requirements and Codes

In 2008, air conditioning equipment represented 19.7% of the electricity consumed in the residential sector [38]. Regarding 2018, 30% of the residential sector's energy consumption was used to achieve adequate comfort levels in hot climates [39]. To reduce energy consumption in the residential sector, various public policies for efficient use and energy savings have been implemented in Mexico. These efficiency measures have allowed an average user's consumption in temperate climates to decrease since 2001 until reaching consumption levels similar to those of 1989 in 2014. On the other hand, the consumption of average users in hot climates has increased by 19.4% for this same period (1989–2014). These differentiated phenomena are explained, to a large extent, because the most effective public policies have been aimed at improving the efficiency of electrical equipment (lighting and refrigerators). In contrast, they have made very little progress regarding the envelope of buildings, which is what determines in a more significant way the energy consumption in the houses located in regions with a hot climate [40].

The NOM-020-ENER-2011 criterion is based on comparing the heat gain of a projected building, which must be less than a reference building. The heat gain of the reference building is established in this standard and depends on the climatic zone where the construction is planned. This code does not specify a minimum R-value for the materials that comprise the walls or ceilings, but this physical property must be considered to calculate heat gains. On the other hand, the standard NMX-C-460-ONNCCE suggests R-values for roof and walls in three categories (minimum habitability and energy savings) for each climate zone [34]. However, this standard is not mandatory in comparison to NOM-020. Although NOM-020 does not establish an R-value, this property can be determined indirectly from the heat fluxes considered for the design of the reference building. In the particular case of Hermosillo, this reference value is 2.1 m²K/W. In comparison, NMX-C-460-ONNCCE suggests a minimum R-value of 1.00 m²K/W and qualifies as an energy-saving level when it presents an equivalent value of 1.40 m²K/W or higher.

Although the current regulations influence the minimum R-value of the walls and ceilings of new homes, they have not been established in the present reality due to various factors. However, some rules and programs allow obtaining social housing subsidies and more generous financing at more affordable interest rates. They include envelope elements as part of a series of "eco-technologies" that must be considered to grant these kinds of support. Thus, these programs are the real factor that promotes insulating materials in social housing construction [40].

1.4. Energy Use Increase Due to Climate Change

The conventional approach of using Typical Meteorological Year (TMY) data to analyze and quantify buildings' energy consumption has been used and discussed for several years. Various investigations indicate that buildings' thermal and energy performances in the long term are not adequately represented with the commonly used TMY. Researchers emphasize the importance of creating future weather data that considers the yearly variations due to the nature of the standard TMY, neglecting the annual variations caused by the weather changes. In the investigation by Zhu et al. [41], they modified the TMYs using the Morphing method to calculate the energy demand of buildings in Shanghai, taking into consideration the RCP4.5 from the Intergovernmental Panel on Climate Change (IPCC). Huld et al. presented a methodology to generate TMYs based on satellite data; then, the weather data was validated against 487 European meteorological stations [42]. The authors mention that the TMY concept, conceived more than 30 years ago, could be replaced by using time series with 10 years or more data and that this will result in accurate information and faster results. Their standard deviation indicates that a better approach could be obtained by applying a more extended time series rather than employing regular TMY data.

In the research by Hosseini et al., a machine learning method is presented to improve the weather files required for the energy performance analysis on buildings, taking into account climate change scenarios [43]. The investigation proposes a methodology for general circulation models (GCM) to

estimate the hourly future building energy performance. The quantile-quantile method was applied to diminish the data bias to fit the GCMs to a specific geographic location. Afterward, a hybrid classification-regression model was applied to reduce the corrected GCM data. The designed workflow utilizes observed weather data to find similar historical weather data patterns and then use it to generate future weather data sets.

Many studies have performed energy and thermal evaluation of buildings to confirm the future use of modified TMYs. Farah et al. calculated the future energy consumption of buildings to increase the cooling requirements between 29% and 31% and a decrease in the heating requirement between 21% and 22% [44]. Pyrgou et al. [45] performed a study to contrast measured weather data from selected weather stations in Perugia to understand the urban heat island (UHI). As a result of this investigation, the authors state that their future work will be centered on creating weather files that consider the impact of the appearance of heatwaves and cold waves, UHI, and other climate change effects. Chakraborty et al. [46] emphasize that accurate weather information is vital to estimate buildings' energy performances, which is currently achieved using TMY files as the TMY3 file, conceived by the Department of Energy (DOE). The TMY3 represents past climate behavior, and it has been found that it does not adequately estimate the economic feasibility and future energy performance. This investigation introduces a novel hybrid modeling methodology that estimates the probability and establishes a machine regression to predict long term performance. Tianzhen Hong et al. [47] performed a large-scale simulation of three office buildings to quantify the impact on the peak electricity demand for 30-year weather data. This study's particular conclusions are that the annual climatic variation affects the peak electricity demand compared to the overall building's energy consumption.

Another issue studied is the impact of the electric grid's energy demand over the years [48]. The electricity demand differences were modest at the early projection time; nevertheless, the changes become more substantial in the last 10 years of the analysis. The cooling demand leads to an increase in energy consumption and the temperature in winter and summer. Clarke et al. [49] found that global energy demand increases by 0.1% for every 2 °C increase in temperature. The results also indicate that the net demand differences are not homogeneous worldwide; for regions where heating requirements are higher, the expectation is that cooling demands will increase. An analysis made within the European scope shows that temperature increase is imminent [50]. As a consequence of climate change, a 2090 scenario shows growth between 50.8% and 119.7% of annual heating and cooling demand. Wang and Chen [51] also found a relationship between energy use and climate change effects depending on the geographic zone. In the U.S., by 2080, an overall energy decrease for climate zones 6 and 7 and an increase in the climate zones 1 to 4 will occur. It was found that by 2080, passive cooling will have a positive impact in San Francisco and Seattle, but it will not be satisfactory in San Diego.

Resch et al. 2021 proposed a dynamic life cycle assessment (LCA) methodology that addresses temporal aspects and future technological improvements [52]. Additionally, a case study was included where 20 buildings were analyzed through the presented technique. The buildings' operations were analyzed considering the climate change impacts related to materials from the production stage, transport, and end-of-life aspects. The estimated metrics expose the implications and drivers required to generate the statistical emission profiles. The encountered results found that the building lifetime, the time horizon, and the construction waste are the most sensitive parameters to mitigate the associated carbon emissions in construction materials.

1.5. Assessment and Early Design Strategies in Residential Buildings to Mitigate Climate Change

Early design approaches and interventions have been mentioned as key to successfully contribute to climate change issues in residential buildings and detached homes. Karimpour et al. [53] evaluated the changes in heating and cooling due to climate change in Adelaide, Australia. Although there is currently a predominant heating demand in the studied city, according to the analysis, by 2070, the city will predominantly require energy for cooling. In the study, the decisive strategies in housing are high insulation levels, increased roof insulation, and highly reflective roof coatings. On the other hand,

glazing appears to be one of the most influential parameters due to all of the evaluated houses obtaining ratings of 7 stars or more (1–10, the fewer stars it means a better energy performance). Figueiredo et al. [54] performed an analysis of the energy demand modification in Portugal's residential buildings. It was found that the energy requirements will increase from 5% to 60%, and the appliances were identified as the main drivers for the energy demand. Likewise, in Hong Kong [55], an increase in the cooling requirements among 12.3% and 21.6% of 2017–2100 was found. An increase in the interior temperature was a costless and straightforward strategy as an adaptive thermal comfort approach.

The energy consumption of residential buildings in a Mediterranean climate was calculated using TRNSYS for 2048–2052 and 2096–2100 [56]. The findings showed that the most effective actions are reducing infiltrations and increasing levels of insulation. Invidiata and Ghisi [57] obtained the change in Brazil's residential buildings' energy requirements using the IPCC A2 scenario. It was found that the cooling needs will increase around 56–112% (2050) and 112–185% (2080), while a decrease of up to 94% on the heating requirements by 2080 can be expected. The use of the proposed passive strategies could reduce the energy requirements by up to 50%.

A study in Chile showed that according to climate change, the mean temperature is expected to rise between 0.68 and 1.51 °C by 2050–2065 [58]. The results point out that the heating demand will decrease between 13% and 27%; likewise, changing the current regulations must be considered due to the foreseen future failure in compliance. Flores-Larsen et al. [59] analyzed the heating and cooling energy consumption in Argentinian representative housing applying the climate change A2 scenario. The authors found that the heating requirement will increase around 6.0–7.6 kWh/m², while the cooling will increase by 1.7–8.4 kWh/m². Finally, Gerek and Arsan [60] explored the increase in energy consumption and CO₂ emissions related to heating and cooling equipment in Turkey's residential buildings by 2080. The analysis showed that the decisions that directly affect the buildings' energy and environmental performances are the ones made on the SHGC and the U-values of the non-opaque surfaces.

This work develops a methodology based on the design of experimental mixtures with cellular concrete, its elaboration, and determination of thermophysical properties, such as fresh state properties, to determine its utility in the constructive activities and dry state to determine the compression strength, thermal conductivity, and specific heat. Subsequently, the evaluation of potential energy savings throughout a year using dynamic simulation and thus quantifying the CO₂ emissions to the atmosphere and a scenario projection of climate change in the future. This research's main contribution is to determine the useful mixture of low density and thermal conductivity and the thermophysical properties experimentally, using specialized equipment. Finally, finding the electric energy savings in the buildings and reducing CO₂ emissions for future scenarios.

2. Materials and Methods

This project was carried out in two stages: experimental and dynamic simulation. The experimental stage consists of the design and manufacture of lightened mixtures according to the corresponding normativity and the measurement of thermophysical properties. Simultaneously, the simulation stage contemplates determining the cases to analyze the prototypical house's related geometry, typical construction materials for the wall, and envelope to compare the results against the proposed materials.

This work begins with designing a mixture of natural mortar (sand–cement–water) in a proportion of 1:4 as a control mixture. A new mix was designed with an additive or foaming agent to reduce the density of the mixture. Once the theoretical design was done, the material was fabricated in the laboratory to test the thermophysical properties such as fluency and air content in a fresh state. The properties related to its rigid state, such as the compression strength, thermal conductivity, and specific heat, were measured for both the control mixture and the lightened mixture.

The second stage contemplates using prototypical social housing [8], developed with traditional constructive systems in the northwest of Mexico (lightened slab, walls made with hollow concrete blocks, and conventional doors, windows, and floors). A series of dynamic simulations were carried out

throughout a year to evaluate the building's thermal performance. Subsequently, further simulations were carried out, integrating the designed cellular concrete on the walls. Finally, the electric energy consumed and the CO₂ emissions were compared to determine the savings to use lightened materials against the conventional materials.

2.1. Experimental Method

The project's experimental stage consists of designing a natural 1:4 sand–cement mortar mixture as a control mixture and then lightening it with foaming agents to obtain densities lower than the original. The mixtures were manufactured, and their physical properties were measured in a fresh state. The test samples were then manufactured, and after a 28-day setting (dry state), the lightened samples were ready to determine the compression strength, thermal conductivity, and specific heat using specialized equipment for six different densities (800, 1000, 1200, 1400, 1600, and 1800 kg/m³); all of the above following current regulations.

From the results, the best samples were selected based on the load capacity and density to be used as construction elements. A natural setting was considered in the manufacturing process, hydrating the mixture with water, a conventional procedure at the worksite, and different from industrial-scale that uses an autoclaving process to produce cellular concrete.

2.1.1. Theoretical Design of a Cellular Concrete Mixture.

Table 1 shows the theoretical proportions of the control and lightened samples. CPC-30-R cement with a density of 3000 kg/m³ graded natural sand and contaminant-free water. The sand was studied using granulometric analysis to determine its properties according to the standard NMX-C-077-ONNCCE-1997 [61]. These analyses showed that the sand has a density of 2560 kg/m³ and an absorption percentage of 1.5%, a contamination percentage of 5.8%, a fineness modulus of 2.8, and 4.5% loss on washing [62]. The recommended foam density to achieve good mix stability is approximately 60 kg/m³. This is assured by using an additive and an instrument that converts the additive to the foam using pressurized air. The volume that the foam will occupy within the mixture must be considered and adjusted through laboratory tests for its proportioning.

Table 1. Proportion of cellular concrete for different densities in a volume of 15 L and percentage of fluidity.

Property	Control	C1	C2	C3	C4	C5	C6
Mixture density (kg/m ³)	2135	1800	1600	1400	1200	1000	800
Mixture volume (m ³)	1.000	0.8432	0.7496	0.6569	0.5622	0.4685	0.3748
Cement CPC 30R (kg)	6.225	5.243	4.661	4.078	3.495	2.913	2.330
Sand (kg)	21.225	17.896	15.91	13.91	11.93	9.942	7.95
Water (kg)	4.575	3.861	3.43	3.00	2.574	2.145	1.71
Foam (kg)	0	0.141	0.22	0.31	0.39	0.478	0.563
Fluidity (%)	106	124	125	125	122	122	122

The cellular concrete volume ratio concerning the original mortar's total volume was determined to obtain a cellular concrete mix of specific density. This was achieved by dividing the desired density by the density of the control mix; in other words, the foam will fill the difference between these volumes; according to these criteria, the proportions were calculated to obtain cellular concrete of different densities, with a fluidity range of 105 ± 15%.

Conventional laboratory equipment and tools such as a mixer, molds for samples, basic tools, and test equipment to obtain the mortar characteristics in a fresh state were used for the manufacture and tests of the samples. Initially, the control mixture was fabricated with natural cement–sand mortar in a 1:4 ratio, according to the dosages presented in [62].

Cellular concrete lightened mortars were also manufactured, adding the foaming agent according to the proportions shown in Table 1, which correspond to the densities of 800, 1000, 1200, 1400, 1600, and 1800 kg/m³. The brand of the additive used to generate the foam is BUINY A.E./C.C.100, a foaming additive.

The equipment used to generate preformed foam for the cellular concrete is called: UTC 400-E/simple. Once the mixtures were made, their properties in the fresh state were measured in the laboratory; in relation to the fluidity and according to NMX-C-144-ONNCCE-2015 [63], the tests determined that the mixture presents an adequate fluidity and an air content of 15–70%. Then, three cubic samples of 0.05 × 0.05 × 0.05 m were manufactured both for the control sample and for each of the cellular concrete samples of different densities; they were tested to determine compression strength after 28 days, according to the standard NMX-C-061-ONNCCE-2015 [64]. Additionally, samples with dimensions of 0.15 × 0.15 × 0.04 m were manufactured to measure thermal conductivity and specific heat.

2.1.2. Manufacture of Samples and Construction Components

According to the current regulations, after manufacturing the mixture, 0.05 × 0.05 × 0.05 m samples were produced to carry out the compression tests (Figure 1a). Additionally, 0.15 × 0.15 × 0.04 m samples were made for the thermal conductivity, specific heat, and density tests (Figure 1b). Once the properties were determined, 0.12 × 0.2 × 0.4 m blocks were manufactured (Figure 1c).



(a) Compression test probes: 0.05 × 0.05 × 0.05 m



(b) Probes for thermal conductivity, specific heat and density tests: 0.15 × 0.15 × 0.04 m



(c) Produced cellular concrete blocks: 0.12 × 0.2 × 0.4 m

Figure 1. Test samples and produced cellular concrete blocks.

The proposed wall constructive systems are based on nonstructural cellular concrete blocks of 0.12 × 0.20 × 0.40 m with a 1600 and 1800 kg/m³ density. The proposed materials are within the range, according to Mexican regulations [65], lightened mortars of a density of 1600 to 1800 kg/m³ can be used on masonry with a compression strength among 60 and 100 kg/cm², respectively. Likewise, according to the NMX-C-486-ONNCCE-2014 [66], a type II mortar with a compression strength value equal or higher than 125 kg/cm² is recommended to attach the blocks.

Compression resistance of 40–45 kg/cm² was determined through interpolation for the 1600 and 1800 kg/m³ designed lightweight blocks, respectively. An additional 800 kg/m³ mortar is proposed for improving lightness and insulation; the use of this material is subject to its use as a filler in nonbearing sections.

2.1.3. Measurement of Thermophysical Properties in the Dry State

After the $0.05 \times 0.05 \times 0.05$ m cubic samples were set, the compression strength was measured at days 3, 7, and 28 by triplicate for each of the studied densities. The mean value of the measurements was used for the calculations. A semiautomatic Digimax Dual Chamber with 33/15 kN capacity of compression and flexion was used for the compression strength measurement on the cellular concrete samples following ASTM C109/C109M [67].

The thermal conductivity and density of the $0.15 \times 0.15 \times 0.04$ m were measured with the guarded hot plate method. The probes were subject to three temperature gradients, and then a polynomial regression was performed to obtain the thermal conductivity value. A Guarded Hot Plate Apparatus Lambda Meter Ep 500e was used for the measurement of thermal conductivity (W/m·K) with an accuracy between 0.7% and 1% and reproducibility between 0.2% and 0.5% in accordance with ISO 8302:1991 [68], ASTM C177-19 [69], EN 1946-2 [70], UNE-EN 12664:2002 [71], UNE-EN 12667:2002 [72], UNE-EN 12939:2001 [73], and DIN52612 [74].

To measure specific heat ($\text{MJ}/\text{m}^3 \cdot \text{K}$), probes of $0.15 \times 0.15 \times 0.04$ m were drilled for the sensor placement. For this purpose, a KD2-PRO Thermal Properties Analyzer, Decagon Devices Inc., was used with a sensor SH-1 for hard materials with an accuracy of $\pm 10\%$ by the standard ASTM D5334-08 [75]. In Figure 2, the utilized equipment for compression strength (a), thermal conductivity (b), and specific heat (c) can be observed.

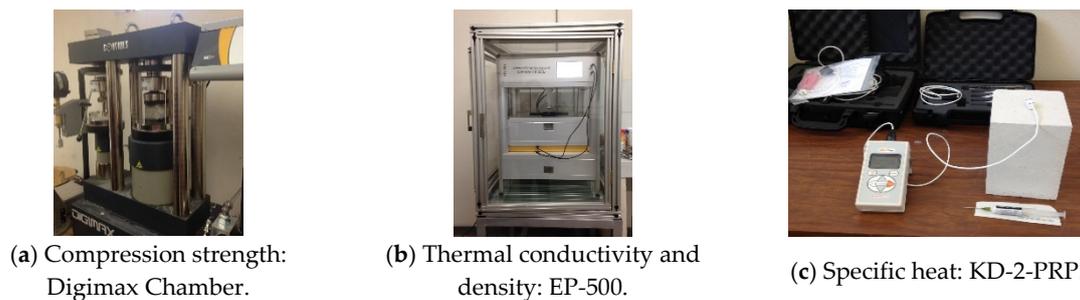


Figure 2. Equipment used in compression strength, thermal conductivity, and specific heat measurements.

2.2. Dynamic Simulation

The software TRNSYS 17 was used to determine the energy performance of the building. This building is located in the city of Hermosillo, Sonora, with a BWh climate which corresponds to a hot desert climate, according to the Köppen–Geiger classification. The software Meteororm provided the weather file for a typical year, and commonly used materials were considered for the house envelope constructive systems.

For this study, the thermal comfort range was calculated according to the ASHRAE 55-2004 standard [76]. The calculated temperature range was $20.6\text{--}27.3$ °C, and it was used to operate the heating and cooling systems with the type 56 from TRNSYS.

The simulation uses a simplified heating and cooling energy requirement estimation through the type 56 mentioned above. The premise is that the cooling and heating demand directly depends on a defined indoor temperature range. Therefore, the required output power to maintain the indoor temperature within the comfort range results in a positive value for the cooling energy and a negative value for the heating necessities. This is related to the convention that heat needs to be added or removed from the studied building.

2.2.1. Physical Model of the House and Location

The studied house represents a typical construction of social housing in the northwest region of Mexico [8]. The house is attached to the neighboring houses, while the main facade is exposed to

the outside. The house's facade is oriented to the south and has a floor to ceiling height of 2.5 m; it has a backyard, and an interior small service patio, one of the rear walls is also adjacent to the posterior home. The house was built on a land of 90 m² and has a construction area of 55.8 m², and has a floor area/window wall ratio of 0.07. The home is divided into the following thermal zones: (1) North Bedroom, (2) South Bedroom, (3) Bathroom, and (4) Kitchen-Living Room. The house layout and facade from the studied case study can be observed in Figure 3.



Figure 3. Analyzed case study. (a) Floor plan layout, (b) facade.

The investigated case study was chosen due to two crucial parameters: extremity on the selected climate and the housing typology classification. The studied city is located in extreme weather; the situation makes it critical to rethink this housing design and propose affordable materials with appropriate thermal properties. In 2015, the population census counted that the state of Sonora has 812,567 households, from which 257,537 are located in the city of Hermosillo, and 99.36% of them had electricity access [77]. On the other hand, Hermosillo consumes 32% of the electricity of the state, and residential buildings located in the city use 13.5% of the annual consumed electricity [78].

The selected house corresponds to a dwelling classified as “popular housing,” according to the Mexican National Housing Commission (CONAVI) [8]. Such classification considers six types of homes; the smaller three are considered as “social housing” and corresponds to the economic (40 m²), popular (50 m²), and traditional (71 m²) housing. While the remaining three are the medium (102 m²), residential (156 m²), and residential plus (+188 m²) houses.

The analyzed building belongs to a housing segment of low-income families and, therefore, the least expensive option on the market. The distinctive low-cost social housing built in Sonora and Mexico has helped massive construction, thus benefiting millions of families. Nevertheless, they are made with basic materials and have a low-quality thermal performance in many climatic circumstances. With the demographic increase and the subsequent surge in housing demand, the immediacy to improve the housing quality within the context of climate change, especially for the most vulnerable sector, is seen as a more than appropriate action.

2.2.2. Climatic Conditions of the Arid Weather

The region of study is considered part of the dry weather (B), according to the Köppen–Geiger classification. This weather presents scarce precipitation, which incites a broad thermal gradient between day and night. It is possible to reach a maximum temperature of up to 50 °C while it drops below −10 °C at night.

The IPCC has six scenarios, with one group in the A2, B1, and B2 families and three within the A1. In the A1 family, the following scenarios were set. The A1F scenario consists of the intensive use of fossil fuels, A1B, a balanced scenario, and the A1T with a predominance of non-fossil fuels. On the other hand, the A2 scenario represents a scheme where regional economic development is more

substantial. The technological change is slower; the coal is again employed, and oil and gas shares are reduced. In this work, additionally to the typical TMY, information from 2030 and 2050 is also integrated, considering a balanced scenario from the A1 storyline (A1B) and the A2 scenario from IPCC [79,80]. Figure 4 shows monthly averages of temperature (T_{amb} , °C) and the global horizontal radiation (Gh, W/m^2) of the historic TMY (T_{amb} : 2000–2009, and Gh: 1991–2010), and the A1B and A2 scenarios.

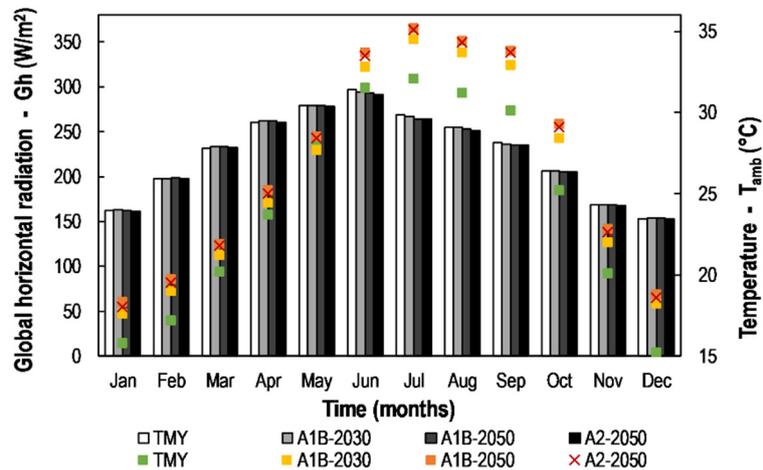


Figure 4. Temperatures and global horizontal radiation.

Table 2 shows a summary of the performance in the radiation, the average and maximum temperatures for the periods considered. According to scenario A1B, an increment of average temperatures (T_{avg}) of 1.84 °C by 2030 and 2.61 °C by 2050. In comparison, reaching maximum temperatures (T_{max}) of up to 46.1 °C in 2030 and up to 45.4 °C by 2050, giving, as a result, an increase in the average temperatures from 2000–2009 of up to 3.7 °C (2030) and 3.0 °C (2050). Within the A2 scenario for the year 2050, the minimum temperatures will increase up to 2.2 °C compared to the TMY from 2000–2009.

Table 2. Summary of the global horizontal radiation and temperatures.

	Global Horizontal Radiation (Gh, W/m^2)				Temperatures (°C)			
	TMY	A1B-2030	A1B-2050	A2-2050	TMY	A1B-2030	A1B-2050	A2-2050
Average	226.55	226.37	225.62	224.74	24.15	25.99	26.75	26.59
Maximum	1206.00	1111.00	1156.00	1124.00	42.40	46.10	45.40	46.50
Minimum	/	/	/	/	3.00	4.50	5.80	5.20

2.3. Case Studies

According to the test results of the lightened mortar, the composition of three constructive systems was proposed. To evaluate the energy savings, the proposed wall systems were compared against a conventional concrete block wall. The house walls are composed of three layers: cement plaster, block, and gypsum plaster, where the block is replaced according to the analyzed systems.

The incorporation of cellular concretes in the manufacturing of construction elements is based on density. According to Ni Frank Mi-Way et al. [81] and Sari and Sani [82], the densities of 1600–1800 are recommended to manufacture slabs and other load elements where greater strength is required, such as partitions for home construction. On the other hand, materials with densities of 800 or less are proposed for fillings.

Table 3 shows the considered blocks for each study case, representing different constructive systems for the wall. Case 0 is the base case where the walls are constructed with a typical hollow

concrete block of 0.12 m of thickness with conventional plaster, lightened slab, with traditional doors and windows. Cases 1 and 2 will vary the composition of the walls, for which the substitution of blocks is made with cellular concrete. Case 3 represents a highly lightweight filler cellular material. In all cases, the house is constructed with a lightened slab composed of white waterproofing, concrete, lightened slab, and gypsum plaster, with an R-value of 0.8 [62].

Table 3. Selected systems for dynamic simulations.

Case	Wall Composition	Mixture (Agreement with Table 1)
Case 0	Concrete hollow block	Control
Case 1	Solid cellular block (1800 kg/m ³)	C1
Case 2	Solid cellular block (1600 kg/m ³)	C2
Case 3	Filler cellular material (800 kg/m ³)	C6

3. Results

3.1. Thermophysical Properties

Table 4 shows the results of compression strength, thermal conductivity, and specific heat tests for the hardened state of the cellular concrete mixtures.

Table 4. Result of thermal conductivity measurements, compression strength, and specific heat for the dry mixtures.

Property	C1-1800	C2-1600	C3-1400	C4-1200	C5-1000	C6-800
Density (kg/m ³)	1810	1610	1457	1216	1065	863
Thermal conductivity (W/m·K)	0.2958	0.2517	0.2480	0.2057	0.1682	0.1399
Compression strength (kg/cm ²)	88.8	77.5	54.3	18.6	10.4	8.3
Volumetric specific heat (MJ/(m ³ ·K))	1.56	1.64	1.14	1.34	0.92	1.72

According to the results shown in Table 2 regarding the compression strength values, it is determined that those with densities of 1800 and 1600 comply with a value greater than 75 kg/cm², according to NMX-486-ONNCCE -2014 standard [66]. It can be observed that a decrease in thermal conductivity is correlated to a reduction of the density. The effectiveness in the reduction of the thermal conductivity as a material with insulating properties will be evaluated in the next section of this paper, throughout a dynamic simulation of a building.

According to all of the above, a contrasting analysis is proposed using conventional materials as a base case against lightened cellular concretes with densities of 1800 and 1600. Besides, a study is carried out with the cellular mortar with a density of 800, which can be used as a confined filling material.

In Table 5, the R-values of the evaluated systems are shown. Here, it can be observed that the R-value of the analyzed cases increases from 0.2874 (Case 0) to up to 0.9651 for the less dense mixture (Case 3). The data in Table 4 was used to carry out the dynamic simulations to determine the energy use and thermal comfort of the cases listed in Table 5.

Table 5. Analyzed systems.

Case	Wall Composition	R _{value} (m ² ·K/W)
Case 0	Concrete hollow block	0.2874
Case 1	Solid cellular block (1800 kg/m ³)	0.5131
Case 2	Solid cellular block (1600 kg/m ³)	0.5841
Case 3	Filler cellular material (800 kg/m ³)	0.9651

3.2. Dynamic Simulations

In this section, the temperatures that occur inside the house are presented. Additionally, the annual energy demand related to heating and cooling systems (kWh) and the CO₂ emissions associated with the systems' use is given.

3.2.1. Indoor Temperatures

Table 6 shows the annual average, maximum, and minimum indoor temperatures that take place inside the house when no HVAC system is operated. The results were obtained from the cases analyzed, representing a traditional concrete block wall (Case 0) and the other three cases (1–3) corresponding to the three different densities of the cellular concrete studied. Likewise, the temperatures that would occur in the scenarios (A1B) of climate change for the years 2030 and 2050 are presented, as well as for the heterogeneous scenario known as A2 for 2050. In Table 6, values in bold black letters were marked to represent average temperatures that are considered as too high and completely out of the thermal comfort range. Additionally, in the maximum and minimum temperatures, the numbers in red and blue bold letters were added to point out very high (in red) and very low (in blue) indoor temperatures.

Table 6. Annual temperature behavior without air conditioning systems.

	Case	TMY	A1B-2030	A1B-2050	A2-2050
Average temperatures (T_{avg} , °C)	Case 0	26.32	28.04	28.80	28.61
	Case 1	26.47	28.20	28.95	28.76
	Case 2	26.51	28.23	28.99	28.80
	Case 3	26.67	28.39	29.14	28.95
Maximum temperatures (T_{max} , °C)	Case 0	39.13	41.55	42.48	41.59
	Case 1	38.85	41.24	42.16	41.22
	Case 2	38.69	41.07	41.98	41.09
	Case 3	38.41	40.75	41.62	40.98
	Case 0	39.13	41.55	42.48	41.59
Maximum temperatures (T_{min} , °C)	Case 0	11.07	12.58	13.54	13.07
	Case 1	11.77	13.25	14.24	13.74
	Case 2	12.01	13.52	14.49	14.00
	Case 3	12.62	14.18	15.10	14.65
	Case 0	11.07	12.58	13.54	13.07

It is observed that when using the TMY with historical information, the average temperatures occurring inside are adequate. However, for all future scenarios, the average annual temperatures that are registered are greater than 28 °C and considered out of the comfort range. On the other hand, the maximum temperatures reached inside the house range between 38.41 °C (Case 3, TMY) and 42.48 °C (Case 0, a1b-2050). It is also noted that cellular concrete's application manages to reduce, on average, 0.75 °C. This maximum temperature occurs inside the house when the temperatures are compared between the case with a conventional block (Case 0) and the lighter cellular concrete (Case 3).

Similarly, when observing the house's minimum temperatures, the lower would be 11.07 °C (Case 0, TMY) and 15.10 °C (Case 3, A1B-2050). The average difference between the conventional block (Case 0) and the cellular concrete of Case 3 would be 1.57 °C.

3.2.2. Thermal Comfort

Table 7 shows the promoted mean vote (PMV) of the houses with no HVAC systems, finding similar tendencies as those found on temperatures. The PMV values were indicated in bold black, red, and blue color. Where the bold black PMV value represents a warm sensation, and the red and blue connote an inappropriately high and low PMV.

Table 7. Averaged promoted mean vote (PMV) without air conditioning systems.

	Case	TMY	A1B-2030	A1B-2050	A2-2050
Average PMV	Case 0	0.39	0.80	0.98	0.94
	Case 1	0.43	0.84	1.02	0.98
	Case 2	0.44	0.85	1.03	0.99
	Case 3	0.48	0.89	1.07	1.02
Maximum PMV	Case 0	3.43	3.99	4.21	4.00
	Case 1	3.36	3.92	4.14	3.91
	Case 2	3.32	3.88	4.09	3.88
	Case 3	3.25	3.79	4.00	3.85
	Case 0	3.43	3.99	4.21	4.00
Maximum PMV	Case 0	-3.42	-3.03	-2.78	-2.90
	Case 1	-3.24	-2.85	-2.60	-2.73
	Case 2	-3.18	-2.78	-2.53	-2.66
	Case 3	-3.01	-2.61	-2.38	-2.48
	Case 0	-3.42	-3.03	-2.78	-2.90

It can be observed that average PMV is mostly around the “slightly warm” condition, especially for the results of the cases related to the year 2050, where values greater than 1.0 were calculated. On the other hand, the maximum PMV values were between 3.21 (Case 3, TMY) and 4.21 (Case 0, A1B-2050). These PMV values would be considered entirely unacceptable from the thermal comfort perspective since it exceeds the “hot” condition, generating extreme heat stress. The minimum PMV values registered are between -2.48 and -3.42, which in the same way would cause extreme cold stress in the occupants of the house.

3.2.3. Annual Energy Demand

The annual energy demand generated in the houses composed of walls with different lightening levels was calculated for the analyzed IPCC scenarios. Figure 5 shows the respective heating and cooling demand. It is observed that the cases where the TMY with historical information is used result in lower energy requirements, meaning that out studies carried out on the use of energy in buildings could result in an underestimation of energy requirements necessary to keep a house in thermal comfort. When analyzing the energy requirements in scenarios A1B (2030 and 2050) and A2 (2050), it is observed that, in general, there would be a greater energy demand. The energy demand associated with air conditioning would increase; however, the heating requirement would be reduced over the years.

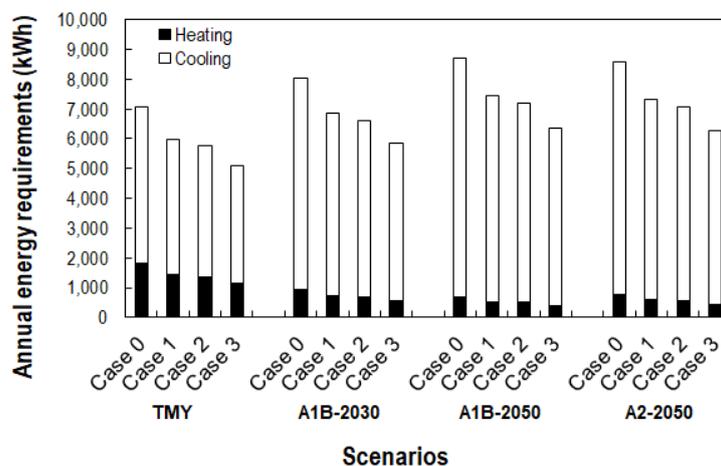


Figure 5. Annual energy requirements per studied case.

This figure clearly shows that applying lightweight cellular concrete would reduce the overall energy requirement of the house. For example, in scenario A1B-2030, when comparing the energy required for the heating and cooling systems in the house for Case 0 (8025 kWh) and Case 3 (5850 kWh), a reduction of 37% is observed. Likewise, the energy demand for cooling the house reduces by 25% for A1B-2030 and A1B-2050. As for the heating, the required energy would be reduced over the years. However, when applying the lightened concrete, it decreases by 43% for both A1B-2030 and A1B-2050 scenarios.

When comparing the energy consumption to cool the house, it was found that these will increase by 35% (A1B-2030), 52% (A1B-2050), and 49% (A2-2050) for the historical TMY and the traditional construction of the house (Case 0). In the same way, energy consumption to heat the house will be reduced, on average, 96% (A1B-2030), 61% (A1B-2050), and 58% (A2-2050).

3.2.4. Reduction of Annual tCO₂e Emissions

The CO₂ emissions calculation was undertaken considering each scenario's annual electricity requirements and based on the Mexican Electricity System "Emissions Factor Report", published in February 2020. The 2019 factor is reported to be 0.505 tCO₂e per MWh [83]. Figure 6 shows the reduction in the annual CO₂ emissions per studied case and scenarios. This figure shows that, as expected, the lower density concrete allows a decrease of CO₂ emissions. For example, for the A2-2050 scenario a reduction of 14.48% of tCO₂e emissions for Case 1 is achieved, 17.52% for Case 2, and 26.88% for Case 3.

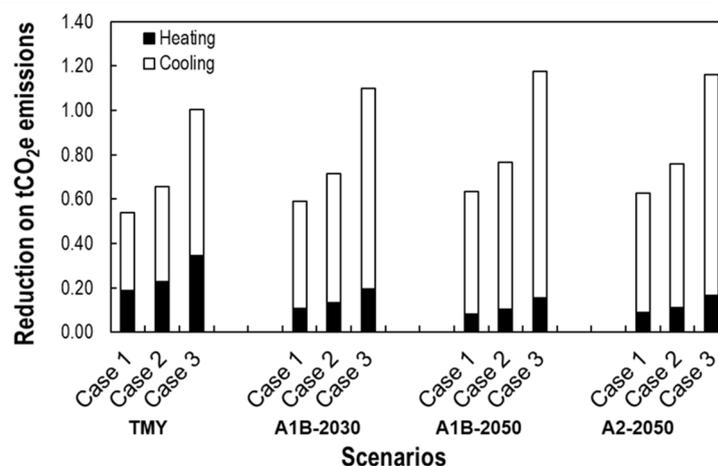


Figure 6. Annual tCO₂e emissions per studied case.

4. Discussion

The residential sector is responsible for the consumption of fair amounts of energy with a substantial environmental impact. The families that live in economic housing in developing countries often face the decision to pay for the energy related to air conditioning systems or live with thermal discomfort. For this reason, in this investigation, lightweight cellular concrete mixtures were proposed for their prospective application on economical housing. The materials were designed and applied to walls to reduce energy consumption due to the use of air conditioning systems in a city with a hot arid climate. The presented methodology's main objective was to acquire accurate information to perform a whole building examination of the material to be recommended for new constructions.

The results showed a reduction in the density and thermal conductivity of the designed materials. The reduced weight and thermal conductivity culminate in energy-saving benefits and the consequent decrease of energy-related CO₂e emissions when applied to a residential building. Thus, this investigation's outcomes show a viable proposal to be immediately used in the construction industry.

The presented methodology can be implemented in a variety of materials and aggregate combinations for numerous building applications. This is especially relevant for on-site materials manufacture, as this practice is scarcely a custom in construction. Additionally, the suitability of implementing measurement with specialized equipment under national and international standards gives certainty to the designed materials' future performance.

The house's thermal performance was calculated through the dynamic simulations, finding very unpleasant indoor conditions when no air conditioning systems are in use. Temperatures of up to 42.48 °C could be achieved inside the home if the traditional concrete blocks continue to be used in construction by 2050. The minimum temperatures are also very low, finding 11 °C in the coldest season of the year. Likewise, even when the average temperatures were analyzed for future scenarios, they are around 28 and 29 °C, which are out of the thermal comfort range.

Similar results were found when the promoted mean vote (PMV) values were explored. For the A1B and A2 scenarios in the year 2050, the averaged PMV is near 1.0, which would result in a "slightly warm" sensation. Even though all of the analyzed mixtures do not result in an adequate average PMV value, the conventional concrete block (Case 0) presents the extreme PMVs. A 4.21 PMV for the 2050 A1B scenario and -3.42 with the historic TMY.

The application of the cellular concrete mixtures results in a lower annual energy requirement. The cooling energy is significantly reduced; nevertheless, a decrease in heating energy was also accomplished. From the yearly energy requirements figure, it can be observed that if the conventional concrete block continues to be used massively for economical housing, the air conditioning energy requirements will increase up to 49% by the year 2030 and 61% by the year 2050 (A1B scenario). Even with the lightweight material application, energy requirements by 2050 will resemble the concrete block energy performance.

The annual energy demand of 7062 kWh was determined for a house located in a hot desert climate through dynamic simulation, where 74% of that energy is destined for cooling. According to the constructed area of the house, this value corresponds to the energy consumption of 126.6 kWh per square meter. This energy consumption is reduced in a range of 15.1–28.1% if the hollow concrete block currently used to construct social housing is replaced with solid blocks of the cellular concrete proposed in this investigation.

If IPCC scenarios are considered, the annual consumption of the base case increases at levels ranging from 143.8 (A1B-2030) to 155.9 kWh/m² (A1B-2050). The percentages of energy reduction given by the use of cellular concrete remain constant for these scenarios, but the magnitude of savings increases from a range of 19.1–35.6 kWh/m² to ranges of 21.0–31.0 and 22.5–41.7 kWh/m² for scenarios A1B-2030 and A1B-2050, respectively.

Finally, through the CO₂e emissions reduction analysis, it was found that the implementation of the novel cellular concrete mixtures accomplishes a fair reduction in the emissions related to the energy use of a relatively small home (55.8 m²).

The study of the thermophysical properties of construction materials should transit to direct applications. This is key to understand the repercussions that imply their implementation in real environments. The knowledge of the mixture's final thermal behavior has implications not only on the technical level, since the benefits are acute at the economic and environmental level, especially with climate change impacts in sight. The environmental benefits of the performed projections are of great usefulness for current decision-making and significant profits for the future, especially in planning public policy for climate change mitigation.

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