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Simulating the impact of air-bubble reinforced concrete on building energy efficiency

Alireza Mohtadi[a,b], Mohammad Ghomeishi[c,*], Ali Dehghanbanadaki[d,e]

[a] *Department of Architecture, Gheshm Branch, Islamic Azad University, Gheshm, Iran*

[b] *Research and Development at the Materials and Technology Institute of Iran Concrete Clinic, Tehran, Iran*

[c] *Department of Architecture, Damavand Branch, Islamic Azad University, Tehran, Iran*

[d] *Department of Civil Engineering, Damavand Branch, Islamic Azad University, Damavand, Iran*

[e] *Research Center of Concrete and Soil, Damavand Branch, Islamic Azad University, Damavand, Iran*

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Abstract

Energy consumption in buildings is predominantly attributed to heating and cooling of enclosed spaces. To address this, a concrete facade system enhanced with additives in ultra-high efficiency concrete has been proposed to potentially lower building energy usage. This study investigates the impact of incorporating air bubbles into concrete on its compressive and thermal properties. A total of 30 samples were tested: 15 for compressive strength and 15 for thermal performance. The test results were utilized to simulate energy consumption in two chambers, each measuring 2×2 meters with a height of 2.5 meters, using concrete walls with varying thermal conductivity coefficients via DesignBuilder software. Multiple scenarios were analyzed to assess building energy performance. The numerical modeling results indicated a positive outcome, with a 30% reduction in energy consumption associated with conventional concrete walls. These findings suggest that advancements in facade systems, including the use of exposed concrete panels or alternative materials, could significantly reduce energy use, fuel consumption, and overall economic costs in large-scale construction.

Keywords: building facade, energy efficiency, energy reduction, cold climates
2020 MSC: 97M80

1 Introduction

Climate change often exceeds natural variability due to human activities, resulting in phenomena that are increasingly at odds with natural patterns. These human-induced disruptions significantly contribute to severe climate changes on Earth. In particular, modern times have seen a surge in greenhouse gas emissions driven by excessive fossil fuel consumption. Evidence of these changes includes the frequent occurrence of sudden and abnormal weather patterns. Researchers and scholars globally are actively seeking solutions to reduce energy consumption in buildings.

*Corresponding author
Email addresses: mohtadi.a@gmail.com (Alireza Mohtadi), ghomeishi.m@damavandiau.ac.ir (Mohammad Ghomeishi), a.dehghanbanadaki@damavandiau.ac.ir (Ali Dehghanbanadaki)

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A key focus is analyzing data from existing constructions and renovations, using simulations to identify ways to improve thermal performance in buildings. This includes examining the efficiency of various construction materials and systems, such as metal, concrete, and newer building technologies [8].

The growing use of concrete frames in construction—due to their availability, cost-effectiveness compared to metal structures, and the material's high plasticity—has made concrete a preferred choice for building facades. This preference highlights concrete's role as a crucial element in both the interior and exterior of buildings, ultimately contributing to occupant comfort [1].

Residential and commercial buildings account for approximately 40% of annual energy consumption in the United States. In Iran, between 2005 and 2018, energy consumption in architecture represented about 50% to 38% [11]. A significant portion of this energy is used for heating and cooling enclosed spaces within buildings [5]. Facade systems, which manage heat transfer between the exterior and interior environments, are crucial for enhancing energy efficiency. Recent research has introduced innovative facade solutions, such as fiber-reinforced plastics, phase change materials, thermal resistance materials [18], and dynamic insulation systems. These studies have provided valuable insights into the energy performance of advanced facade systems. However, there is a gap in research concerning concrete facades incorporating foaming materials, which is the focus of this study. Therefore, we will review existing research on similar topics to address this gap.

This research investigates the use of steel, aluminum, and metal fibers in concrete mixtures to develop a method for calculating the effective thermal conductivity of concrete. The study combines these fibers and analyzes their impact using simulation methods. Concrete samples with and without fibers (control) were prepared, and the effects of air voids, coarse grain shape, and fiber type on thermal conductivity were examined. To validate the results, cylindrical specimens with a diameter of 100 mm and a height of 50 mm were extracted from both the control and fiber-reinforced concrete samples [17]. These specimens were then subjected to a heat transfer test.

The findings indicate that incorporating these fibers into concrete can significantly reduce heat transfer through walls, particularly in concrete pavings. Laboratory results showed a notable reduction in energy consumption, approximately 5% [3]. Additionally, the inclusion of carbon and glass fibers in concrete panels enhances structural strength and improves energy efficiency. These panels demonstrated superior performance in cold climates and moderate conditions, especially in terms of moisture transfer, compared to conventional concrete panels [1].

The use of phase change materials (PCMs) in buildings can significantly impact thermal comfort and energy consumption, particularly in the desert climate of Iran. Research conducted over four selected days in Shahrizad demonstrated that rooms equipped with PCMs experienced a temperature increase of nearly 2 degrees Celsius both day and night. In terms of thermal comfort, these rooms exhibited optimal performance, with the Predicted Mean Vote (PMV) index ranging from 0 to 0.5 throughout the day and night [12]. Consequently, incorporating PCMs into wall compositions can reduce the maximum heat load by approximately 5.7% and overall energy consumption by around 3.3% [13]. Additionally, a foaming agent was combined with cement, sand, and water to create concrete panels. A half-cut newspaper, measuring 395×580 mm, was used as a form for these panels. The specific weight of the concrete was 1100 kg/m^3. The results revealed that the thermal conductivity coefficient of this concrete was reduced by 18 to 21% compared to Autoclaved Lightweight Concrete (ALC) panels [4]. Furthermore, the use of sand in the concrete mix led to a reduction in thermal conductivity by 0.492 W/m·K, representing a 28% decrease compared to conventional concrete [16].

In cold regions, both urban and rural environments are typically designed to be dense and compact to reduce thermal exchange between indoor and outdoor spaces. This design strategy aims to minimize drafts and prevent indoor heat from escaping during the winter months. Natural ventilation is often limited in these climates to enhance heat retention. Many homes in these areas have traditionally placed the kitchen at the center of the building to optimize heating efficiency and reduce heat loss. However, living conditions and socio-cultural factors in cold climates have evolved over time. The once-dominant architectural styles and urban patterns are now less common, giving way to new preferences in residential design. As cultural and social dynamics shift, along with rapid technological advancements, contemporary architectural practices increasingly reflect these changes. The growing emphasis on reducing reliance on fossil fuels and addressing the scarcity of non-renewable resources has led to a push towards cleaner, more sustainable energy methods with minimal environmental impact [15].

In the Iranian plateau, traditional building designs were tailored to specific climatic conditions. However, changing tastes and diverse preferences have significantly influenced modern residential and housing styles [9]. For instance, both designers and residents have altered building facades in response to increased utilization of interior spaces. Previously, thick walls were used in cold climates to reduce heat exchange by increasing wall density. As a result of evolving preferences, these walls have become thinner over time, which has led to higher energy consumption in colder cities.

The need for this research is evident when examining building patterns and designs that are adapted to specific climatic conditions without altering current accepted standards or incurring significant costs in the design or construction of concrete structures. It is essential to optimize precast concrete walls and structures according to the local climate and building type to significantly reduce energy consumption in these buildings and achieve economic benefits on a national scale. Therefore, the objectives of this research are:

- Investigate how incorporating air bubbles into ultra-high efficiency concrete affects its compressive strength and thermal properties.
- Conduct tests on concrete samples to measure thermal conductivity and assess the performance of concrete facades with different thermal conductivity coefficients.
- Use DesignBuilder software to simulate and compare energy consumption in two chamber models (2×2 meters with a height of 2.5 meters) featuring concrete walls with varying thermal properties.
- Analyze the simulation results to determine the potential reduction in energy consumption associated with the use of advanced concrete facade systems compared to conventional concrete walls.

2 Research methodology

2.1 Compressive strength tests

Concrete samples were prepared using $15 \times 15 \times 15$ cm cube molds, following the standard method outlined in BS EN 12350-1 [7]. This mold size and sampling standard were consistent with practices used in other research. The cement grades selected for the study were 300, 350, and 400 kilograms per cubic meter (see Table 1). Initially, concrete mixtures with these cement grades were prepared without any additives. Subsequent samples were made using bubble-forming materials, as specified in Table 2. The bubble-forming compounds and their proportions adhered to ASTM C-260-86 standards [2]. The compressive strength of the samples was tested according to BS EN 12390-3 standards [6], and the thermal conductivity coefficient was measured using ISO 10456 standards [10]. Figure 1 illustrates the test setup and procedures in detail.

2.2 Determination of thermal conductivity coefficient

To determine the thermal conductivity coefficient of concrete, established standards and methodologies were followed. Concrete samples were initially prepared and cured according to standard procedures. Cylindrical specimens with a diameter of 100 mm and a height of 50 mm were used, adhering to the ASTM C-518 standard for measuring thermal conductivity. The samples were placed in a thermal conductivity testing device, designed to measure the rate of heat transfer through the concrete. The device, which was powered by electricity, facilitated controlled heating and cooling with one disc fixed at the bottom and another at the top of the sample. As heat was applied, the temperature differences between the discs were recorded. The thermal conductivity coefficient was calculated based on the recorded data, which assessed the heat flow through the sample and its thermal response. This method ensured accurate measurements of the thermal conductivity coefficient, enabling a comprehensive evaluation of the concrete's insulating properties.

2.3 Simulation

Based on the laboratory results from both the reference concrete sample and the modified sample, the data was entered into DesignBuilder software for modeling and analysis. This information was then presented in tables and diagrams to compare the heat transfer performance of the simulated rooms with the reference sample.Two rooms, each with dimensions of $2 \times 2 \times 5.2$ meters, were selected for the simulation (Figure 3). One room served as the reference model, constructed with concrete walls and roof with a specific weight of 2400 kg/m^3 and a thermal conductivity coefficient of 2.5 W/m·K, as determined by the tests. The other room, designated as the main example, also featured concrete walls and roof with the same specific weight but had a lower thermal conductivity coefficient of 1.7 W/m·K, as found in the tests.

The simulation was conducted under the coldest weather conditions near the city of Eshtehard, and for improved accuracy, a UPVC door was included in the model to better reflect real conditions. The concrete composition details are provided in Table 1.

Table 1: Concrete mixing plan

Approximate concrete volume mixing ratio (for bag cement)			grade of concrete (KG)	Weight of dry concrete without water (KG)
Cement	gravel	Sand		
300	1135	760	300	2195
350	1140	735	350	2210
400	1104	736	400	2240

Table 2: Details of the tests

Test	Addition percentage of air bubble	Type of additives	Cement grade	Sample dimensions
Ts-1	0	No air bubble	300	$15 \times 15 \times 15$
Ts-2	1	air bubble	300	$15 \times 15 \times 15$
Ts-3	2	air bubble	300	$15 \times 15 \times 15$
Ts-4	3	air bubble	300	$15 \times 15 \times 15$
Ts-5	4	air bubble	300	$15 \times 15 \times 15$
Ts-6	0	air bubble	350	$15 \times 15 \times 15$
Ts-7	1	air bubble	350	$15 \times 15 \times 15$
Ts-8	2	air bubble	350	$15 \times 15 \times 15$
Ts-9	3	air bubble	350	$15 \times 15 \times 15$
Ts-10	4	air bubble	350	$15 \times 15 \times 15$
Ts-11	0	air bubble	400	$15 \times 15 \times 15$
Ts-12	1	air bubble	400	$15 \times 15 \times 15$
Ts-13	2	air bubble	400	$15 \times 15 \times 15$
Ts-14	3	air bubble	400	$15 \times 15 \times 15$
Ts-15	4	air bubble	400	$15 \times 15 \times 15$

Figure 1: The method of making samples and preparing samples

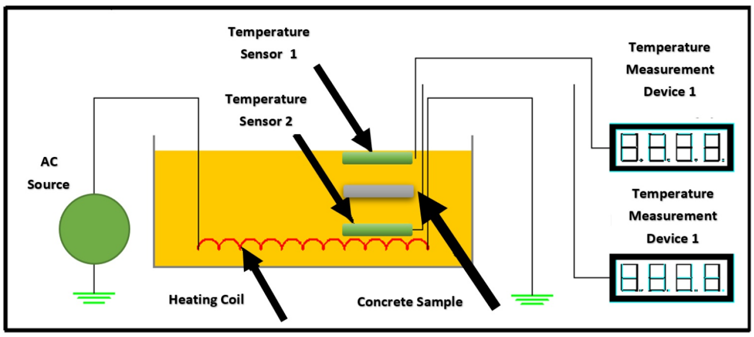


Figure 2: Schematic of the thermal conductivity coefficient test

Figure 3: The plan and view of the prefab Benti room for simulation.

3 Results and discussions

3.1 Compressive strength

Since the primary focus of this study is the evaluation of thermal conductivity, we will briefly address compressive strength while emphasizing the results of thermal conductivity and simulations. Figure 4(a) illustrates the proportionality limit (p), which represents the stress value at which the stress-strain curve remains linear. In the diagram, samples TS-6 and TS-11 are nearly aligned with the elastic limit, while sample TS-1 reaches its elastic limit sooner. After surpassing the elastic limit, samples TS-6 and TS-11 continue to exhibit behavior close to the yield point, indicating that the stress levels after this point lead to a rapid and linear increase in strain, approaching the ultimate resistance point.

It is worth noting that the yield point in some materials is not always distinctly clear, and the offset method is typically used to determine this point. However, this method was not necessary for this research. The test results show that the TS-11 sample, with a water-to-cement ratio of 40%, exhibits higher compressive strength compared to the other samples. In Figure 4(b), the proportionality limit (p) is shown as the stress value where the curve maintains linearity. Concrete samples with a grade of 300 display behavior close to the elastic limit (E). The control sample and the TS-5 sample, which contains 4% foaming material, approach the elastic limit sooner. After crossing the elastic limit, samples TS-2, TS-3, and TS-4 show similar behavior and approach the yield point in a comparable manner. This pattern indicates that, beyond this stress point, strain increases rapidly and linearly, leading to the ultimate resistance point. Thus, the test demonstrates that the TS-1 sample, with a water-to-cement ratio of 40% and 1% bubble-forming compound, exhibits superior compressive strength compared to other samples with higher concentrations of bubble-forming additives.

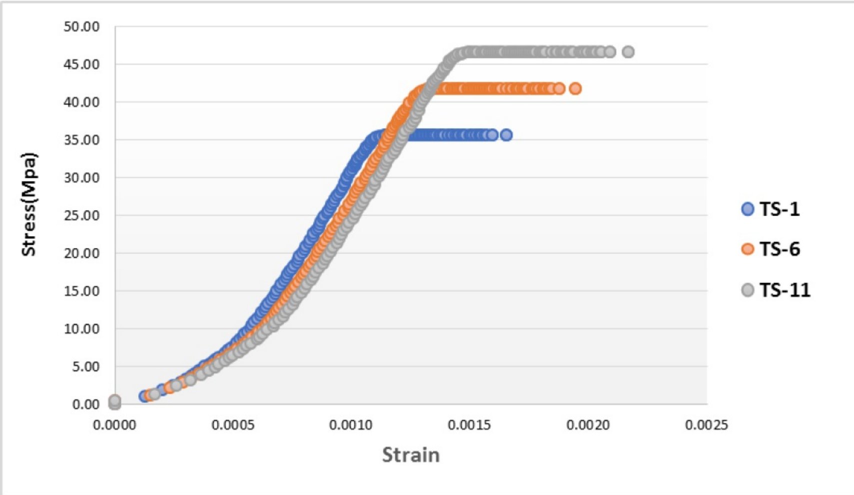
3.2 Thermal conductivity

To better understand the results from the thermal conductivity coefficient test of physical samples, refer to Table 3. The data indicates that increasing the percentage of aerating additives in concrete reduces its compressive strength. However, this increase in additives also raises the number of bubbles in the concrete, which in turn lowers the heat transfer coefficient. The results from the concrete samples containing 1% foaming agent show the following thermal conductivity coefficients: the TS-2 concrete sample with a cement grade of 300 has a coefficient of approximately 1.40, while the TS-7 concrete sample with a cement grade of 350 has a coefficient of about 1.60. The thermal conductivity of the TS-2 sample is roughly 15% lower compared to the TS-7 sample. Additionally, the TS-12 concrete sample with a cement grade of 400 has a thermal conductivity coefficient of 1.70, which is about 22% higher than the TS-2 sample with a cement grade of 300 and approximately 7% higher than the TS-7 sample with a cement grade of 350.

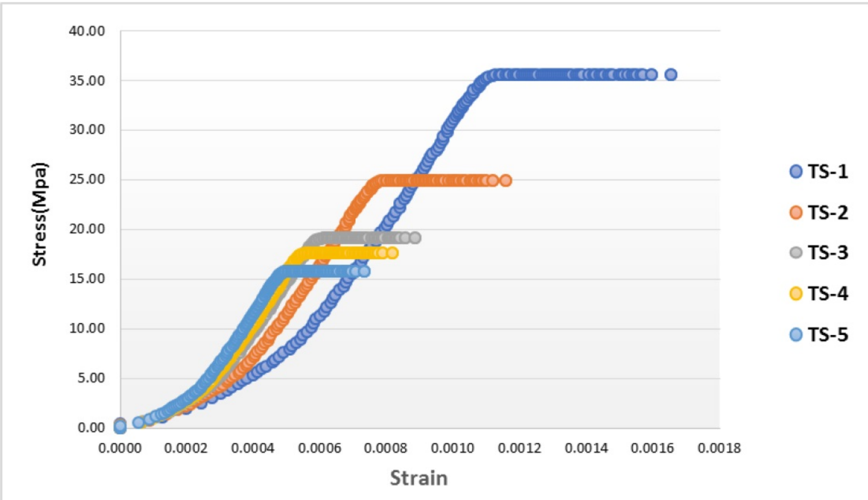
Based on the results from concrete samples containing 1% foaming agent, the thermal conductivity coefficients were as follows: The TS-2 concrete sample with a cement grade of 300 had a coefficient of approximately 1.40, while the TS-7 concrete sample with a cement grade of 350 had a coefficient of around 1.60. The thermal conductivity of the TS-2 sample was about 15% lower compared to the TS-7 sample. Additionally, the TS-12 concrete sample with a cement grade of 400 exhibited a thermal conductivity coefficient of 1.70, which is approximately 22% higher than the TS-2 sample with a grade of 300 and about 7% higher than the TS-7 sample with a grade of 350.

3.3 Results of numerical modeling

To calculate heating energy consumption in a building, a detailed model was first created using DesignBuilder software. The building's dimensions and specifications, including wall materials and their thermal properties, were input into the software. The building's thermal zones were then set up, and the internal heat loads and external



(a)



(b)

Figure 4: Compressive strength results of the tests

Table 3: Comparison of thermal conductivity coefficient of composite samples

Reduction rate; Thermal conductivity coefficient (Percent)	pushing resistance (MPA)	Conductivity coefficient thermal	temperature of unknown sample	Average temperature of two disks	Sample diameter	Sample thickness	Cement grade	Sample type	Sample code
0	35.57	1.90	100	38	10	2.54	300	witness	Ts-1
26	24.93	1.40	91	25	10	2.54	300	1 percent	Ts-2
0	41.80	2.1	92	39	10	2.54	350	witness	Ts-6
22	27.13	1.60	74	24	10	2.54	350	1 percent	Ts-7
0	46.57	2.5	90	46	10	2.54	400	witness	Ts-11
30	31.90	1.70	98	34	10	2.54	400	Ts-12	

climate conditions were defined. Simulations were subsequently run to analyze heating energy requirements. Insights were gained into how different design variables affected energy consumption, which allowed for the assessment and optimization of the building's heating efficiency. The process of simulating two chambers, each with dimensions of $2 \times 2 \times 2.5$ meters (Figure 5), using concrete wall materials with varying thermal conductivity coefficients, is detailed in this report. DesignBuilder version 6 software was employed for the simulation. Initially, after opening the software, the simulation model name, simulation engine, and building climate were selected. Climate data files in EPW format were used to input weather information, and as climatic data for Eshtehard was not available, weather data from nearby cities, Tehran and Qazvin, were utilized instead. The building was then drawn by selecting the appropriate option and setting the extrusion height. Since the simulated building had no windows, the window-to-wall ratio was set to 0 during the drawing process to ensure the building remained windowless.

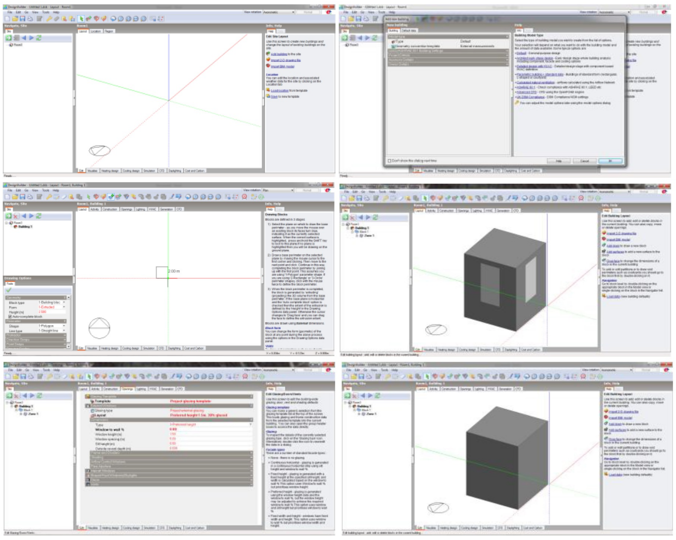


Figure 5: 3-D modeling of the chamber

After the project's details were drawn, its technical information was adjusted accordingly. To calculate the cooling and heating load, parameters such as the internal temperature for summer and winter, as well as usage patterns, were defined. Information regarding the concrete room, which had a thickness of 20 cm, was also specified, and the thermal conductivity coefficient of the concrete was established. Other software settings, including lighting and ventilation systems, were left unchanged from the software's default configurations. The process of configuring these settings is illustrated in the images below. For altering the wall type, a wall with similar specifications to the defined part was used, with concrete material information applied to all external walls, the roof, and the floor. By selecting the heating design option in the software, the results of the heating load calculations for the building were generated, as shown in Figures 6 to 8. It should be noted that all procedures were performed consistently with those used models.

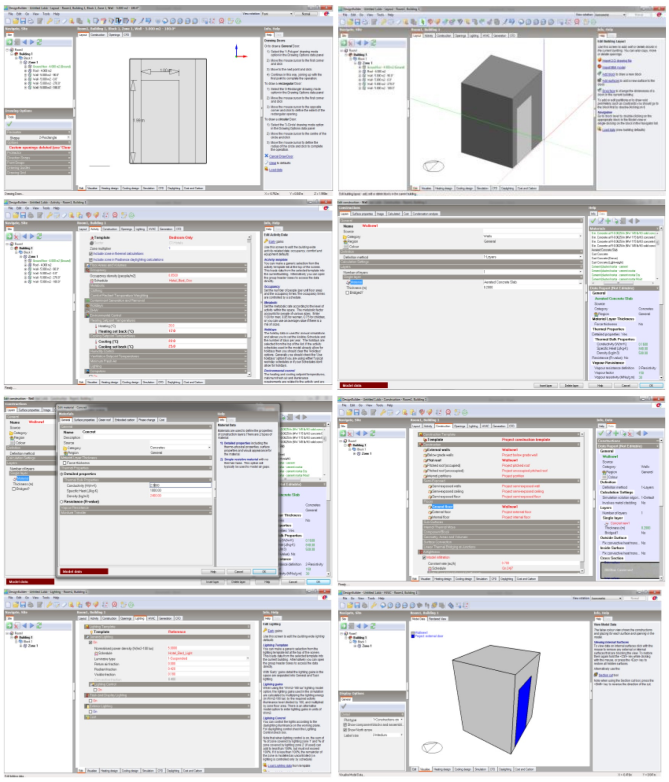


Figure 6: Simulations of various properties of the chambers

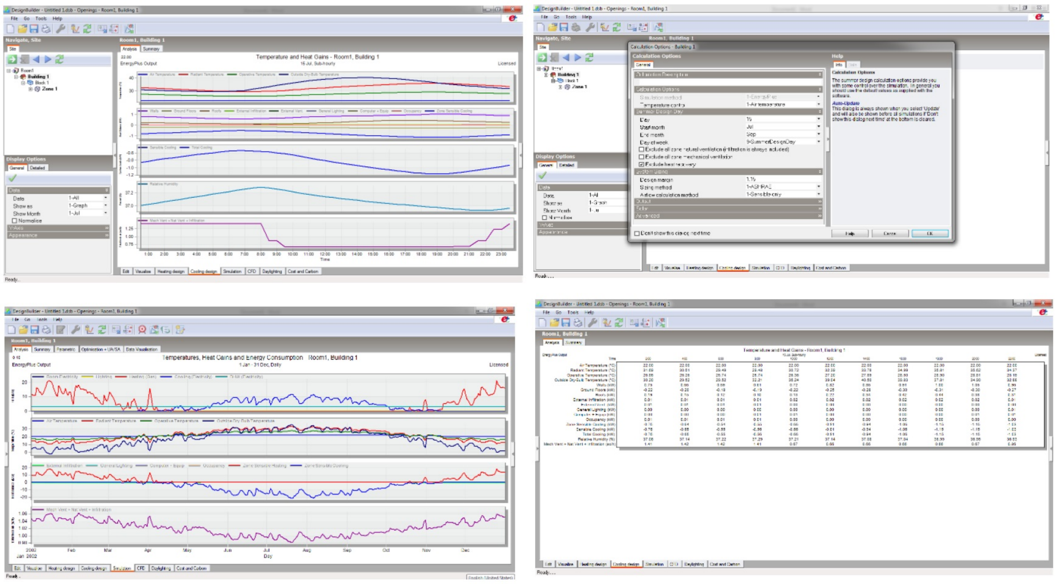


Figure 7: The process of receiving the result of the cooling load calculations of the concrete wall model with the thermal conductivity coefficient of 2.5 W/MK

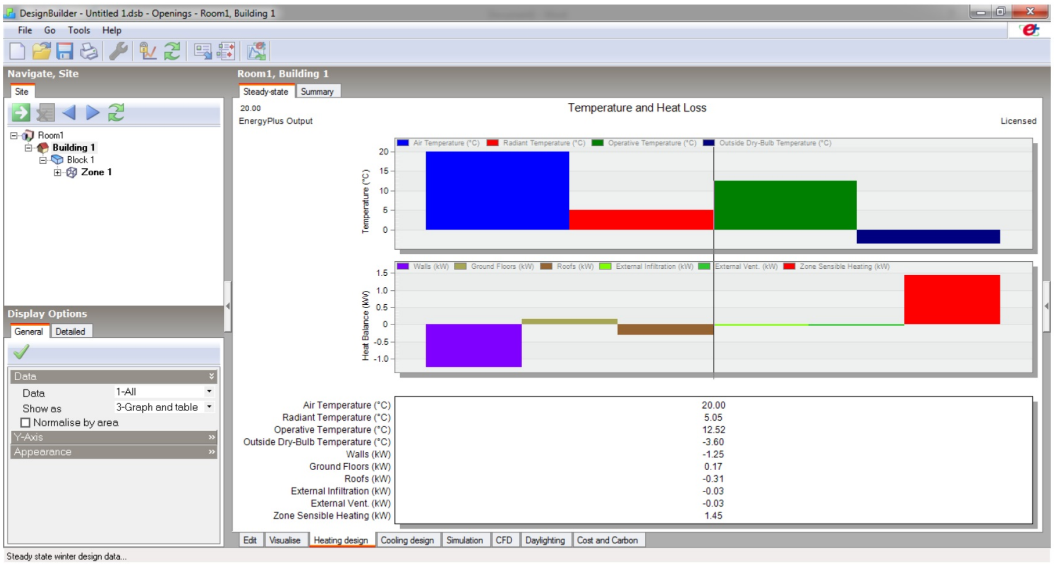


Figure 8: The process of receiving the result of the calculation of the heating load of the concrete wall model with a thermal conductivity coefficient of 1.7 W/MK

4 Comparison of the tests

To gain a clearer understanding of the results obtained from the simulation of the models, refer to Tables 4 to 7. The simulation results indicate that the energy consumption in the TS-12 sample decreased by approximately 7% compared to the control sample. Additionally, the user's thermal comfort was assessed according to the ASHRAE 55 standard, with detailed data presented in Tables. The findings reveal a reduction of 48 hours annually in thermal comfort during winter clothing use and a decrease of 41.5 hours annually when summer clothing was used, in comparison to the control model. These results underscore the potential for improved energy efficiency and thermal comfort through the use of the TS-12 sample, highlighting its effectiveness in optimizing building performance.

The results of this section demonstrated how the incorporation of air bubbles into concrete can enhance its thermal conductivity properties. Concrete samples with varying air bubble content were tested and their thermal performance was compared. It was found that air-bubble-reinforced concrete significantly lowered thermal conductivity, thereby improving the material's insulating properties. The findings indicate that the inclusion of air bubbles in concrete can effectively increase its energy efficiency by reducing heat transfer, presenting a promising method for optimizing building insulation and decreasing overall energy consumption.

Table 4: The results of annual energy consumption in the room model (TS-11) considering the thermal conductivity coefficient: 2.5 W/MK

Energy per building area (KWH/M^2)	**Energy of the total area of the building (kilowatt hours per square meter)**	**Total energy (kWh)**	**Components**
1696.05	1696.05	4341.89	Total energy
1696.05	1696.05	4341.89	Pure energy
4095.79	4095.79	10485.22	The total energy source
4095.79	4095.79	10485.22	Pure energy source

Table 5: The results of annual energy consumption in the unknown room model (TS-12) considering the thermal conductivity coefficient: 1.7 W/MK

Energy per building area (KWH/M^2)	**Energy of the total area of the building (kilowatt hours per square meter)**	**Total energy (kWh)**	**Components**
1596.44	1596.44	4086.88	Total energy
1596.44	1596.44	4086.88	Pure energy
3892.87	3892.87	9965.74	The total energy source
3892.87	3892.87	9965.74	Pure energy source

Table 6: The results of thermal comfort of the user on an annual basis (hours) in the witness room model (TS-11) considering the thermal conductivity coefficient: 2.5 W/MK

Winter or summer clothes (hours)	**Summer clothes (hours)**	**Winter clothes (hours)**	**Components**
2179.50	3161	3050.50	TS-11 simulated witness room

Table 7: The results of the user's thermal comfort annually (hours) in the room model (TS-12) considering the thermal conductivity coefficient of 1.7 W/MK

Winter or summer clothes (hours)	**Summer clothes (hours)**	**Winter clothes (hours)**	**Components**
2112	3119.50	3002.50	TS-12 simulated witness room

5 Conclusion

In conclusion, this study has demonstrated that energy consumption in buildings, largely driven by the need for heating and cooling, can be mitigated through the use of enhanced concrete facade systems. By incorporating air bubbles into concrete, the research assessed both compressive and thermal properties of the material. Testing of 30 concrete samples—15 for compressive strength and 15 for thermal performance—provided valuable data. Simulations conducted with DesignBuilder software for two chambers, each measuring 2×2 meters and 2.5 meters high, revealed that walls made from concrete with varying thermal conductivity coefficients resulted in a 30% reduction in energy consumption compared to conventional concrete walls. These results underscore the potential of advanced facade systems, such as those utilizing air-bubble-reinforced concrete, to significantly improve building energy efficiency, reduce fuel consumption, and lower economic costs in large-scale construction projects.

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