Thermally Active Concrete and Zero Energy Building Research

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Keywords: zero energy buildings, heat transfer, insulated wall panel, concrete surface optimization

The paper will discuss a research initiative for Zero Energy Building (ZEB) at Lehigh University. While interest in ZEBs has taken off, research and development in this area is lagging. The development of commercial energy-efficient building envelopes, utilization of geothermal energy, and integration of solar collection into the building system is not widespread. The work was performed over a year by a team of faculty and industry members uniquely experienced in research on the fundamental aspects of the proposed concept: thermodynamics, heat transfer, energy piles, surface optimization, and insulated wall panel development.

PROJECT BACKGROUND

In 2019 Lehigh University (LU) assembled a uniquely qualified team with research experience in the fundamental aspects of thermodynamics, heat transfer, energy piles, surface optimization, and insulated wall panel development. The team included faculty and researchers from LU, including: the Energy Research Center (ERC), which was established in 1978 to find solutions to national and global energy and energy-related problems through fundamental and applied research; the Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center, which was established in 1986 and serves as a national center for research and education on structures and materials used in infrastructure; and the Departments of Civil and Environmental Engineering (CEE), Architecture and Design (Arch), and Mechanical Engineering & Mechanics (MEM). The team also included industry partners from Carrier UTC Climate Control and Security, and Metromont Corporation. Metromont, one of the largest precast concrete producers in the U.S., has large-scale manufacturing facilities to fabricate prototypes for the research effort. Carrier has significant research and development (R&D) facilities, as well as off-the-shelf equipment that can be modified to support the proposed work.

This work leverages the proven capabilities of ground source heat pumps (GSHPs) and energy piles with precast concrete panels to provide improved energy efficiency with no additional first cost in an architecturally optimized and appealing manner. The technical baseline is current commercial and residential building construction utilizing insulated precast concrete wall and roof panels, supported on piles, with hot water heating supplied through an electric water heater and winter building heat provided by a heat pump and cooling tower.

PROJECT DESCRIPTION

The project team has developed a coupled energy pile and solar insulated concrete collector cladding (CEP-SIC) system for reducing building energy consumption (Figure 1). The system consists of insulated concrete wall and roof elements and structural piles with embedded PEX piping. The system is connected to a heat pump to provide heat exchange between the solar and ground elements lowering heating and cooling costs for the building. These components are well established but have not been integrated to form a composite system.

In the cooling season, the system functions by circulating a glycol mixture from the ground piles through the cladding elements. The circulating fluid leaves the ground at a temperature of approximately 50F. This low-temperature liquid cools the wall elements subject to solar radiation. As the liquid passes through the wall and the roof elements, its temperature is elevated to allow hot water heating and significant reductions in natural gas or electric usage. Any excess heat not needed for water heating is dissipated through the ground piles.

In the heating season, the glycol mixture is circulated from the ground piles through the cladding elements. During sun exposure, the south-facing wall and roof elements heat up the liquid. Once an adequate temperature is achieved it is transferred to the hot water heater and/or directly to the fan coil for room heating. When a solar collection is not possible the cladding elements is heated by circulating water from the ground piles. This circulation minimizes transmission of winter temperatures into the building envelope and thermal gain, as

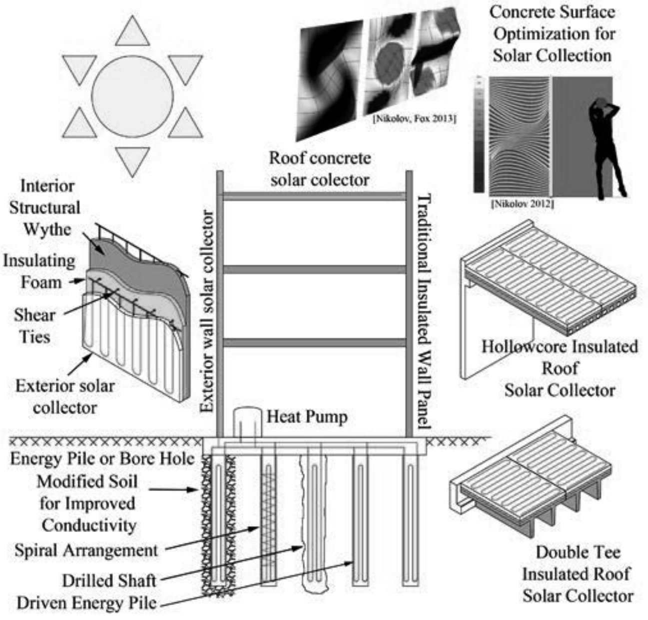

Figure 1. CEP-SIC Building System.

well as the associated time needed to raise the temperature of the panels in the morning.

The research team targeted efforts are to increase the thermal conductivity of the concrete materials to enhance ground and solar collector heat exchange, develop the surface optimized façade solar collector system to collect thermal energy for use in space and hot water heating while increasing the effective R-value through the removal of heat from the outer layer of the façade, enhance the ground heat exchange through improvements in the pile piping layout, and develop a heat exchange system that can efficiently utilize both the ground and solar collectors. Success is evaluated for achieving a 50% increase in energy efficiency per current ASHRAE 90.1-2016 at no additional first cost.

REVIEW OF CONCRETE SOLAR COLLECTORS

Fabrication of insulated concrete wall panels dates to the 1950's and integration of piping into these components has been done on a limited basis. Past work has demonstrated that excessive heat can be dissipated through the integration of piping in the exterior concrete layer of the panel [1]. Feasibility of achieving the energy performance goals is contingent on identification of cost-effective concrete materials, improvements in concrete solar collectors, effective solar radiation collection in the winter and thermal heat dissipation in the summer, improvements in-ground heat energy transfer, and effective integration of the system into a building HVAC system.

Concrete solar collectors (CSC) consist of embedded piping in concrete cladding elements. Work by Abbott [2] demonstrated through numerical modeling that concrete solar collector panels can provide a significant reduction in energy use in the U.S. when using a solar assisted heat pump regardless of location. Work by Sarachitti et al. [3] illustrated that roof CSC can be effective in lowering the interior temperatures of building structures. Parametric studies conducted by O'Hegarty et al. demonstrated that performance of CSC is most sensitive to concrete thermal conductivity with a minimum of 2 W/mK to provide useful temperature gains. A follow-on study by O'Hegarty et al. [4] provided a comprehensive illustration of the viability of CSC. Recent work by Tempest et al. [1] examines the used of geopolymer concrete in combination with insulated precast concrete panels and piping. As illustrated, the viability of CSC is well established and initial steps have been taken by others to show that these systems can be built at scale in precast concrete plants. This project combines the ideas of Tempest et al. and O'Hegarty et al. into a new insulated precast CSC roof and wall components that will be integrated into the CEP-SIC system.

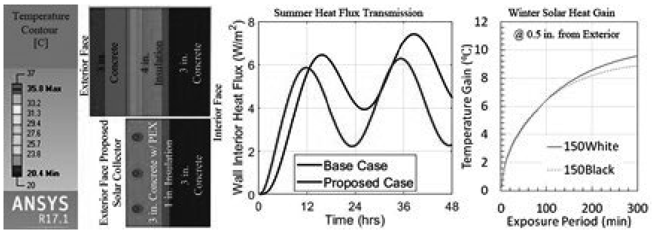

Figure 2. Modeling of Thermal Heat Transfer in Existing and Proposed Wall Section

The effectiveness of solar collectors can be improved even further through surface topology optimization. Previous work by Nikolov achieved significant increases in surface exposure to solar radiation by modifying the panel's exterior surface. For instance, numerical simulations indicated an 11% increase of the surface area of the modified panel compared to that of a conventional flat panel, which leads to an overall increase of total surface available for energy absorption and transfer [6]. Physical testing of full-scale prototypes [5] has confirmed the numerical simulation and concluded that the optimized surface produced as much as 45% higher levels of exposure for longer periods of time per day in comparison to a flat surface of identical orientation and overall dimensions. Due to the difference in solar trajectory in the heating (winter) and cooling (summer) seasons, it is possible to design the surface topology such that the thermal gains from direct solar radiation are maximized during the heating season and minimized during the cooling season. In previous work by Nikolov panel surfaces were fabricated using CNC milled foam form liners. This approach was accommodated for the current effort with the goal of developing surface contour recommendations for the three different climate regions. It is expected that the surface contours will vary for each building site and orientation and potentially within each building façade. This variation is more complex than typical precast panel formwork, however

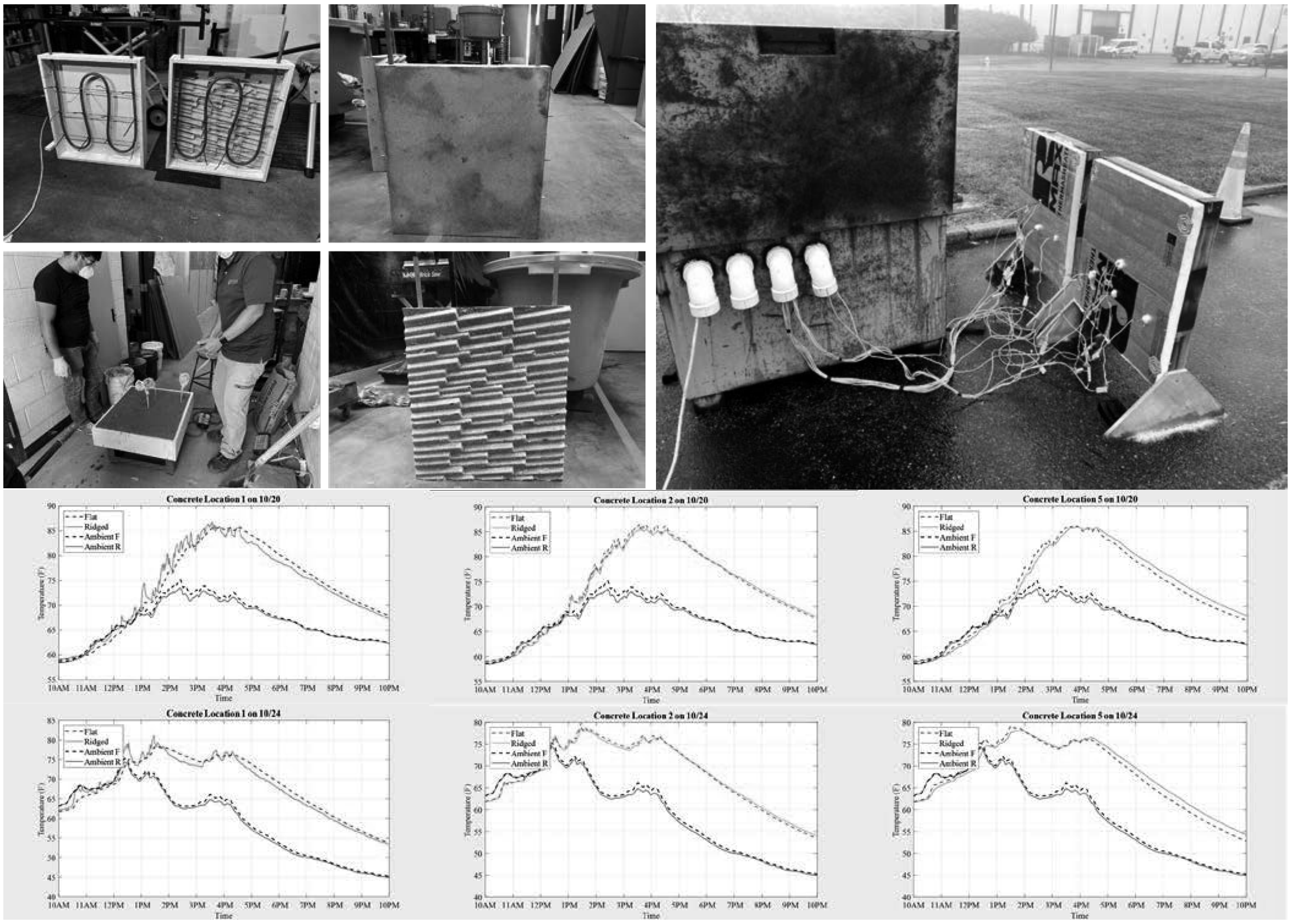

Figure 3. Prototype fabriaction and data collection

recent advantages in big area additive manufacturing techniques has shown that 3D printed forms are viable for building construction [6].

COMPUTATION AND PROTOTYPES

The validity of the designed insulated precast concrete solar collectors is contingent on the ability of the panels to enhance insulation properties of the cladding, generate thermal heat gain from absorbed solar radiation, which can be used to decrease heating and cooling loads. Preliminary numerical studies (using ANSYS) were conducted by the research team that demonstrate the ability of the system to achieve these performance metrics. The conventional precast panel consists of 4-in. of polystyrene sandwiched between two 3-in. concrete wythes. The solar collector panel includes two 3-in. concrete wythes with a reduction in the interior insulation to a 1 in. thickness. The exterior concrete wythe contains nested, 0.5-in. PEX heat pipes OD filled with ethylene glycol at 20C. To assess the cooling potential of the proposed panel thermal conditions are applied to model cooling loads in summer. The results for the heat flux on the inner wall surface show that there is a 26% difference in the heat loss between the base and designed case over the analysis period (Figure 2). It is shown that the heat pipes can remove the build-up heat at the exterior side of the insulation. The heat removed by the heat pipes can be used for hot water generation, which results in a significant energy saving for the overall system. In the heating season, the concern is whether the panels can provide positive temperature gain through solar radiation. The analysis results shown in Figure 3 indicate that a 9 to 10C temperature gain can be achieved over a 5-hour exposure period. This heat increase can be used to supplement the building heating requirements in the winter. The data collected from the physical prototypes comprehensive, Figure 3. Specific days can compared to overall performance over a period of 2, 4, and 6 months. In general, the proposed panel surface consistently undergoes larger temperature fluctuation than a conventional flat panel. However in overall it stays cooler. More importantly, the heat gain and loss are offset by about an hour. This can lead to delay in cooling demand and potential cost savings.

CONCLUSION

Data continues to be collected as it offers insights into the relationship between performance and geometry. Further simulations are needed to determine the relationship between the performance of the solar collectors and the energy piles. In its summation this research examines and maps the multivalent intersections of climate, infrastructure and the built environment. It adds a necessary perspective to a number of disciplinary programs, such as architecture, civil and environmental engineering and, more importantly, it lays the groundwork for better understanding of the complexity of the intersecting issues at hand through the medium of design research and discourse.

ENDNOTES

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