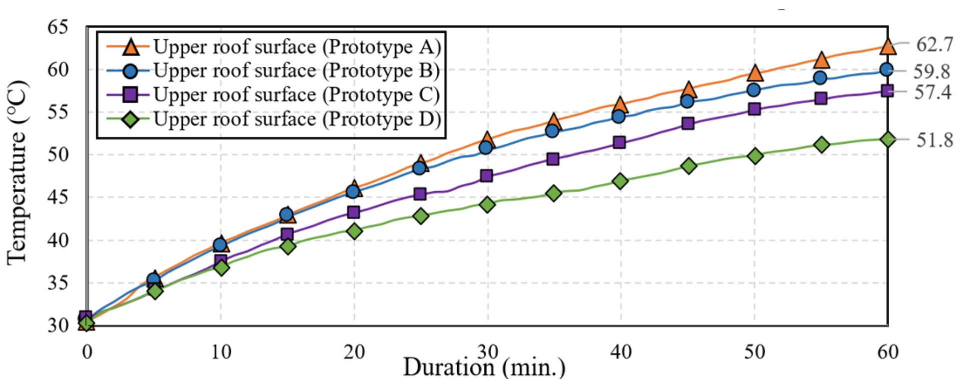

FIGURE 5. The upper roof surface temperatures

According to Figure 5, the upper roof surface temperatures of roof prototypes showed a bigger drop in peak temperatures when the roofs were additionally applied with thermal reflective coating than reducing the concrete density. When the density of roof was reduced, the peak temperature reduced from 62.7 to 57.4 (-5.3). When the same roof was applied with reflective coating, the peak temperature reduced from 57.4 to 51.8 (-5.6). The addition of reflective coating is more pronounced in reducing the upper roof surface temperature, as well as providing a cooler roof. The reflective coating application increased the roof surface solar reflectivity from 0.18 to 0.8 (Rawat & Singh, 2022). The high solar reflectivity plays a critical role in reflecting incident solar irradiation. Standard roofs with lesser solar waves reflected tend to absorb higher thermal waves due to its darker surface color.

Besides, when the roofs densities were reduced from 2500 kg/m^3 to 1300 kg/m^3 (Prototypes A to B), the decrease in surface heat gain was 9.63 %. In another case, when Prototype D was coated with reflective paint, it leads to a 18.8 % decrease in surface heat gain compared to Prototype C without the coating. The higher decrease in surface heat gain after the application of reflective coating was mainly due to 80 % of the incident solar irradiation was reflected by its high solar reflectivity. The integration of reflective paint can reduce the roof surface temperatures in the range of 1.4 to 4.7 (Rawat & Singh, 2022). In Prototype D, the roof surface temperature was brought down by 5.6 , besides proven higher than the temperature range, its effectiveness in providing a cool lightweight foam concrete roof tile surface was proven too. Practically, the accumulation of dirt on roof surface can decrease the roof's solar reflectivity. However, with annual washing practices, the solar reflectivity of roof's surface can recover up to 90 % (Al-Obaidi et al. 2014).

ROOF LOWER SURFACE

The roof lower surface temperatures of four roof prototypes are shown in Figure 6. When a standard roof (Prototype A) was upgraded to a lower density roof tile with lightweight foam concrete technology, its density decreased from 2500 kg/m3 to 1300 and 1100 kg/m3 (Prototypes B and C), respectively. For instance, the density of roof influenced the roof lower surface temperature. Roof Prototype A reached 60.4 , while Prototype C achieved 48.8 after 60 min of exposure to heatwaves. The roof lower surface temperatures gained a decrease of 19.20 % when the roof structures were changed from Prototypes A to C. The initial roof s lower surface temperatures of Prototypes A and C were 30.1 and 30.5 , respectively. The increase of roof lower surface temperatures in Prototype A was 30.3 , while for Prototype C, it was lower at 18.3 . The differences in the increment of lower roof surface temperatures among these two prototypes was 12 , and their lower roof surface temperature increment rates were 0.505 /min and 0.305 /min, respectively.

One of the factors affecting the amount of heat attained at roof lower surface in the prototypes are their thermal conductivities. The thermal conductivity of the basic concrete roof was 2.0 W/m.K (Wu et al. 2017). For lightweight foam concrete roofs with densities 1300 and 1100 kg/m^3, their thermal conductivities were 0.39 and 0.29 W/m.K, respectively (Cong & Chen, 2015). A huge drop of thermal conductivities from 2.0 to 0.39 W/m.K caused the roof lower surface heat gain to experience a decrease of 28.38 %. Further reduction of thermal conductivity values to 0.29 W/m.K had reduced the lower roof surface heat gain at a greater extend by 15.67 %. Thermal conductivity is explained as the quantity of heat transferred across the specimen with a constant specimen's distance between the planes and surface area ratio (Sengul et al. 2011). According to the definition, when the thermal conductivity of the specimen is lower, the heat transferred across the specimen to another plane is lesser.

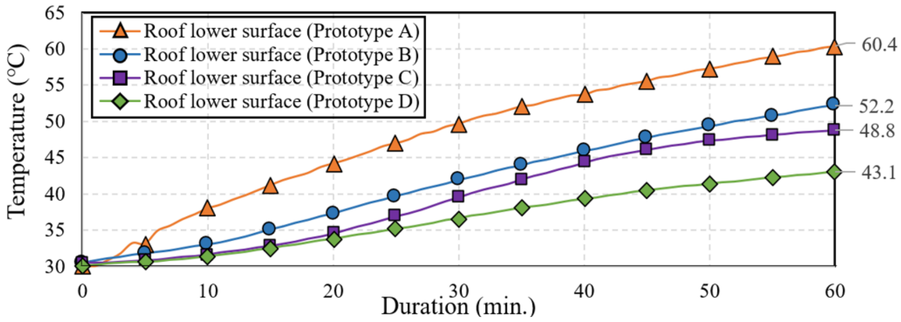

FIGURE 6. The roof lower surface temperatures

In addition, the temperature differences in upper and lower roof surfaces temperatures by the end of experiment for Prototypes A and C were 2.3 °C and 8.6 °C, respectively. The distance between the planes of concretes were fixed at 50 mm. Thus, their temperature gradients were 46 and 172 K/m, respectively. A higher temperature gradient indicated a higher thermal lagging effect as more thermal energies are opposed to flow through the lightweight foam concrete. The cellular microstructural roof is the main reason of its excellent thermal lagging effect (Ramamurthy et al., 2009).

The roof lower surface temperature can be decreased by 8 °C when a basic roof was upgraded to lightweight concrete roof with reflective coating (Wu et al. 2017). In Prototype D, the lower roof surface temperature achieved 43.1 °C, as in 12.7 °C cooler than the Prototype A. Besides the introduction of hollow longitude sections causes the higher reduction in lower roof surface temperature than the experiment studies in Wu et al. (2017), the higher efficiency of thermal reflective coating in the roof prototype is noticeable. Moreover, the heat gain attained at roof lower surface was observed to reduce by 57.10 %. A roof with reflective coating tends to have lower stored thermal energy owing to its lower temperatures in roof upper and lower surfaces (Revel et al. 2014).

The merging of a low thermal conductivity concrete and a high surface reflectance roof had brought down the lower roof surface temperature increment rate. From Prototypes A to D, the lower roof surface temperature increment rates were 0.505 °C/min and 0.271 °C/min, respectively. Thermal performance in roof lower surface equals to the thermal performance in building interior, accordingly, the low temperature increment rate represents the high performance of roof's thermal lag (Wu et al. 2017). Roof Prototype D is an appropriate cool roof structure due to its roof lower surface temperature trend and low increment rate that can lead to low building interior temperature and high thermal lagging.

BUILDING INTERIOR HEAT GAIN

The efficiency of the cool roof system that merged the lightweight foam concrete technology, hollow sections fabrication and reflective coating application was determined based on the building interior (attic model) heat gain. Table 1 shows the roof prototypes' attic thermal performances. The thermal performances of different cool roof systems in Prototypes B, C and D were compared with the conventional roof, Prototype A, the basic roof without the cool roof features.

TABLE 1. The attic thermal performances.

Roof	Features	Density (kg/m^3)	Final attic temperature (°C)	Average attic temperature (°C)	Standard deviation (°C)	Coefficient of variation (%)
A	Basic roof	2500	40.8	35.78	3.400	9.50
B	Lightweight foam concrete	1300	36.5	34.03	1.936	5.69
C	Lightweight foam concrete, hollow sections	1100	34.6	32.48	1.367	4.21
D	Lightweight foam concrete, hollow sections, reflective coating	1100	33.5	32.16	1.060	3.30

Amran, M., Onaizi, A.M., Feduik, R., Danish, A., Vatin, N.I., Murali, G., Abdelgader, H.S., Mosaberpanah, M.A., Cecchin, D., & Azevedo, A. 2022. An ultra-lightweight cellular concrete for geotechnical applications – A review. *Case Studies in Construction Materials* 16: e01096.

Asadi, I., Shafigh, P., Abu Hassan, Z.F., & Mahyuddin, N.B. 2018. Thermal conductivity of concrete – A review. *Journal of Building Engineering* 20: 81-93.

Chen, C.M., Lin, Y.P., Chung, S.C., & Lai, C.M. 2022. Effects of the design parameters of ridge vents on induced buoyancy-driven ventilation. *Buildings* 12: 112.

Chihab, Y., Essaleh, L., Bouferra, R., & Bouchehma, A. 2021. Numerical study for energy performance optimization of hollow concrete blocks for roofing in a hot climate of Morocco. *Energy Conversion and Management X* 12: 100113.

Cong, M., & Chen, B. 2015. Properties of a foamed concrete with soil as filler. *Construction and Building Materials* 76: 61-69.

Falliano, D., Domenico, D., Ricciardi, G., & Gugliandolo, E. 2020. 3D-printable lightweight foamed concrete and comparison with classical foamed concrete in terms of fresh state properties and mechanical strength. *Construction and Building Materials* 254: 119271.

Hernández-Pérez, I., Álvarez, G., Xamán, J., Zavala-Guillén, I., Arce, J., & Simá, E. 2014. Thermal performance of reflective materials applied to exterior building components – A review. *Energy and Buildings* 80: 81-105.

Huang, J. Yu, J., & Yang, H. 2018. Effects of key factors on the heat insulation performance of a hollow block ventilated wall. *Applied Energy* 232: 409-423.

Lee, S.W., Lim, C.H., & Salleh, Ilias. 2016. Reflective thermal insulation systems in building: A review on radiant barrier and reflective insulation. *Renewable and Sustainable Energy Reviews* 65: 643-661.

Mahmoud, A.M. Ben-Nakhi, A., Ben-Nakhi, A., & Alajmi, R. 2012. Conjugate conduction convection and radiation heat transfer through hollow autoclaved aerated concrete blocks. *Journal of Building Performance Simulation* 5(4): 248-262.

Mohd Ashhar, M.Z., & Lim, C.H. 2022. Recent research and development on the use of reflective technology in building – A review. *Journal of Building Engineering* 45: 103552.

Muda, Z.C., Shafigh, P., Mahyuddin, N.B. Sepasgozar, S.M.E., Beddu, S., & Zakaria, A. 2020. Energy performance of a high-rise residential building using fibre-reinforced structural lightweight aggregate concrete. *Applied Sciences* 10(13): 4489.

Mugahed Amran, Y.H. 2020. Influence of structural parameters on the properties of fibred-foamed concrete. *Innovative Infrastructure Solutions* 5(1).

Ng, S.C. & Low, K.S. 2010. Thermal conductivity of newspaper sandwiched aerated lightweight concrete panel. *Energy and Buildings* 42(12): 2452-2456.

Oluwole, O., Joshua, J., & Nwagwo, H. 2012. Finite element modeling of low heat conducting building bricks. *Journal of Minerals and Materials Characterization and Engineering* 11: 800-806.

Othman, R., Jaya, R.P. Muthusamy, K., Sulaiman, M., Duraisamy, Y., Abdullah, M.M.A.B., Przybył, A., Sochacki, W., Skrzypczak, T., Vizureanu, P., & Sandu, A. V. 2021. Relation between density and compressive strength of foamed concrete. *Materials* 14(11).

Qi, R., Lu, L., & Yang, H. 2012. Investigation on air-conditioning load profile and energy consumption of desiccant cooling system for commercial buildings in Hong Kong. *Energy and Buildings* 49: 509-518.

Qiu, T., Wang, G., Xu, Q., & Ni, G. 2018. Study on the thermal performance and design method of solar reflective-thermal insulation hybrid system for wall and road in Shanghai. *Solar Energy* 171: 851-862.

Ramamurthy, K., Kunhanandan Nambiar, E.K. & Ranjani, G.I.S. 2009. A classification of studies on properties of foam concrete. *Cement and Concrete Composities* 31(6): 388-396.

Rawat, M., & Singh, R.N. 2022. A study on the comparative review of cool roof thermal performance in various region. *Energy and Built Environment* 3(3): 327-347.

Revel, G.M., Martarelli, M., Emiliani, M., Celotti, L., Nadalini, R., Ferrari, A., Hermanns, S., & Beckers, E. 2014. Cool products for building envelope – Part II: Experimental and numerical evaluation of thermal performances. *Solar Energy* 105: 780-791.

Saber, H.H., Maref, W., & Hajiah, A.E. 2019. Hygrothermal performance of cool roofs subjected to Saudi climates. *Frontiers in Energy Research* 7.

Sang, G., Zhu, Y., Yang, G., & Zhang, H. 2015. Preparation and characterization of high porosity cement-based foam material. *Construction and Building Materials* 91: 133-137.

Saygılı, A., & Baykal, G. 2011. A new method for improving the thermal insulation properties of fly ash. *Energy and Buildings* 43(11): 3236-3242.

Sengul., O., Azizi, S., Karaosmanoglu, F., & Tasdemir, M.A. 2011. Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete. *Energy and Buildings* 43: 671-676.

Strzałkowski, J., Sikora, P., Chung, S.Y., & Elrahman, M.A. 2021. Thermal performance of building envelopes with structural layers of the same density: Lightweight aggregate concrete versus foamed concrete. *Building and Environment* 196: 107799.

Tong, S., Li, H., Zingre, K.T., Wan, M.P., Chang, V.W.C., Wong, S.K., Boo, W., & Yen, I. 2014. Thermal performance of concrete-based roofs in tropical climate. *Energy and Buildings* 76: 392-401.

Uemoto, K.L. Sato, N.M.N., & John, V.M. 2010. Estimating thermal performance of cool colored paints. *Energy and Buildings* 42(1): 17-22.

Vejmelková, E., Koňáková, D., Kulovaná, T., Keppert, M., Žumár, J., Rovnaníková, P., Keršner, Z., Sedlmajer, M., & Černý, R. 2015. Engineering properties of concrete containing natural zeolite as supplementary cementitious material: Strength, toughness, durability, and hygrothermal performance. *Cement and Concrete Composites* 55:259–267.

Wu, Y., Krishnan, R., Yu, L.E., & Zhang, M.H. 2017. Using lightweight cement composite and photocatalytic coating to reduce cooling energy consumption of buildings. *Construction and Building Materials* 145: 555-564.

Yu, J., Leng, K., Ye, H., Xu, X., Luo, Y., Wang, J., Yang, X., Yang, Q., & Gang, W. 2020. Study on thermal insulation characteristics and optimized design of pipeembedded ventilation roof with outer-layer shape-stabilized PCM in different climate zones. *Renewable Energy* 147: 1609–1622.

Yu, J., Yang, J., & Chao, X. 2015. Study of dynamic thermal performance of hollow block ventilated wall. *Renewable Energy* 84: 154-151.

Zhang, Y., Du, K., He, J., Yang, L., Li, Y., & Li, S. 2014. Impact factors analysis on the thermal performance of hollow block wall. *Energy and Buildings* 75: 330-341.