Energy Performance of High-Rise Residential Buildings Using Fly Ash Cenosphere as Partial Replacement of Fine Aggregate in Mortar

Salmia Beddu[1], *Nur Amalina Nadiah* Basri[2], *Nur Liyana* Mohd Kamal[1], *Daud* Mohamad[1], *Zarina* Itam[1], *N.* Sivakumar[3], *Warid Wazien* Ahmad Zailani[4]

[1] Department of Civil Engineering, College of Engineering, Universiti Tenaga Nasional (UNITEN), 43000, Kajang, Selangor, Malaysia.
[2] College of Graduate Studies, Universiti Tenaga Nasional (UNITEN), 43000, Kajang, Selangor, Malaysia.
[3]School Department of Civil Engineering, SSN College of Engineering, Old Mahabalipuram Road, SSN Nagar, Kalavakkam.
[4]School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia.

Abstract. Energy consumption in residential buildings soared enormously during the pandemic. To construct highly efficient residence, materials are one of factors that need to be considered due to their impact of climate change, power consumption and operational cost. It was found that power plants produced various types of waste products that can be utilized in many applications. For instance, Cenosphere produced from power plants could promote thermal properties of mortar brick to a certain extent. The aim of this study is to evaluate the effects of Cenosphere as partial sand replacement on thermal properties of mortar and buildings' energy efficiency at different percentages (0%, 5%, 10%, 15% and 20%). Both thermal conductivity and specific heat capacity were detected by using Fox 50 instrumentation while energy efficiency was determined by using Autodesk Revit and Green Building Studio (GBS) software. The findings of thermal properties show that the replacement of sand with 20% Cenosphere as partial sand replacement have significantly reduces thermal conductivity while increasing the specific heat capacity of mortar. This study revealed that the k value of mortar bricks have reduced as low as 0.62 W/m.K and as high as 932 J/kg.K for specific heat capacity due to incorporation of Cenosphere and mixtures at 20%. On the other hand, the EUI of 5% Cenosphere has reduced 2.13 kWh/m^2 or 1.4% lower than control mix. The energy saving measure largely influenced by the composition of Cenosphere as compared to the buildings' orientations.

1. Introduction

According to [1], it is expected that around 7.5 billion m^3 will be produced a year by 2050. The enormous utilization of concrete leads to higher demands of natural aggregates. Hence having an impact on the environment as natural sources such as rock and sand are being depleted. The prohibition on mining in some areas makes materials supply problems worsen.

Most structural concrete have good mechanical properties but lack in providing thermal comfort for the users. To deal with this problem, proper action should be taken such as utilizing the usage of waste produced from coal fired power plants. Coal composed of heavy metals such as Arsenic (As), Chromium (Cr) and Mercury (Hg) that can be toxic to human and environment [2] [3]. By carrying out proper action, it's not only giving solutions in reducing the environmental pollutions but providing good thermal comfort while maintaining mechanical properties of bricks at safe strength.

Coal is a major material used for combustion to generate electricity around the world. After going through complex combustion processes, large volumes of waste are produced. Fly Ash Cenosphere (FAC) is one of unwanted products produced during coal combustion process. It has tiny, small, spherical, lower density (0.4 to 0.8 g/cm^3) than water and lightweight properties [4], [5]. This grey to white colour hollow spheres has high composition of Alumina and Silica which are important elements for pozzolanic reaction to occur compared to sand. Besides, Cenosphere has low thermal conductivity (0.06 W/m.K) and highest specific heat capacity (1172.3 J/kg.K) compared to fly ash 711.76 J/kg. K and cement 753.62 J/kg.K [6]. Due to its special characteristics which are low-density properties, good insulation, good flowability, chemically inert and high specific heat capacity, it can be applied to many areas.

As Malaysia moving towards being developed country by year 2025, the amount of electricity uses in many sectors such as constructions, healthcare, banking and more have increase exponentially. Providing thermal comfort in any buildings while minimizing electric consumption is an important criterion that needs to be considered. To increase the energy efficiency of the building, the type and composition of bricks plays an important role. In general, clay bricks, cement bricks, concrete bricks are examples of materials used during building construction. This research aims to explore the effects of mortar containing cenosphere on energy efficiency in Malaysia.

2. Design of Experiment Set-up

2.1. Energy simulation for Mortar containing FAC in High Rise Buildings

A 29-storey residential high-rise apartment was used in this study for energy simulations. 28th days cured mortar bricks (0%, 5%, 10%, 15% and 20%) then cored at 50mm diameter and sliced into 10mm thickness. Prepared samples then tested for both thermal conductivity and specific heat capacity by using Fox 50 instrumentations at 28˚C. Both thermal testing (thermal conductivity, specific heat capacity) was based on ASTM C518 and ASTM C1784 respectively.

The energy consumption of mortar containing different percentage of cenosphere was used to evaluate energy saving in high rise residential building located in Putrajaya, Malaysia. According to Climate Data, Malaysia has tropical, hot, and humid climate throughout the year. The average temperature was 28˚C with coolest (23˚C) around November and warmest (33˚C) around June. The rainfall remains high throughout the year with 3085 mm. Malaysia receive approximately six hours of direct sunlight per day, with the cloud cover mostly during afternoon/evening.

The apartment used as case study in energy modelling in AutoCAD@Revit and passed over to AutoCAD@GBS to run the analysis at different orientation (0˚, 45˚ and 90˚). The Energy Usage Intensity (EUI), and its energy saving for various percentage of cenosphere, cement and clay bricks were then determined

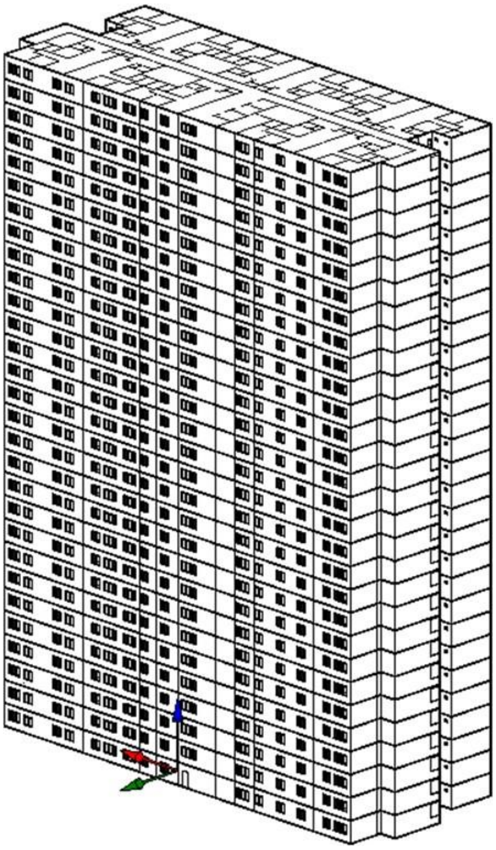

Figure 1 29 storey high rise residential building

3. Results and Discussion

3.1. Thermal conductivity

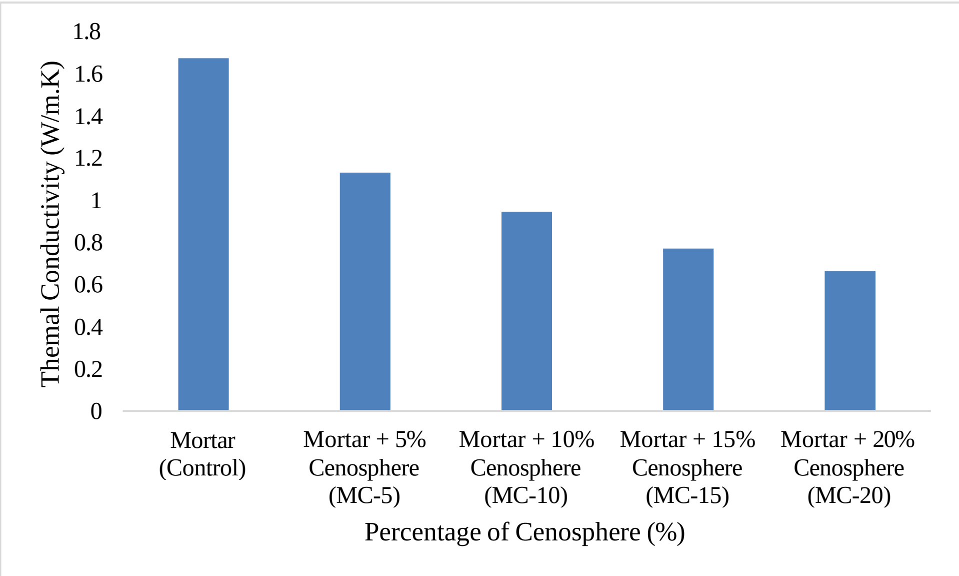

Figure 2 Thermal Conductivity versus Cenosphere Dosage

The thermal measurements of samples using Fox 50 were given in table above. The temperature differential between the upper and lower plates was 10 °C during the thermal conductivity test, which was conducted at a mean temperature of 28 °C. By observing the figure below, it can be noticed that in general, inclusion of cenosphere will cause *k* values drop. The lowest *k* values obtained was for MC-20 mixtures series which caused a 60.4% decrement in thermal conductivity compared to the CM. The thermal conductivity of all mixture's series is 1.67 W/mK for CM, 1.13 W/mK for MC-5, 0.95 W/mK for MC-10, 0.77 W/mK for MC-15 and 0.66 W/mK for MC-20 respectively. There are many explanations for this, including, spherical and hollow structure of Cenosphere included influenced density and k value. It is because hollow structures caused heat transfer between the particles to become inefficient due to gap presented in Cenosphere hence reducing density as well as thermal conductivity.

3.2. *Specific heat capacity*

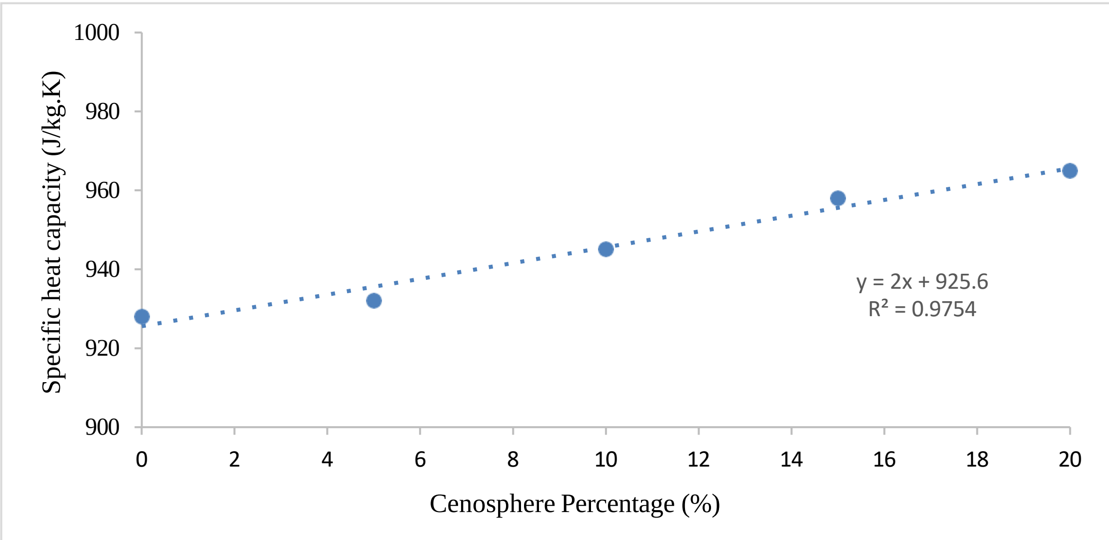

Figure 3 Specific Heat Capacity at different Cenosphere percentages

Specific heat capacity (Cp value) is the amount of energy required to increase the temperature by 1˚C. The results demonstrated in figure 2 show that the heat capacity of mortar does not significantly affect the percentage of cenosphere as sand replacement. However, it shows increment in specific heat capacity value as the percentage of cenosphere increases. The relationship between the percentage of cenosphere and Cp value shown below:

$$C_p = 2_{M_c} + 925.6$$
$$R^2 = 0.9754$$

Where Cp = Specific heat capacity (J/kg.K) , M_C = Dosage of cenosphere (%)

The lowest Cp values to highest are (MC-5) 932 J/kg.K, (MC-10) 945 J/kg.K, (MC-15) 958 J/kg.K, (MC-20) 965 J/kg.K while control 928 J/kg.K. The highest heat capacity is about 3% higher than control. The tested traditional construction materials are sand-cement brick (895 J/kg.K) and 729 J/kg.K for clay bricks. 20% cenosphere as sand replacement in mortar have highest specific heat capacity than the rest of the samples. It is due to the properties of Cenosphere which is hollow in shape required more energy to transfer the heat from one particle to another [7]. The increment of specific heat capacity are consistent with previous study where the Cp value of the mortar is between 941 J/kg.K to 1000 J/kg.K while clay and cement bricks are 800 J/kg.K and 1000 J/kg.K separately according to [8] and [9].

3.3. Energy used Intensity (EUI) performance of Mortar containing Cenosphere

Table 1 Energy Use Intensity (EUI) and saving at different orientations and saving (90˚-0˚)

Building Orientation Energy Consumption kWh/year	**0˚ Orientation – (Base Model) kWh/m²**	**45˚ Orientation kWh/m²**	**90˚ Orientation kWh/m²**	**0-90o % saving (90˚-0˚)**
Sand-cement Brick	151.4	153.3	155.6	2.8
Clay Brick	151.9	154.0	156.3	2.9
Mortar + 0% Ceno (MC-0)	146.3	147.8	150.2	2.7
Mortar + 5% Ceno (MC-5)	144.3	145.7	148.0	2.5
Mortar + 10% Ceno (MC-10)	143.5	144.9	147.1	2.5
Mortar + 15% Ceno (MC-15)	142.3	143.7	145.9	2.5
Mortar + 20% Ceno (MC-20)	141.7	143.0	145.2	2.5

Energy Use Intensity (EUI) is calculated by dividing the annual energy consumption of buildings with the total floor area and the unit used usually (GJm^{-2}). As shown in Table 1 above, electricity consumption is reduced as the percentage of cenosphere increases.

The requirement EUI to be certified as Green Building Index (GBI) for residential high-rise buildings in Kuala Lumpur is150 $Kw.h.m^{-2}$ [10], [11]. Control mortar shows the highest energy consumption for all orientation as compared to other percentages. Putrajaya annual EUI values at 90˚ orientation for 5%, 10%, 15% and 20% ranging from 148.02 kW/h/m² to 145.22 kW/h/m² qualify for GBI requirements which is less than 150 kW/h/m². However, control mortar, cement and clay bricks have slightly higher EUI value than the requirement which are 150.15 kW/h/m², 155.58 kW/h/m² and 156.27 kW/h/m² respectively. Hence, does not satisfy the standard EUI value. It is the fact that control, cement, and clay use more electricity than mortar containing cenosphere as sand replacement. The best EUI performance was presented by 20% of cenosphere (145.23 kW/h/m²) where save 3% as compared to control (150.227 kW/h/m²).

3.4. Effect of Building Orientations on Energy Saving of High-Rise Residential buildings

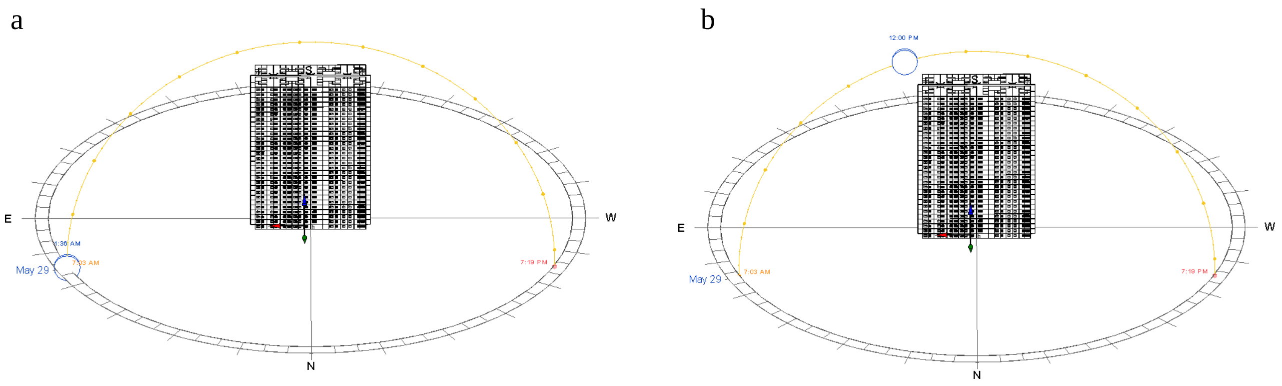

Figure 4 Building Orientations at 0˚ (a) and 90˚(b)

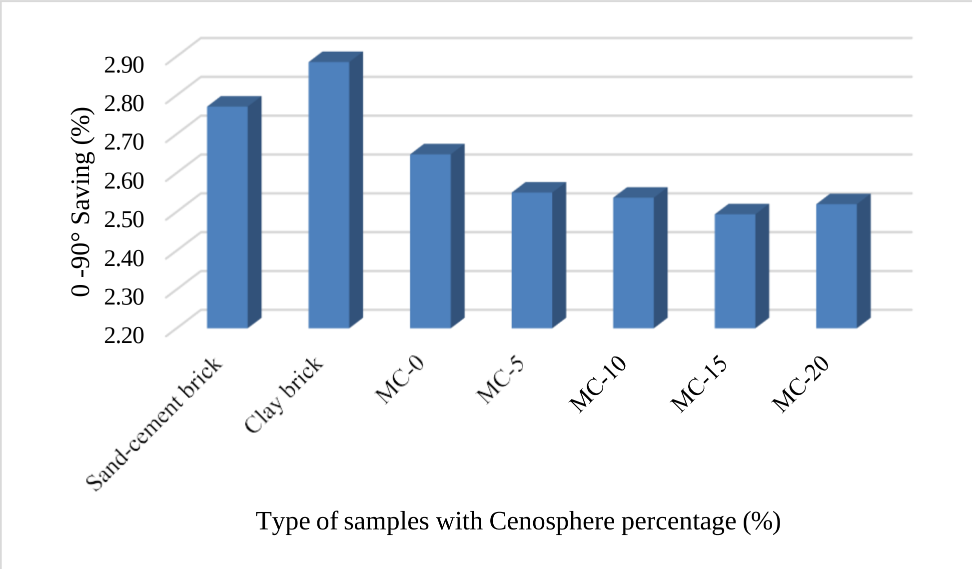

Figure 5 Percentage of energy saving (90˚-0˚) using mortar containing Cenosphere

In this study, three different buildings' orientation were used (0˚ (base model), 45˚ and 90˚). Figure 4(a) and (b) shows 29-storey high-rise residential building at 0˚ and 90˚ orientations. The changes in energy consumption value are not significantly lessened with the increment of Cenosphere dosage as constructed in Figure 5. As for MC-20, changing the orientation from 90˚ to 0˚ have reduced the energy consumption by 3.569 kW/h/m^2 or 2.52%. Next, mortar containing 15% of Cenosphere have slightly lower energy consumption than MC-20 3.55 kW/h/m^2 or 2.43%. As contra with cement bricks and the rest of samples, Clay bricks recorded highest EUI reduction which is 2.84% or 4.446 kW/h/m^2. This aligned with previous study shown that a two-storey residential house in Brunei using clay bricks walls could reduce the EUI by 2.3 kW/h/m^2[12].

4. Conclusion

Overall, the utilization of Cenosphere as sand replacement in mortar has influenced the thermal properties and energy efficiency of high-rise residential buildings. The energy consumption was compared with the Malaysia Green Building Index standard (GBI) and conventional bricks together with the buildings' orientation in hot-humid tropical climatic regions, Putrajaya, Malaysia.

• Due to the gap presented in mortar, 20% of Cenosphere demonstrated highest specific heat capacity (965 J/kg.K) while control gives 928 J/kg.K reading.

•The use of Cenosphere in mortar as sand replacement meets the LEED-Certified Green Building requirements which is lower than 150 kWh/m2. For instance, MC-5 and MC-20 show 148 kWh/m2 and 145 kWh/m2 respectively.

•Traditional bricks such as clay brick, sand-cement bricks and control mortar uncessfully meet the EUI-certified requirements.

•The energy saving measure largely influenced by the composition of Cenosphere as compared to the buildings' orientations.

References

[1] M. Rafieizonooz, J. Mirza, M. R. Salim, M. W. Hussin, and E. Khankhaje, "Investigation of coal bottom ash and fly ash in concrete as replacement for sand and cement," *Constr Build Mater*, vol. 116, pp. 15–24, Jul. 2016, doi: 10.1016/j.conbuildmat.2016.04.080.

[2] "Trace Elements in Coal Ash."

[3] S. Beddu, M. Zainoodin, A. Basri, Z. Itam, R. Ahmadi, and T. S. Abd Manan, "The Potential Of Cenospheres Production From Malaysian Coal Power Plants," *IOP Conf Ser Mater Sci Eng*, vol. 1101, no. 1, p. 012012, Mar. 2021, doi: 10.1088/1757-899x/1101/1/012012.
[4] N. Ranjbar and C. Kuenzel, "Cenospheres: A review," *Fuel*, vol. 207, pp. 1–12, 2017, doi: 10.1016/j.fuel.2017.06.059.
[5] A. Danish and M. A. Mosaberpanah, "Formation mechanism and applications of cenospheres: a review," *J Mater Sci*, vol. 55, no. 11, pp. 4539–4557, 2020, doi: 10.1007/s10853-019-04341-7.
[6] P. Choktaweekarn, W. Saengsoy, and S. Tangtermsirikul, "A model for predicting the specific heat capacity of fly-ashconcrete," *ScienceAsia*, vol. 35, no. 2, p. 178, 2009, doi: 10.2306/scienceasia1513-1874.2009.35.178.
[7] A. Shishkin *et al.*, "Physical, Thermal, and Chemical Properties of Fly Ash Cenospheres Obtained from Different Sources," *Materials*, vol. 16, no. 5, Mar. 2023, doi: 10.3390/ma16052035.
[8] Z. C. Muda, P. Shafigh, N. B. Mahyuddin, S. M. E. Sepasgozar, S. Beddu, and A. Zakaria, "Energy performance of a high-rise residential building using fibre-reinforced structural lightweight aggregate concrete," *Applied Sciences (Switzerland)*, vol. 10, no. 13, Jul. 2020, doi: 10.3390/app10134489.
[9] V. F. Mendes, W. Fardin, R. R. Barreto, L. F. Caetano, and J. C. Mendes, "Sensitivity analysis of coating mortars according to their specific heat, specific gravity, thermal conductivity, and thickness in contribution to the global thermal performance of buildings," *Sustainable Materials and Technologies*, vol. 31, Apr. 2022, doi: 10.1016/j.susmat. 2021.e00381.
[10] "GBI Assessment crIterIA for." [Online]. Available: www.greenbuildingindex.org
[11] E. Mohareb, C. Kennedy, D. Harvey, and K. Pressnail, "Decoupling of Building Energy Use and Climate," *Energy Build*, vol. 43, p. 2961, Oct. 2011, doi: 10.1016/j.enbuild.2011.06.032.
[12] V. Shabunko, C. M. Lim, and S. Mathew, "EnergyPlus models for the benchmarking of residential buildings in Brunei Darussalam," *Energy Build*, vol. 169, pp. 507–516, Jun. 2018, doi: 10.1016/j.enbuild.2016.03.039.

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