



Article

Enhancing Sustainability in Construction: Investigating the Thermal Advantages of Fly Ash-Coated Expanded Polystyrene Lightweight Concrete

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Abstract: This study investigates a sustainable coating method for modified expanded polystyrene (MEPS) beads to improve the thermal insulation of lightweight concrete intended for wall application. The method employed in this study is based on a novel coating technique that represents a significant advancement in modifying Expanded Polystyrene (EPS) beads for enhanced lightweight concrete. This study experimentally assessed the energy-saving capabilities of MEPS concrete in comparison to control groups of uncoated EPS beads and normal concrete by analysing early-stage temperature, thermal conductivity, specific heat capacity, heat flux, and thermal diffusivity. The thermal conductivity of MEPS concrete is approximately 40% lower than that of normal concrete, demonstrating its usefulness in enhancing insulation. The heat flux calculated for MEPS concrete is significantly reduced (approximately 35%), and it has a 20% lower specific heat capacity than ordinary concrete, indicating a reduction in energy transfer through the material and, thus, potential energy-efficiency benefits. Furthermore, the study discovered that all test objects have very low thermal diffusivity values (less than $0.5 \times 10^{-6} \text{ m}^2/\text{s}$), indicating a slower heat transport through the material. The sustainable coating method utilized fly ash-enhanced thermal efficiency and employed recycled materials, hence decreasing the environmental impact. MEPS concrete provides a practical option for creating sustainable and comfortable buildings through the promotion of energy-efficient wall construction. Concrete incorporating coated EPS can be a viable option for constructing walls where there is a need to balance structural integrity and adequate insulation.

Keywords: lightweight concrete; thermal properties; fly ash; modified expanded polystyrene (MEPS)



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1. Introduction

The thermal properties of concrete, such as thermal conductivity, specific heat, and thermal diffusivity, determine how the material responds to changes in external temperature. This is crucial for constructing energy-efficient buildings and improving thermal efficiency. Therefore, thermal properties are important in concrete for several reasons. Firstly, thermal conductivity is a key factor controlling heat transfer in concrete [1]; it indicates the material's ability to conduct heat, with lower values indicating better insulation performance [2]. The benefits of thermal insulation, reduced energy consumption and building costs, improved building efficiency, and easier construction are all displayed by lightweight aggregate concrete (LWAC) [3]. Concrete with low thermal conductivity and high specific heat capacity is desirable for energy-saving in buildings [4]. Secondly, the thermal properties of concrete play a significant role in the heat transfer into the material during fire exposure [5]. Understanding these properties can help in evaluating the safety

of concrete structures during fire incidents. Just as importantly, the thermal properties of concrete affect human comfort in buildings. In regions that have tropical climates, the implementation of this strategy can contribute to the cooling of indoor spaces. Conversely, in areas subject to cold winters, it can serve to minimise heat loss from the building, thereby potentially alleviating the economic burden associated with home heating expenses. It is possible to improve energy efficiency and reduce residential energy consumption by studying and optimising the thermal properties of concrete. Thermal properties in concrete are important because of their impact on energy efficiency, safety, and human comfort in buildings.

Expanded polystyrene (EPS) has impressive capabilities as a thermal insulator; however, its suitability as a component in concrete remains in doubt due to its insufficient mechanical strength. A study conducted in Sri Lanka demonstrated that incorporating EPS panels into flat building could result in a significant reduction of 40–50% in environmental effect [6]. Although the use of EPS sandwich panels offers a significant alternative for sustainable building construction in the context of cheap housing, owing to its questionable safety and durability [7], its suitability as a component in concrete has been called into concern.

Regarding sustainable construction, it is of the utmost importance to consider the possibility of including other waste material from industry, i.e., fly ash. The use of this by-product raises concerns about the potential for negative environmental impacts if it is not handled appropriately. Although fly ash has been used in concrete, its primary function has been limited to supplementary cementitious material. Adding fly ash powder to the new composite material improves its mechanical properties in a direct and beneficial way [8]. However, there is an opportunity to discover and develop other innovative uses for this material. This investigation stage becomes appealing as it explores the potential integration between EPS beads and fly ash in concrete, which eventually ends up in a custom-made procedure. This research project aims to develop a lightweight concrete material that demonstrates significant thermal insulation properties and mechanical strength.

The method employed in this study is based on a novel coating technique that represents a significant advancement in modifying Expanded Polystyrene (EPS) beads for enhanced lightweight concrete, which differentiates from previous research [9,10]. This novel technique involves applying a specialised coating to the surface of the EPS beads to improve their adhesion to the cementitious matrix. The procedure for generating coated EPS was briefly described in a prior publication that is associated with this research [11]. The present methodology capitalises on the advantageous combination of EPS beads with fly ash, renowned for their lightweight characteristics and insulating capabilities. By coating EPS beads with fly ash, the modified beads exhibit enhanced compatibility with the concrete matrix, resulting in improved mechanical strength, durability, and thermal performance. The coating technique addresses the problem of weak adhesion between EPS and the cement matrix. It capitalises on the sustainable utilisation of fly ash, contributing to environmentally responsible building practices. This novel technique demonstrates a search for innovation in lightweight concrete, suggesting a transformative approach with the potential to improve building materials for more efficient and sustainable infrastructure.

2. Materials and Methods

2.1. Materials

The basic components utilised in concrete production, including cement, sand, gravel, and water, were sourced from the existing inventory at Coventry University's building materials laboratory (John Laing Building). This investigation used Hanson 52.5N High Strength Cement, manufactured by the Heidelberg Cement Group, United Kingdom. The sand had a fineness modulus of 1.95, whereas the coarse aggregate had a fineness modulus of 6.22. Meanwhile, the fly ash and EPS beads were purchased from providers based in the United Kingdom. The modified EPS utilised in this study corresponds to prior research [11] that has also been incorporated into this study.

The concrete composition for the test specimens can be found in Table 1. This mixture design has been implemented in prior investigations as well [11]. The explanation related to the specimen code is given below.

Table 1. Composition for making 1 m³ concrete sample.

Specimen Code	Cement (+PFA) (kg)	Water (kg)	Sand (kg)	Gravel (kg)	EPS Beads (kg)
NC	490	225	572	1063	-
PFAC	343 (+147)	225	572	1063	-
EPSC	490	225	572	-	7.25 ^a
EPS-PFAC	343 (+147)	225	572	-	7.25 ^a
MEPS-PFA	490	225	572	-	190 ^b

^a non-coated EPS beads; ^b coated EPS beads.

The specimens used were as follows: NC (normal concrete—as control), PFAC (concrete with 30% cement replacement with fly ash), EPSC (concrete with 100% coarse aggregate replacement with EPS beads), EPS-PFAC (concrete with 100% coarse aggregate replacement with EPS beads and 30% cement replacement with fly ash), and MEPS-PFA (concrete with 100% coarse aggregate replacement with modified/coated EPS beads).

2.2. Test Procedures

A 100 mm cube-shaped sample of concrete is utilised for the initial temperature measurement. Then, the temperature sensor or thermocouple is embedded into the concrete and positioned as close to the cube’s centre as possible to obtain data that more accurately reflects the temperature of the concrete sample. In addition to the temperature sensor on the concrete sample, it is necessary to have a temperature sensor that records the temperature of the room as a comparison. These temperature sensors are then linked to data loggers or monitoring devices. The temperature sensor data are then periodically recorded every 30 s for a period of 72 h. A customised insulation box was used as a Semi-Adiabatic chamber (Figure 1) in order to determine the early age temperature of the concrete.

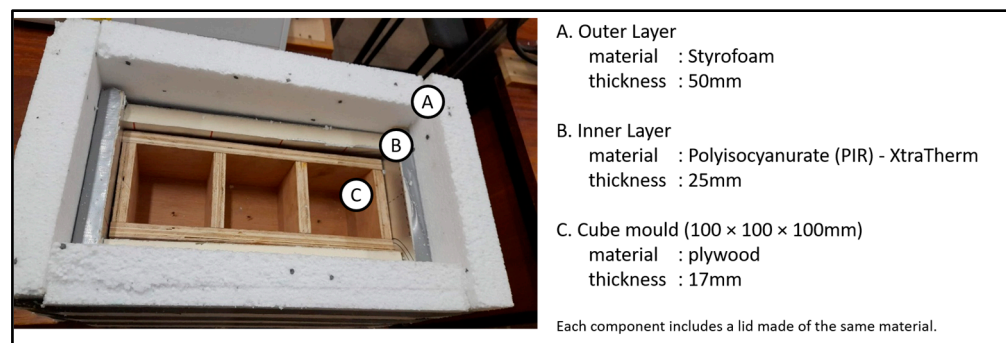


Figure 1. The insulation box (Semi-Adiabatic Chamber).

The thermal conductivity testing was conducted using the FOX200 device manufactured by Laser Comp, TA Instruments, New Castle, USA (Figure 2). This instrument utilises a steady-state approach using the Heat Flow metre method, which adheres to international standards such as ASTM C518 [12], ISO 8301 [13], and DIN EN 12667 [14]. For the size of the specimen, the maximum sample thickness is 51 mm (2 inch), and the square sample width is 200 mm (8 inch), but no less than 75 mm is needed. To meet this requirement, a horizontal cut direction and a vertical cut direction for cube specimens was applied in order to produce the shape of a plate with a thickness of about 25 mm. Afterwards, the sample was inserted into the testing instrument. A polystyrene board with a hole in its centre positioned the sample in the centre (Figure 3).



Figure 2. FOX200 apparatus by LaserComp for thermal conductivity testing.



Figure 3. Sample preparation for thermal conductivity testing.

To assess the specific heat capacity, this research utilised the method of mixture found in [15] as a viable alternative to the standard testing procedure. In certain scenarios, the utilisation of simple methods may be more advantageous compared to standard methods for testing due to their reduced reliance on complex equipment and procedural steps. These simple techniques enable testing to be conducted without the necessity of complex and expensive equipment. This enhances usability and reduces cost. Moreover, it is worth noting that straightforward techniques typically entail simpler procedures, thereby requiring minimal training and experience for their utilisation. By adopting this approach, the usability and installation process of the technology are enhanced, thereby accommodating individuals with limited technological proficiency. Efficient techniques can also yield time and cost savings as they often require fewer procedural steps and entail reduced data analysis. In general, the utilisation of straightforward methodologies may avoid the challenges associated with the utilisation of expensive tools and complicated methods, thereby facilitating the convenience and efficiency of testing.

Scientists worldwide rely on the mixture method because it provides a relatively reliable estimate of the specific heat of a solid sample in a short amount of time. The accuracy of the results is improved by repeating the experiment and using the average of the results, regardless of whether the experiment is performed with very expensive equipment in a high-tech lab or in a home kitchen with some glassware. The quality of the calorimeter used will have the greatest impact on the reliability of the findings.

Calorimetry is a scientific methodology used to quantify heat, while a calorimeter is a device utilised for measuring the heat transfer related to a chemical or physical reaction. Calorimeters are employed for the purpose of quantifying the thermal energy exchange occurring between a specimen and a container filled with water. It is essential to keep in mind that, in the context of this experiment, the quality of insulation of the calorimeter directly influences the precision and accuracy of the obtained results. The primary source of error in this experiment comes from the conduction-based heat loss.

The theory underlying this specific heat test is based on energy conservation. In this case, heat is a type of energy that will be transferred between the sample and the water. We were able to measure the change in the temperature of the water using the calorimeter, which allowed us to calculate the change in heat of the water in the calorimeter (Figure 4). It is now apparent how practical this particular heat capacity test is, given that once the experiment begins, the sole requirement is to quantify the water’s temperature variation, which serves as an indirect indicator of the solid’s heat change. Relevant and basic equations, which are known as Change in Heat equations, are explained as follows:

$$Q = c \cdot m \cdot \Delta T \tag{1}$$

Q = change in heat
 m = mass of object
 c = specific heat capacity
 ΔT = change in temperature

Using principle of calorimetry,		
Heat loss by hot object	=	Heat gained by cold object
Q_{sampel}	=	$Q_{\text{water+container}}$
$c_3 \cdot m_3 \cdot (T_2 - T)$	=	$(c_1 \cdot m_1 + c_2 \cdot m_2) (T - T_1)$
c_3	=	$\frac{(c_1 \cdot m_1 + c_2 \cdot m_2) (T_0 - T_1)}{m_3 \cdot (T_2 - T_{01})}$

- m_1 : Mass of calorimeter
- c_1 : Specific heat capacity of calorimeter
- m_2 : mass of water
- c_2 : specific heat capacity of water
- T_1 : initial temperature of calorimeter and water
- m_3 : mass of solid (specimen)
- T_2 : initial temperature of solid (specimen)
- T : Final temperature of mixture
- c_3 : Specific heat of solid (specimen)

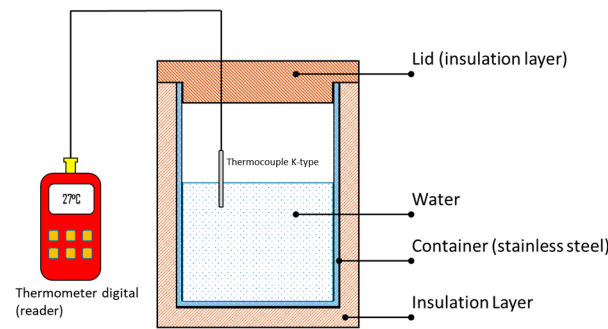


Figure 4. Calorimeter for Specific Heat Testing.

3. Results and Discussion

In addition to observing the density of several types of lightweight concrete, our study also examined their thermal properties, beginning with measuring temperature changes in concrete at an early stage. We then investigated thermal conductivity, heat flow, specific heat capacity, and thermal diffusivity. The thermal conductivity and heat flux results offer valuable information about the material’s efficiency in transferring heat and, thus, affecting energy distribution. Meanwhile, the analysis of specific heat capacity revealed subtle factors that affect the material’s capacity to absorb and release thermal energy at different temperatures. Finally, investigating thermal diffusivity will elucidate crucial factors that influence the speed at which heat spreads, thus enhancing our overall comprehension of the thermal characteristics of the material. These findings collectively establish the foundation for more investigation and future practical implementations.

3.1. Density of Concrete

As expected, based on the mix design calculation, the reference/control weight of concrete is in the range of 2340 kg/m³. Meanwhile, concrete made by replacing up to 30% of the cement with PFA has a significantly reduced weight, averaging 2300 kg/m³. On the other hand, the weight of concrete made with EPS beads to replace coarse material is approximately 1240 kg/m³. This weight remained relatively constant when the cement was substituted with 30% PFA by weight. MEPS beads coated with PFA powder had a substantial influence on the density, roughly 13% from around 1200 into 1400 kg/m³, compared with the other concrete made from EPS beads. There was no significant difference between cube and cylinder specimens for all types of concrete. This indicates that there was no distinct significant difference in the level of compactness between the cube and the cylinder.

In order to evaluate the evolution of the density of the produced concrete samples, the weight of the specimens was quantified and documented upon their removal from the mould (1 day), as illustrated in Figure 5. Additionally, the density of the concrete after 28 days of curing (immersed in water) was measured and is presented on the right side of Figure 5. It is commonly believed that 28 days is required for concrete to reach a state of stability. In light of this, the measurements for 28 days were conducted for samples in dry surface conditions. The average concrete density shown in Table 2 provides a general view of the weight of each piece of concrete produced during this study. This average result will be used as part of the comparison/discussion chapter.

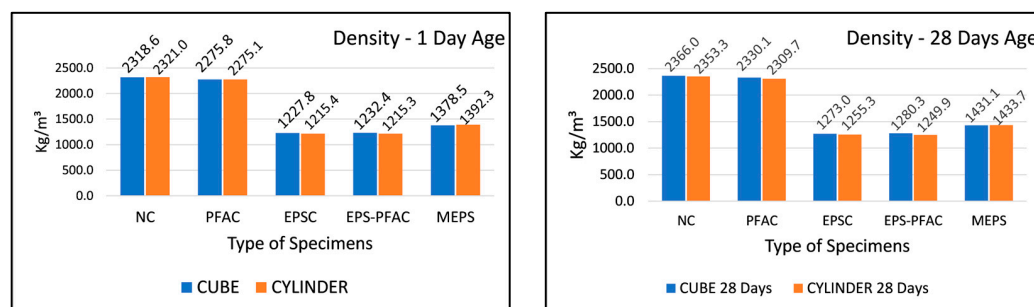


Figure 5. The density of concrete. One day following the demoulding process (left). The 28-days period (right).

Table 2. The density of different types of concrete samples (in Kg/m³).

Specimens	Cube 1 Day	Cylinder 1 Day	Cube 28 Days	Cylinder 28 Days	Average
NC	2318.61	2320.99	2365.97	2353.28	2339.71
PFAC	2275.83	2275.08	2330.10	2309.66	2297.67
EPSC	1227.82	1215.36	1272.97	1255.28	1242.86
EPS-PFAC	1232.39	1215.31	1280.30	1249.86	1244.47
MEPS	1378.51	1392.32	1431.10	1433.69	1408.90

The density and compressive strength features of cured concrete are influenced by the percentage of EPS beads present in the concrete mixture [16]. As the percentage of expanded polystyrene bead content increases, the density of concrete decreases [17,18]. The possible reduction in density of EPS lightweight concrete can be achieved through the insertion of silica dust and fly ash [19]. However, this effect is not observed when fibre is added [20]. Upon doing a comparative analysis with other research, it is apparent that the present study exhibits correlations and similarities in terms of trends.

While in other studies the EPS-foam concrete showed a reduction in self-weight of up to 20% [21], EPS concrete from this study achieved an almost 50% reduction. Therefore,

the use of EPS can once again be considered as an option for the creation of a reliable lightweight concrete.

3.2. Early Age Temperature of Concrete

The use of fly ash as a 30% partial substitute for cement seems to have influenced temperature reduction throughout the cement hydration process. This effect is most noticeable in concrete with EPS, while it is barely noticeable in regular concrete. Figure 6 shows that EPS concrete with a typical mortar composition, with no fly ash substitution, has a higher heat of hydration than EPS concrete with a mortar that includes a combination of fly ash as a partial replacement for cement. This conclusion is consistent with previous research findings, which show a favourable relation between the amounts of fly ash employed as a cement substitute and the moderating effect of temperature reduction on the early stages of hardened concrete [22].

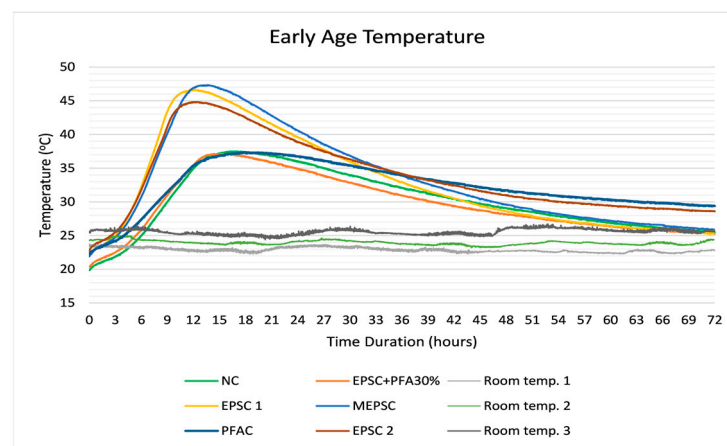


Figure 6. Graph of early age temperature of specimens.

The peak temperature occurred between nine and fifteen hours after the concrete was poured into the mould in the insulating box. Table 3 shows that EPSC and MEPSC concrete, in contrast with the other specimen types tested, can reach temperatures beyond 40 °C. This phenomenon was likely due to the EPS beads’ insulating qualities, preventing them from absorbing heat created during cement hydration. However, a completely different conclusion occurred in the case of EPS-PFAC concrete, which attained a maximum temperature of around 37 °C. Although those samples used EPS in the concrete manufacturing process, the relatively low heat of hydration is most likely attributable to cement reduction caused by fly ash replacement.

Table 3. Temperature of specimens in early 72 h.

Specimens	Temperature (°C)		
	Min	Max	At 72 h
NC	19.84	37.49	25.58
PFAC	22.22	37.35	29.42
EPS-PFAC	20.40	37.13	25.34
EPSC1	22.05	46.62	25.32
EPSC2	22.63	44.83	28.60
MEPSC	21.86	47.34	25.32
Room temp. 1	22.26	23.76	22.86
Room temp. 2	23.22	25.06	24.34
Room temp. 3	24.40	26.71	25.70

3.3. Thermal Conductivity

According to the test results, coated EPS concrete has a greater conductivity value than plain EPS concrete. Based on this, concrete with coated EPS has no better insulating capability than plain EPS concrete. Another intriguing observation is that substituting cement with fly ash lowers thermal conductivity values. According to Table 4, the value of PFAC concrete is lower than NC, and EPSC-PFA is lower than EPSC.

Table 4. Thermal conductivity of specimens.

Specimens	Thermal Conductivity (W/m·K)		
	Lower	Upper	Average
NC	1.157	1.268	1.213
PFAC	1.100	1.104	1.102
EPSC	0.359	0.403	0.377
EPS-PFAC	0.331	0.314	0.322
MEPS	0.482	0.497	0.489

The LWC panel with the highest thermal mass was the best at reducing energy usage and severe discomfort hours, despite having the maximum thermal conductivity [23]. However, most prior studies have indicated that the implementation of lightweight aggregates, specifically those possessing favourable insulating characteristics, may result in a decrease in thermal conductivity values. As insulators, substances possessing lower thermal conductivity values are preferable.

The correlation between the density and thermal conductivity in lightweight concrete is substantial. As the density of the concrete material increases, the thermal conductivity also increases. This phenomenon occurs due to the higher density of the material, which results in a more compact arrangement of its particles. This denser arrangement facilitates the more efficient transfer of thermal energy. Therefore, a higher density of concrete results in enhanced thermal conductivity. Nevertheless, when discussing the use of concrete as insulation, it is important to highlight that a lower thermal conductivity value indicates better insulation properties.

Adding Expanded Polystyrene (EPS) beads to the concrete matrix changes the density and thermal conductivity relationship (Figure 7). As EPS beads were added, the overall density of the material went down because the lightweight beads created air pockets in the composite. The air pockets in the concrete might cause a lightweight concrete with EPS beads to have a much lower thermal conductivity than denser concrete that does not have these beads. The alteration of the EPS aggregates somewhat affects the thermal conductivity of the overall material [24]. This trend shows that adding EPS beads lowers the overall density. It makes the material more thermally insulating, which is crucial for energy conservation and temperature control.

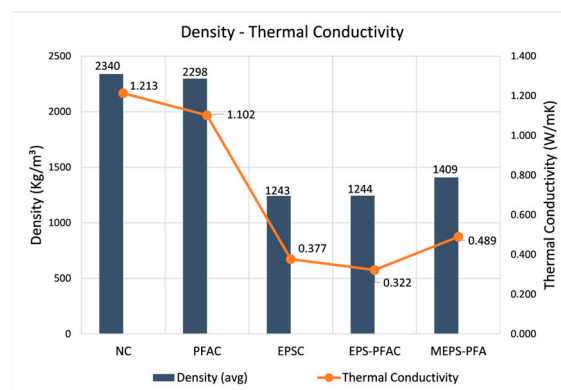


Figure 7. Relationship between density and thermal conductivity.

Interestingly, the application of fly ash as a coating material on EPS beads leads to unfavourable results in terms of thermal conductivity. Compared to EPSC, coated EPS beads cannot reduce the concrete’s thermal conductivity. Despite this, it continues to be a considerably lower than that of NC and PFAC. It is thought that the higher thermal conductivity of concrete made from coated EPS beads is caused by the higher density of the concrete that results from using coated EPS beads as an aggregate. Another study has also documented the phenomenon whereby the thermal conductivity value elevates as the density of the material increases (Figures 8 and 9).

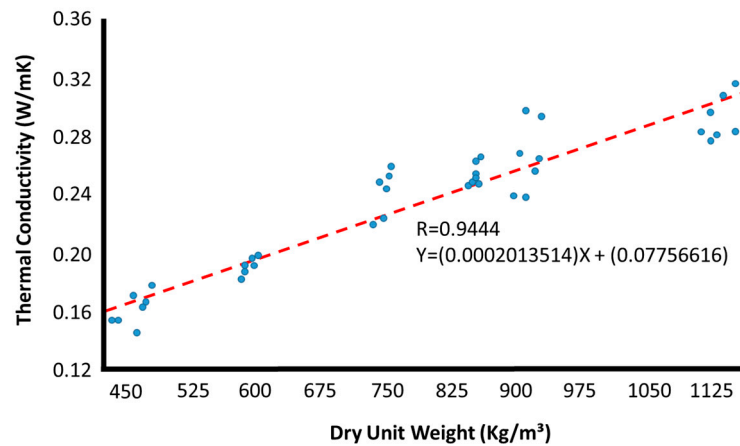


Figure 8. Correlation between thermal conductivity and dry unit weights [25].

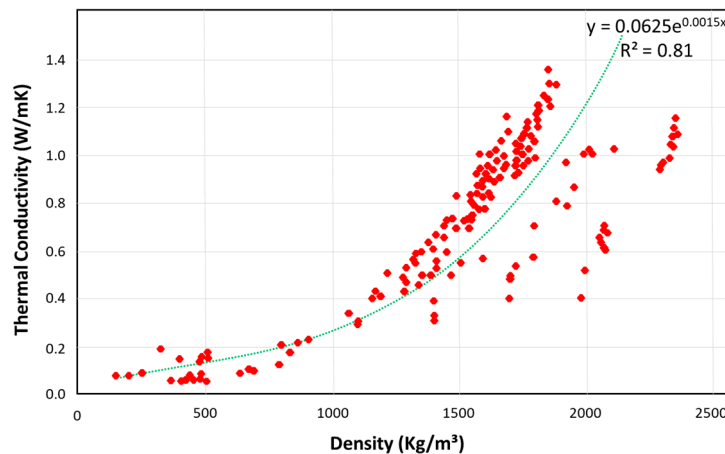


Figure 9. Density and thermal conductivity—a general correlation [26].

On the other hand, the incorporation of fly ash as a partial substitute for cement has a more significant impact on the thermal conductivity value. These findings are supported by the fact that the thermal conductivity values of PFAC and EPS-PFAC are lower than those of EPSC and NC, respectively.

In order to achieve the primary goal of this study, which is to determine the effects of coated EPS on mechanical and thermal properties, it is necessary to conduct a comparative analysis of these two aspects, as seen on Figure 10. This analysis will involve evaluating the compressive strength, which indicates mechanical properties, and the thermal conductivity value, which represents the thermal properties. These two aspects are considered pivotal in examining and studying the properties of concrete, particularly when assessing its suitability as a material for building insulation.

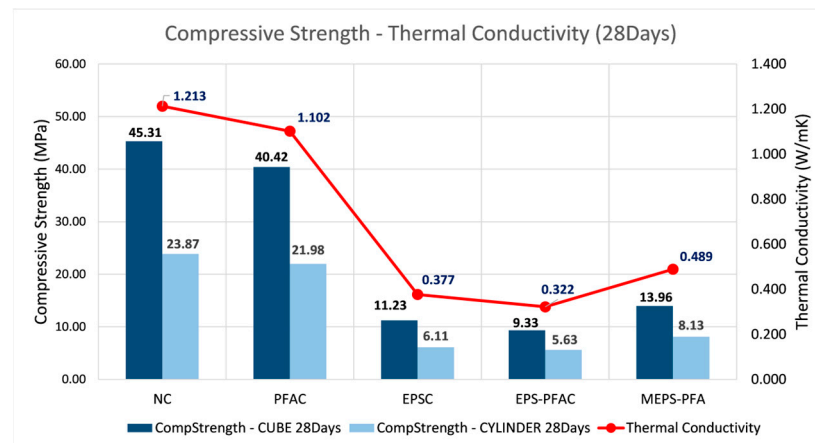


Figure 10. Compressive strength and thermal conductivity.

The research findings demonstrate a positive correlation between the increase in compressive strength and the rise in thermal conductivity values. This trend is consistent with previous studies [27]. Coated EPS displays higher compressive strength compared to concrete, which only uses uncoated EPS as aggregate. However, there is a direct correlation between the increase in compressive strength and the rise in thermal conductivity value. This result is possible because of the density parameter of the concrete that was produced. The comparison graph of compressive strength and thermal conductivity reveals an intriguing finding: substituting a portion of the cement with fly ash can effectively decrease the thermal conductivity value, as observed in PFAC and EPS-PFAC concrete. These findings suggest that using fly ash as a coating material is more successful in enhancing concrete's compressive strength than decreasing its thermal conductivity value.

Utilising fly ash as a replacement for cement and as a coating substance has a distinct impact on the thermal performance of the resulting concrete. This outcome is anticipated due to the incorporation and interaction of fly ash as a coating with the binder during the initial stages of MEPS production. Consequently, the reaction with cement will differ from fly ash used as a substitute for cement, which may react promptly upon mixing.

3.4. Specific Heat Capacity

Specific heat is a fundamental property of a material that measures its ability to absorb or release thermal energy when its temperature changes. The specific heat is defined as the amount of energy required to raise the temperature of a unit mass by one unit of temperature difference. The commonly utilized units in the metric system are expressed as Joules per kilogram per Kelvin (J/Kg·K).

The concept of specific heat is crucial for comprehending how a material reacts to variations in temperature. Thermal conductivity tests help us understand how well a material can conduct or transport thermal energy, while specific heat capacity refers to the amount of thermal energy needed to increase the temperature of a substance. Specifically, when the specific heat value increases, the energy required to increase the temperature of a given amount of material by one degree also increases.

NC had the greatest measured specific heat capacity value, whereas EPSC-PFA had the lowest. Utilising coated EPS as a replacement for coarse aggregate offers a value that is lower than EPSC but not as minimal as EPS-PFAC. The complete results are displayed in Table 5.

Table 5. Specific heat capacity of specimens.

Specimens	Specific Heat Capacity (J/Kg·K)		
	Lower	Upper	Average
NC	940.47	1232.24	1086.36
PFAC	1056.09	1146.48	1101.29
EPSC	860.89	996.01	928.45
EPS-PFAC	637.85	715.07	676.46
MEPS	841.62	884.84	863.23

In the context of insulation materials, a lower specific heat capacity tends to be seen as a desirable value. The specific heat capacity of a substance is the quantity of heat energy needed to increase the temperature of one unit of mass by one degree Celsius. A lower specific heat capacity leads to more rapid thermal transfer, causing the material to heat up or cool down faster as heat is gained or lost.

The weight of the material is a variable in the calculation used to determine the specific heat value. However, it appears that there is no clear correlation between the specific heat value and density, as shown in Figure 11. Despite having similar densities, EPSC and EPS-PFAC concrete exhibit different specific heat values. From this premise, it can be inferred that, while the weight of a material is a factor in determining the specific heat value, the composition of the concrete can also have an impact on the specific heat value.

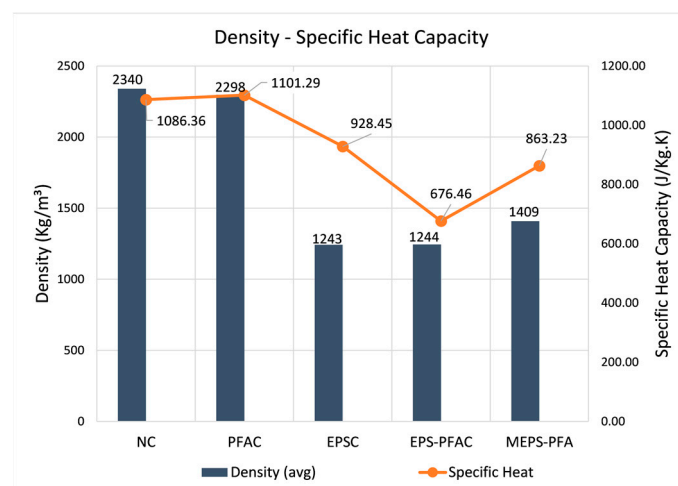


Figure 11. Relationship between density and specific heat capacity.

Based on the current trend, it is highly likely that fly ash will impact the specific heat capacity value. Using fly ash as a substitute for cement appears to reduce the specific heat value, as indicated by the notable decrease in EPSC and EPS-PFAC concrete. The decrease in specific heat value indicates that concrete can rapidly absorb and release heat. However, this trend does not correspond to what occurred with NC and PFAC. Additional investigation is required in order to further examine this issue. Given the close relationship between specific heat and the time required to absorb and release heat, the testing measurement process appears to rely heavily on the measurements’ timing and duration. During this test, the duration required to observe the temperature variation in the substance was merely 5 min, which might require additional time to ensure a precise measurement.

The future assurance of the test results’ validity hinges on several factors. Firstly, the standardisation of the tools used needs to be addressed. Further testing is required to ensure consistency in the measurement methods used to interpret the test results. Lastly, it is crucial to acknowledge the potential occurrence of human error factors. Nevertheless, the tools and methods employed in this study are adequate for obtaining a comprehensive

understanding of the observed trends and for comparing concrete specimens of different types. The data obtained from this test can be compared to standards and other tests on specific heat for masonry and concrete materials. The specific heat values of normal concrete in this study are relatively similar. The specific heat values of masonry and concrete materials range from 0.79 to 0.92 kJ/Kg·K [28], while another study described the values of specific heat capacities as 0.88 and 0.92 kJ/Kg°C for concretes with densities between 1280 and 1920 kg/m³ and 2080 and 2240 kg/m³, respectively [29].

Overall, the use of fly ash as a coating material does not have a significant enough effect in achieving the desired reduction in specific heat value. As previously mentioned, when selecting a material for insulation purposes, the material should have a specific heat value that is as low as possible. This aligns with what has been stated in previous research. Specific heat capacity plays an essential role because it helps lower energy consumption and improve thermal comfort in any situation, regardless of location or building type [30]. Nevertheless, further research can be conducted to explore the potential of using coated EPS beads as concrete aggregate material in order to decrease the specific heat value. This objective could be achieved by carefully controlling the composition of cement and fly ash in the concrete mixture. Reducing the cement content may offer results similar to or better than EPS-PFAC concrete.

The correlation between thermal conductivity and specific heat significantly influences the thermal performance of lightweight concrete. Thermal conductivity quantifies the concrete's capacity to conduct heat, directly impacting its insulation characteristics. Lightweight concrete, typically formulated with porous aggregates or air-entraining additives, generally demonstrates reduced thermal conductivity compared to conventional concrete. The decreased thermal conductivity of lightweight concrete reduces heat transfer, enhancing its insulation properties. The composition of lightweight concrete influences its specific heat capacity, quantifying the material's capacity to absorb and release heat simultaneously. Lightweight aggregates reduce thermal conductivity and increase specific heat capacity, enabling efficient absorption and retention of heat by the material. Although materials with low thermal conductivity and low specific heat capacity are often preferred for typical insulation applications where the primary goal is to resist heat transfer, the correlation between these characteristics in lightweight concrete results in a material that provides insulation by slowing heat transfer and can regulate temperature fluctuations, thereby improving its overall thermal efficiency in construction applications.

However, obtaining the desired material with the specific characteristics mentioned earlier, which is a material with low thermal conductivity and high specific heat, can be challenging. Substituting coarse aggregate with EPS beads can decrease thermal conductivity. Still, it also lowers the specific heat value and vice versa. The overall trend is linear, as demonstrated by the correlation between a decrease in thermal conductivity and a corresponding decrease in specific heat value, as illustrated in Figure 12 of the research findings.

Nevertheless, adding fly ash as a substitute for cement appeared to decrease the thermal conductivity values effectively and even achieved an ideal trend in PFAC concrete. Even so, the fact requires additional research due to the requirement for more sample test results and the implementation of more dependable tools to guarantee data consistency.

Using fly ash as a coating material for EPS beads leads to a higher specific heat than using fly ash as a replacement for cement in EPS concrete. This situation appeared due to the elevated thermal conductivity value, as demonstrated by the correlation and pattern observed in this study between thermal conductivity and specific heat.

Prior research provides findings on the general pattern that higher thermal conductivity values correlate with a greater specific heat capacity [31,32]. Nevertheless, other research has shown a favourable pattern [33–35], which aligns with the concept that insulation materials should have a high specific heat but a low thermal conductivity. Figure 13 presents a comparative analysis of the trend observed in the relationship between specific heat capacity and thermal conductivity, as investigated in this study and others.

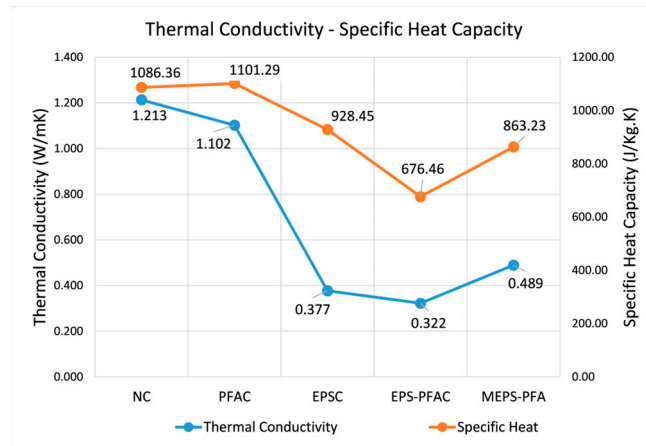


Figure 12. Relationship between thermal conductivity and specific heat capacity.

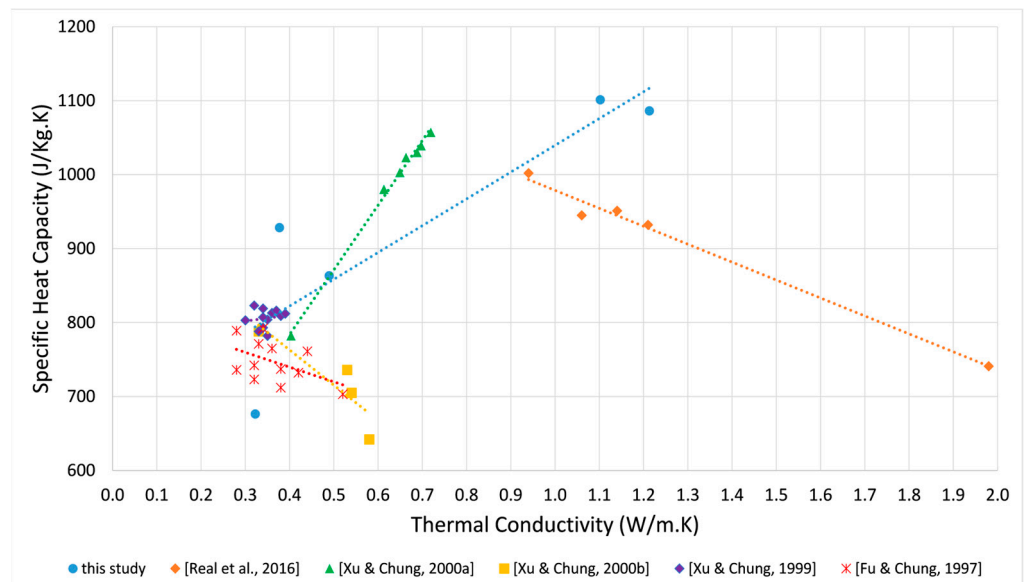


Figure 13. Trend line of relationship between thermal conductivity and specific heat capacity [31–35].

3.5. Heat Flux

The heat flow rate (Q) is a measure of how much heat travels within a material over a given length of time. Heat flux (q) is the amount of heat transmitted per unit area and time to or from a surface. Given our prior knowledge of the thermal conductivity coefficient (k -value), we can calculate the heat flux (q) using Fourier’s Law.

$$Q = \frac{k \cdot A \cdot (T_2 - T_1)}{\Delta x} \tag{2}$$

k = thermal conductivity (Watt/m·K)

Q = the amount of heat transferred through the material (Joules/second) or (Watts)

Δx = the distance between the two isothermal planes (width or thickness of material)

A = the area of the surface (m^2)

$(T_2 - T_1)$ = the difference in temperature

The thermal conductivity value of a material is generally directly proportional to the heat flux. However, the value of heat flux could vary from the overall pattern due to the influence of additional variables, such as the thickness of the material. Table 6 illustrates that, despite EPS-PFAC concrete having a lower thermal conductivity than EPSC, the

increased heat flow rate due to the reduced thickness of the EPSC-PFAC material ultimately impacts the heat flux value of the material.

Table 6. Calculation of Heat Flux (q).

Specimens	<i>k</i> (W/m·K)	<i>A</i> (m ²)	<i>T</i> ₂ (°C)	<i>T</i> ₁ (°C)	Δx (m)	<i>Q</i> (watt = J/s)	<i>q</i> (W/m ²)
NC	1.2130	0.01	35	10	0.021361	14.20	1419.62
PFAC	1.1020	0.01	35	10	0.021273	12.95	1295.10
EPSC	0.3773	0.01	35	10	0.023381	4.03	403.43
EPS-PFAC	0.3223	0.01	35	10	0.018879	4.27	426.81
MEPS	0.4893	0.01	35	10	0.024835	4.93	492.55

3.6. Thermal Diffusivity

Thermal diffusivity is a physical property that quantifies the relative rate at which a material can conduct heat regarding its capacity to store heat. Thermal conductivity and thermal diffusivity are two distinct physical properties that correspond to the heat conduction capabilities of a material. However, they differ significantly in their respective approaches for quantifying heat transfer. The thermal conductivity (*k*) is a property used to quantify a material’s capacity to conduct heat, regardless of time-related variables. The measurement refers to the conductivity of heat of a material in a state of thermal equilibrium when the material’s temperature remains constant over a given period. Compared to that, thermal diffusivity (α) is a parameter that quantifies the capacity of a material to conduct heat over a given time. The measurement refers to the rate at which thermal energy may travel within a material when subjected to a change in temperature.

The thermal diffusivity value (α) can be determined using the formula (3), where *k* represents thermal conductivity, ρ denotes density, and *c* represents specific heat. Hence, the thermal diffusivity of a material develops a direct relationship with its thermal conductivity, while have an inverse relationship with its specific heat.

While EPSC recorded the lowest value for thermal diffusivity, NC recorded the highest value. Unless otherwise specified, using coated EPS as a replacement for coarse aggregate cannot deliver a substantial favourable result, as demonstrated by the observation that the value is higher than that of EPSC and EPS-PFAC. Complete results can be seen in Table 7.

$$\alpha = \frac{k}{\rho \cdot c} \tag{3}$$

α = Thermal Diffusivity (m²/s)

k = thermal conductivity (Watt/m·K)

ρ = density of material/sample (Kg/m³)

c = specific heat capacity of material (J/Kg·K)

Table 7. Calculation of thermal diffusivity (α).

Specimens	<i>k</i> (Watt/m·K)	ρ (Kg/m ³)	<i>c</i> (J/Kg·K)	α (m ² /s)
NC	1.2130	2339.71	1086.36	0.477×10^{-6}
PFAC	1.1020	2297.67	1101.29	0.436×10^{-6}
EPSC	0.3773	1242.86	928.45	0.327×10^{-6}
EPS-PFAC	0.3223	1244.47	676.46	0.383×10^{-6}
MEPS	0.4893	1408.90	863.23	0.402×10^{-6}

Insulation materials with a reduced thermal diffusivity are considered more advantageous. A lower value in thermal diffusivity indicates that the material conducts heat more gradually. The principal purpose of insulation is to prevent the convection of thermal energy across a designated substance. A decreased thermal diffusivity signifies that the

material possesses the capacity to slow down heat transfer and withstand abrupt temperature fluctuations. Materials with a diminished thermal diffusivity are often preferred for insulation objectives due to their capacity to slow down heat transfer, thus facilitating the preservation of an insulated and stable environment.

The relationship between density and thermal diffusivity exhibits a more pronounced trend when compared to the preceding comparison graph that compared density and specific heat. However, it is worth noting that the thermal diffusivity values for all material types are relatively similar. As demonstrated, the thermal diffusivity value is directly proportional to the material’s density (Figure 14).

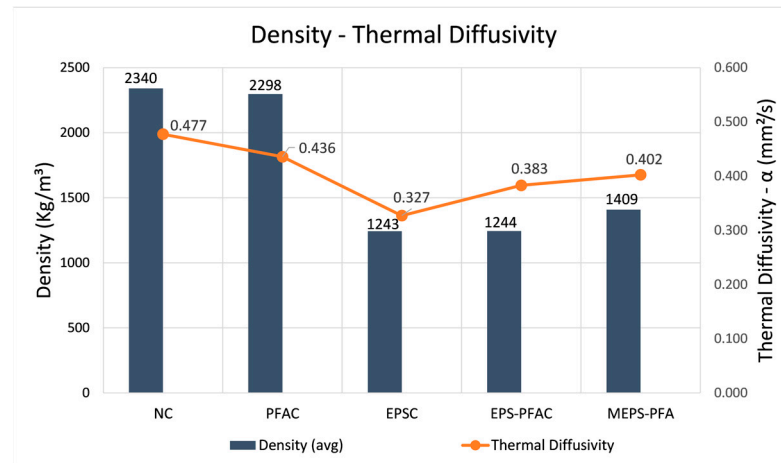


Figure 14. Relationship between density and thermal diffusivity.

The use of EPS beads as a concrete aggregate to replace gravel has quite a good impact on reducing the thermal diffusivity value. This result aligns with previous research where the more significant the proportion of lightweight aggregate used, the lower the thermal diffusivity value (Figure 15). However, the use of coated EPS does not give the expected results. Using fly ash as a partial replacement material for cement also does not show much influence in these findings. This effect can be seen from the trend of thermal diffusivity values, which decrease when used in PFAC but show increasing values when used in EPS-PFAC. Considering that the obtained thermal diffusivity value is the result of calculations using a formula, perhaps in the future, further investigation will be needed regarding the use of appropriate tools to obtain a more accurate thermal diffusivity value.

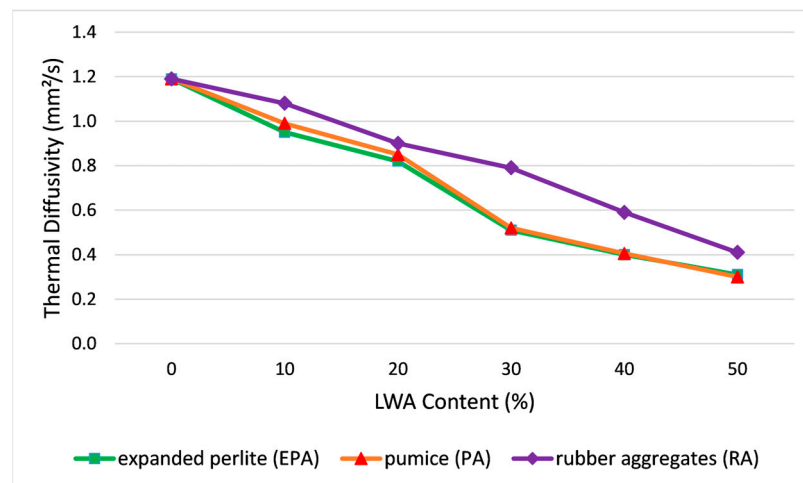


Figure 15. Thermal diffusivity of concrete made from different LWA [36].

In the same way that specific heat and thermal conductivity are considered, a low thermal diffusivity is thought of as advantageous for insulation. Thermal diffusivity is a property that quantifies the rate at which a substance conducts heat relative to its retention of heat capacity. A decreased thermal diffusivity indicates an increased resistance to heat conduction, suggesting that the substance is more efficient at preventing heat flow.

Due to its ability to prevent heat transfer, an insulating material with a low thermal diffusivity is more practical in terms of efficiency. This characteristic is desirable for insulation applications in which the goal is to minimise heat transfer between two environments (e.g., maintaining a building's temperature at a comfortable level during the winter or summer). Therefore, in the context of insulation, a decrease in thermal diffusivity is generally considered advantageous.

4. Conclusions

This study comprehensively explored the thermal properties of the investigated material, including thermal conductivity, heat flow, specific heat capacity, and thermal diffusivity. The findings offer valuable insights into the material's response to heat transfer processes, holding significance for both academic research and practical applications. These findings contribute to a deeper understanding of the material's thermal behaviour, laying the groundwork for further research and potential applications in various fields.

Key findings:

- Coating treatment on expanded polystyrene (EPS) offers no advantage in terms of thermal properties compared to uncoated EPS aggregate concrete. However, MEPS concrete exhibits superior thermal properties compared to ordinary concrete.
- MEPS concrete demonstrates a remarkable 40% reduction in thermal conductivity compared to conventional concrete. This signifies the effectiveness of EPS as an aggregate in reducing heat transfer, a crucial factor in thermal insulation.
- Heat flux analysis reveals a significant 35% decrease in MEPS concrete compared to normal concrete. This indicates a substantially lower rate of energy transmission through the material, enhancing its insulating potential.
- While the specific heat capacity of MEPS concrete is 20% lower than normal concrete, the difference is not as significant as thermal conductivity and heat flux. Nevertheless, a lower specific heat capacity remains advantageous for insulation materials.
- All test objects exhibited relatively low thermal diffusivity values, implying slow heat transfer through the material. This is a desirable characteristic for building insulation materials.
- Employing coated EPS as an aggregate did not yield a significant impact on thermal diffusivity beyond what normal concrete already offers. This is likely due to the inherent low diffusivity of concrete itself.

In conclusion, this study highlights the potential of MEPS concrete as an effective thermal insulator due to its superior thermal conductivity, heat flux, and specific heat capacity compared to conventional concrete. While a coating treatment offered no additional advantage, MEPS itself stands as a viable option in the search for sustainable and energy-efficient construction materials. An investigation into alternative waste materials and additives that could potentially improve lightweight concrete's thermal or mechanical properties could be undertaken. It is also necessary to further examine the microstructure characteristics while optimizing the composition and properties of MEPS concrete for even greater thermal performance. Given the possibility of expanding this product for commercial purposes, conducting additional research on cost-production analysis might be also beneficial.

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