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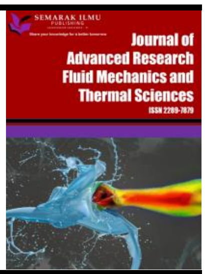

The Influence of Pulverized Fuel Ash (PFA) on the Thermal and Transport Properties of Foamed Concrete

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ABSTRACT

The incorporation of materials derived from industrial waste presents a viable avenue for mitigating the exorbitant production expenses associated with building materials, while concurrently ameliorating the deleterious ecological ramifications of said waste. The utilization of pulverized fuel ash (PFA), an industrial residue resulting from the combustion of powdered coal in an electricity-generating facility, as a substitute for cement in the composition of concrete, is a viable option owing to its inherent pozzolanic properties. The present study endeavours to investigate the potential of Partially-Fumed Ash (PFA) as a viable substitute for cement in the production of foamed concrete (FC). The thermal and transport properties were meticulously assessed, with a particular focus on thermal conductivity, thermal diffusivity, specific heat capacity, water absorption, and porosity. A series of experiments have been undertaken wherein varying proportions of Portland Pozzolan Cement have been substituted for PFA, specifically at levels of 10%, 20%, 30%, 40%, and 50% by weight. The findings suggest a prospective application of PFA in the manufacturing of FC. The utilization of PFA (Pulverised Fuel Ash) assumes a pivotal role in enhancing the thermal conductivity, thermal diffusivity, specific heat capacity, water absorption, and porosity of FC. Therefore, it can be inferred that the utilization of PFA holds promising potential in the production of cost-effective, lightweight construction materials, while simultaneously mitigating the adverse environmental consequences.

1. Introduction

The prevailing trajectory of research within the construction industry is gravitating towards the development and application of green concrete as a means to surmount the constraints associated with traditional concrete materials [1-8]. The utilization of green concrete materials presents a plethora of advantageous attributes in terms of their environmental, technical, and economic aspects. It facilitates the augmentation of high-caliber concrete products, contributes to the preservation of natural resources, and mitigates environmental pollution and waste management concerns [9-17].

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Supplementary cementing materials for concrete matrices have emerged as a captivating realm of research inquiry [18-28]. The incorporation of pulverized fuel ash (PFA) as a partial substitute for cement in concrete has demonstrated notable improvements in compressive strength, both in the initial and subsequent stages. These enhancements can be attributed to the substantial presence of silica oxide and calcium oxide within these materials. The implementation of SiO_2-CaO in the industrial sector for the enhancement of concrete strength, encompassing both early and later strength, is a relatively nascent development [29-35]. Considering their notable advancements in durability and their potential to foster a more ecologically conscious environment, green composite materials have garnered considerable interest as a viable avenue for the advancement of superior construction materials. In view of the ubiquity and economical nature of commercial and natural pozzolans, as well as accelerator materials, there remains a growing emphasis on waste materials to champion environmental sustainability [36-40].

Foamed concrete (FC) is a widely recognized version of lightweight concrete that is created through the combination of mortar and foam. There are numerous advantages associated with the use of this material in comparison to conventional OPC concrete, primarily due to the reduction in weight resulting from the presence of voids. Typically, it is employed for the purposes of noise reduction and insulation [41-46]. Thermal insulation is improved as a result of the presence of multiple pores. The foaming agent is a primary constituent involved in the generation of FC. The foaming agents commonly employed in this context consist of synthetic and protein surfactants [47-53]. In general, it has been observed that FC with a higher water absorption capacity tends to exhibit lower mechanical strength. While the presence of water in cement enhances the hydration process, it concurrently diminishes the air voids within the concrete, thereby impacting its strength. The strength of FC is affected by various factors, including the water to cement ratio, air to cement ratio, lower air content resulting from a high water to cement ratio, and the nature of the foamed agent [54-58]. These factors collectively influence the strength of FC. In addition, it should be noted that the sand content has an impact on the compressive strength of FC. The strength of FC is reduced with an increase in the sand to cement ratio [59-63].

In the present era, the construction industry has witnessed the emergence of FC as a novel product, owing to technological advancements. FC exhibits several advantages over conventional concrete, including lower densities ranging from 550 to 1850 kg/m^3, enhanced fire protection, improved thermal insulation, and superior sound insulation [64]. FC displays a reduced weight in comparison to conventional weight concrete, primarily attributed to the presence of artificial air bubbles that are entrapped within its cement mortar. This effect is achieved through the utilization of an appropriate foaming agent [65]. The maintenance of consistency and stability in freshly mixed FC is crucial to prevent the separation of artificial air bubbles and cement mortar, as well as the rupture of these bubbles. These factors can ultimately impact the hardened properties of concrete. The cone spread test is a commonly utilized method for evaluating the rheological properties of freshly prepared FC [66].

The measurement in question is also associated with the rheological property of the fresh mix, as indicated by previous studies. A prior investigation indicated that the substitution of sand with coarse fly ash as a filler in FC resulted in a spread value that was three times greater than that of a cement-sand mixture. The improved uniformity and feasibility can be ascribed to the varying particle morphology and dimensions of the fine aggregate. The utilization of fly ash, in comparison to sand, resulted in an increase in the water-to-solid ratio, thereby meeting the consistency requirement. The utilization of pozzolans, whether they are naturally occurring or artificially produced, in the composition of concrete has been a longstanding practice, dating back to early civilizations. In addition to their economic benefits, the primary rationale for their utilization lies in their capacity to provide valuable modifications or enhancements to the properties of concrete. This paper is centered around examining the impact of PFA, used as a filler component, on the thermal and transport properties of FC.

2. Methodology

This section will provide an overview of the materials utilized in the present study, including the mix design and the experimental setup.

2.1 Materials

To fabricate FC, there were four main materials employed namely Ordinary Portland Cement, fine river sand, clean tap water, and stable aqueous foam. The cement employed in this study was Ordinary Portland Cement, which conformed to the BS EN 12 specification The fine sand was procured from a nearby supplier and was derived from natural sources. The sand sample being analyzed displayed a maximum width of 2mm and underwent sieving using a 600-micron sieve. Figure 1 shows the sand grading curve for the fine river sand used in this research. The suitability of the sand was required to conform to the specifications delineated in the BS-EN822. The foaming agent utilized in the research was Noraite PA-1, a foaming agent derived from proteins. The foam was produced utilizing a portable foaming generator device referred to as the Portafoam TM-1 machine. The water-cement ratio of 0.45 was chosen for this research project based on its capacity to achieve a desirable degree of workability. The Pulverized Fuel Ash (PFA) was procured from DRN Technologies Sdn. Bhd., as depicted in Figure 2. Table 1 presents a comprehensive overview of the chemical composition of the PFA, while Table 2 provides an exposition of its physical properties.

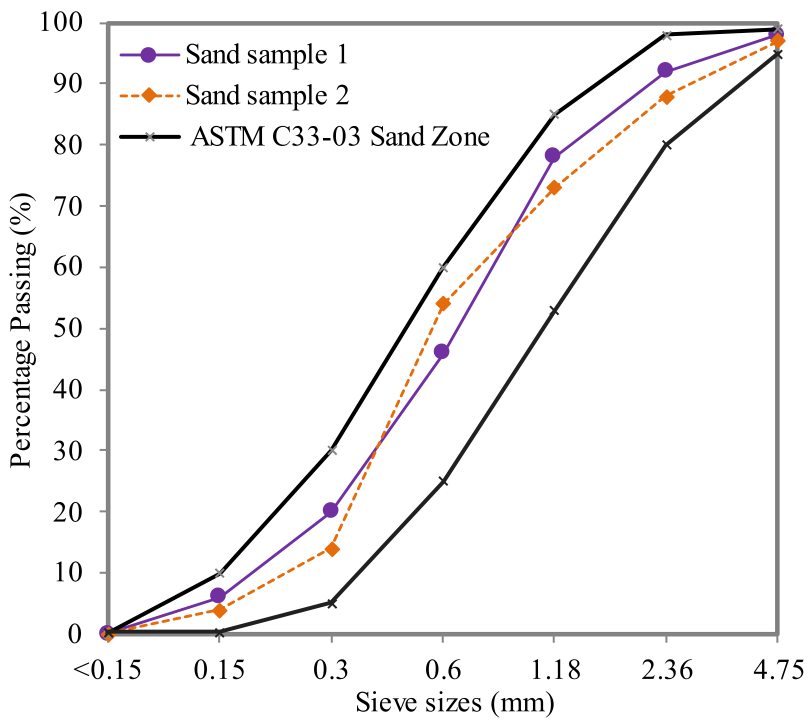
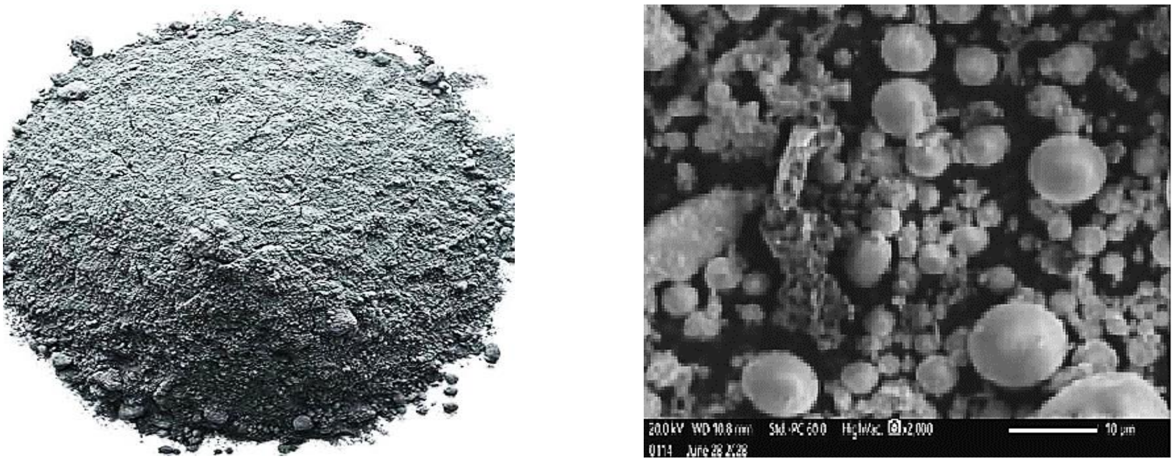


Fig. 1. River sand sieve analysis result



(a) (b)

Fig. 2. PFA used as partial cement replacement (a) raw PFA; (b) SEM micrograph of PFA

Table 1
Chemical compositions of PFA

Components	Percentage
SiO_2	59.75
Al_2O_3	20.94
Fe_2O_3	3.87
CaO	8.95
MgO	1.24
SO_3	0.98
K_2O	0.89
L.O.I	3.38

Table 2
Physical properties of PFA

Components	Value
Specific gravity	2.17
Density (kg/m^3)	895
Fineness modulus (cm^2/gm)	3690
Moisture contents (%)	14.5

2.2 Foamed Concrete Mix Design

A comprehensive assemblage of six distinct compositions of FC mixtures was meticulously devised. An FC, boasting a moderate density of 800 kg/m^3, was successfully produced. The experimental parameters entailed the deliberate alteration of the ratio of cement substitutions utilizing PFA at varying intervals, namely 0% (acting as the reference mix), 10%, 20%, 30%, 40%, and 50%. In each instance, a sand-cement ratio of 1:1.5 was employed, while the water-cement ratio was consistently upheld at a fixed value of 0.45. The delineation of the mix design for FC in this investigation is explicated in Table 3.

Table 3
The formulation of an FC mixture incorporating diverse ratios of PFA

Mix	PFA (%)	PFA (kg/m^3)	Sand (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Foam (kg/m^3)
PFA-0	0	0.0	454	303	136	37
PFA-10	10	30.3	454	272	136	37
PFA-20	20	60.5	454	242	136	37
PFA-30	30	90.8	454	212	136	37
PFA-40	40	121.0	454	182	136	37
PFA-50	50	151.3	454	151	136	37

2.3 Tests

The thermal conductivity and thermal diffusivity of FC were ascertained through the utilization of a guarded hot-plate apparatus, adhering to the esteemed ASTM C177-19 standard as shown in Figure 3. The experimental investigation entailed the scrutiny of FC specimens measuring 25x25x12mm in size. The placement of the sensor was strategically positioned between a set of composite discs, while an additional pair of discs were subsequently layered on top of the initial configuration. The experiment pertaining to the permeable porosity was conducted in strict adherence to the prescribed methodologies outlined in the ASTM C1202-17a standard as demonstrated in Figure 4. The diligent execution of the water absorption capacity examination was conducted at regular intervals of 7, 14, and 28 days, adhering to the prescribed protocols as outlined in BS 1881-122.

Fig. 3. Guarded hot-plate apparatus

Fig. 4. Permeable porosity test

3. Results
3.1 Thermal Conductivity

Figure 5 displays the thermal conductivity outcomes for all blends of LFC. The figure presented in Figure 5 demonstrates that the control LFC specimen exhibits the maximum heat conductivity. The thermal conductivity value of the control sample is 0.258 W/m/K. The findings conclusively demonstrate that the incorporation of PFA leads to a reduction in thermal conductivity, hence yielding desirable thermal insulation characteristics. Therefore, the utilization of PFA significantly decreases the thermal conductivity of LFC, a crucial factor in the construction of energy-efficient structures. As the cement replacement level increases, there is a corresponding decrease in thermal conductivity. The findings indicate that the thermal conductivity decreased by 6.5%, 12.4%, 17.8%, and 24.0% for specimens with PFA concentrations of 0%, 10%, 20%, 30%, 40%, and 50%, respectively, in comparison to the control LFC. The substitution of PFA leads to an elevation in air content and a decrease in density, resulting in a decrease in heat conductivity for the specimens. Furthermore, as a result of the composition of PFA, the closed porosity of LFC structures is enhanced, leading to a decrease in heat conductivity. The decrease in thermal conductivity of the LFC can be attributed to the augmentation in pore quantity and diameter resulting from the utilization of PFA as a substitute for cement in the LFC mixture. The concrete specimen with a 50% replacement of cement exhibits a significant quantity of voids, resulting in reduced conductivity. Hence, the decrease in thermal conductivity can be linked to the diminished density and the presence of porous ash structures [67]. Given the global prevalence of PFA and the observed reduction in heat conductivity in LFC materials including PFA, the use of PFA demonstrates significant economic and energy advantages.

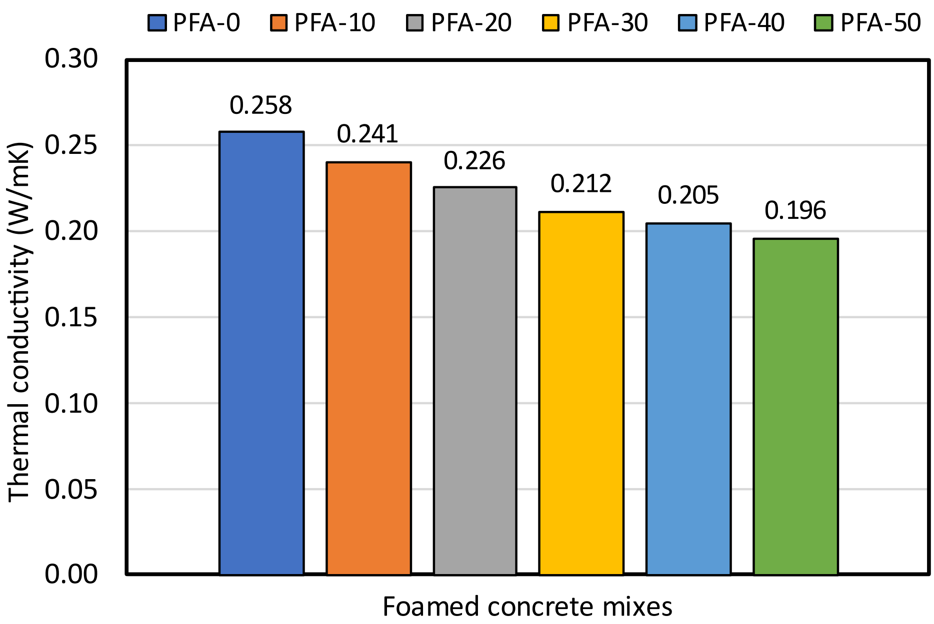


Fig. 5. Thermal conductivity of FC using different amounts of PFA as cement replacement

3.2 Thermal Diffusivity

The thermal diffusivity results for all mixes of LFC are presented in Figure 6. The data depicted in Figure 6 illustrates that the control LFC specimen has the highest diffusivity. The thermal diffusivity value of the control sample is determined to be 0.468 W/m/K. The results unequivocally establish that the inclusion of PFA results in a decrease in the thermal diffusivity of FC, hence producing favorable thermal insulation properties. Hence, the incorporation of PFA results in a substantial reduction in the thermal conductivity of LFC, which is a pivotal parameter in the development of energy-efficient architectural systems. As the proportion of cement replacement increases, there is a concomitant reduction in heat conductivity [68]. The results suggest that the thermal diffusivity exhibited a reduction of 2.8%, 7.3%, 8.3%, and 14.3% for specimens containing varying concentrations of PFA (0%, 10%, 20%, 30%, 40%, and 50%, respectively) as compared to the control LFC.

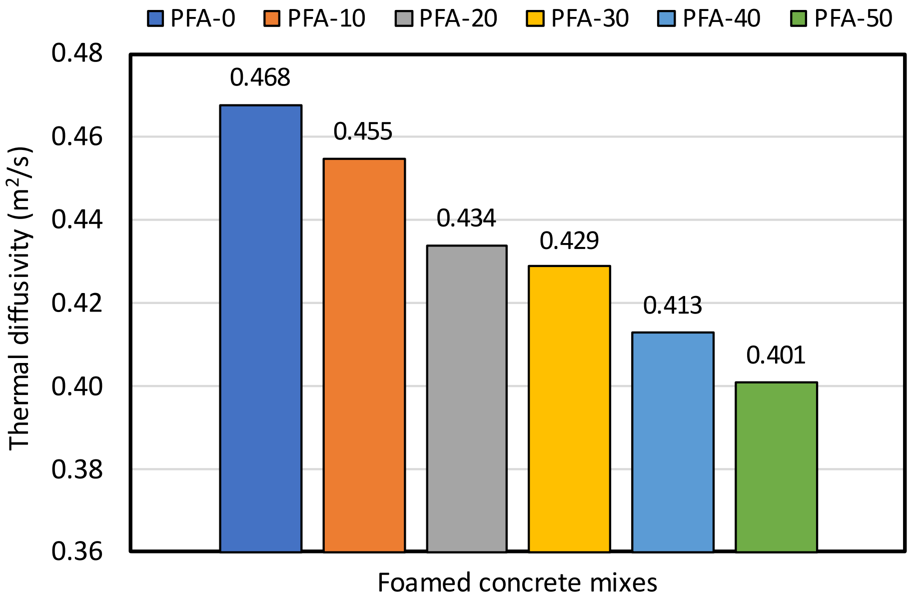


Fig. 6. Thermal diffusivity of FC using different amounts of PFA as cement replacement

3.3 Dry Unit Weight

Figure 7 provides the dry unit weight values for the LFC samples containing different percentages of PFA as cement replacement. An inverse relationship between the proportion of PFA used as a substitute for cement in LFC and the corresponding sample unit weights was observed. The control sample exhibited the greatest unit weight of 1207 kg/m^3, whereas the PFA-50 specimen displayed the lowest dry unit weight value of 1150 kg/m^3. Based on the utilization of PFA in the conducted investigation, it was observed that the dry unit weights of PFA-10, PFA-20, PFA-30, PFA-40, and PFA-50 mixtures exhibited reductions of 1.3%, 2.4%, 3.3%, 4.0% and 4.7% when compared to the control specimen of LFC. The utilization of PFA as a substitute for cement in LFC was evidently accountable for the observed reduction in dry-weight measurements. Nevertheless, the dry unit weight values acquired did not surpass the minimum limit for low dry unit weight in LFC [69].

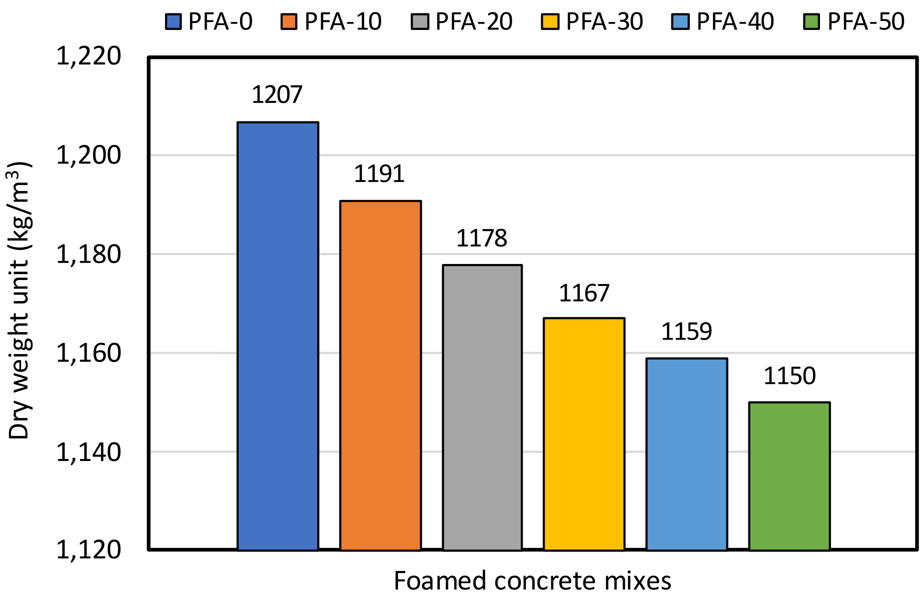


Fig. 7. Dry weight unit of FC using different amounts of PFA as cement replacement

3.4 Water Absorption

The laboratory findings, depicted in Figure 8, indicate that the utilization of PFA can result in less water absorption, hence enhancing the overall durability. Moreover, the findings suggest that the incorporation of increased proportions of PFA led to decreased water absorption. In comparison to the control LFC specimen, the substitution of 50% cement with PFA led to a decrease in water absorption of 29.6%. The water absorption of the control FC specimen is reduced when increasing percentages of PFA are used as a replacement for cement. This reduction can be attributed to the finer particle size of PFA compared to cement. The pozzolanic reactivity of PFA in LFC is primarily influenced by its chemical composition. It should be noted that not all components of PFA exhibit reactivity in this context. The remaining portion, characterized by its lack of reactivity and amorphous nature, remains unreacted and functions as filler material [70]. The reduced water absorption seen in specimens incorporating PFA can be attributed to the presence of unreacted particles. These particles improved the porosity nature of the mixtures by effectively filling spaces and pores [71]. The incorporation of PFA particles, which possess a smaller particle size compared to cement particles, into the PFC mixture resulted in the filling of gaps and cavities, hence causing a reduction in water absorption [72]. It is important to acknowledge that the porous nature of PFA particles significantly decreases the thermal conductivity of FC. Nevertheless, these cavities are not interconnected and hence would not enhance the process of water absorption.

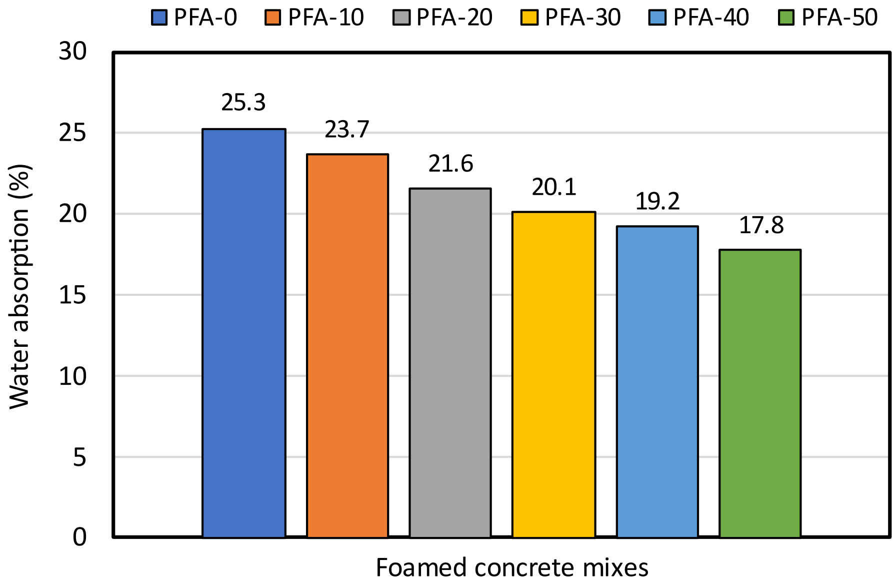


Fig. 8. Water absorption of FC using different amounts of PFA as cement replacement

3.5 Permeable Porosity

Figure 9 displays the outcomes of permeable porosity on FC samples with varying quantities of PFA incorporation. The incorporation of PFA has been demonstrated to enhance the porosity of concrete when utilized at replacement levels ranging from 0% to 50%. The control specimen recorded the lowest permeable porosity of 63.8%. Compared to the control LFC, the permeable porosity of FC mixtures increased by 0.63%, 1.25%, 1.72%, 2.04% and 2.51%, respectively, for specimens with PFA concentrations of 0%, 10%, 20%, 30%, 40%, and 50%. The increase in cement replacement with PFA results in a higher packing degree density, which in turn leads to the development of voids [73]. These voids contribute to an increased permeable porosity of LFC.

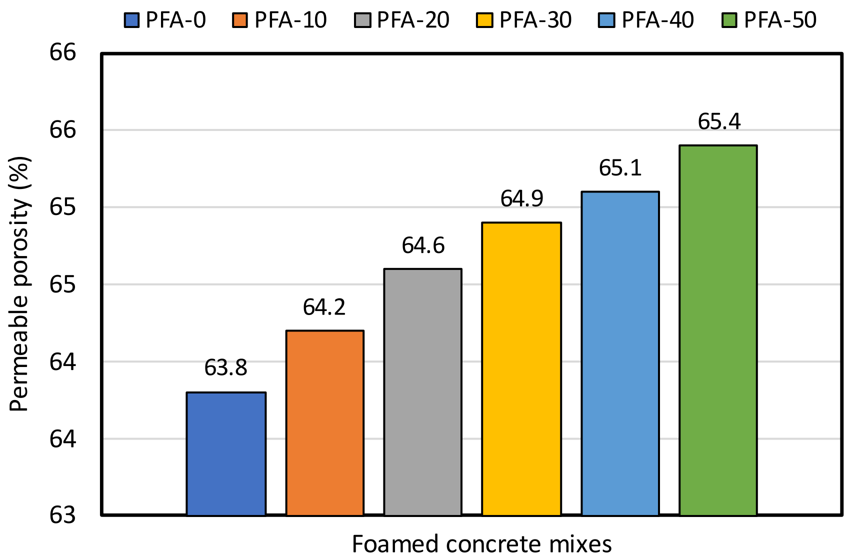


Fig. 9. Permeable porosity of FC using different amounts of PFA as cement replacement

4. Conclusions

The investigation conducted in the present study has showcased the potential of substituting up to 50% of cement with Pulverized Fuel Ash (PFA) in the production of foamed concrete (FC). The investigation has yielded several key conclusions, which are outlined below:

i. The inclusion of PFA as cement replacement in FC resulted in an enhancement in thermal conductivity when compared to the reference sample, which exhibited a thermal conductivity value of 0.258 W/mK. The substitution of 50% cement with PFA yielded the most favorable outcome in terms of thermal conductivity. The thermal conductivity measurement resulted in a value of 0.196 W/mK.
ii. The experimental results demonstrate a significant decrease in thermal diffusivity as the proportion of PFA increases. As the percentage of PFA in FC gradually increased from 10% to 30% and then to 50%, a corresponding decrease in thermal diffusivity is observed. The thermal diffusivity values corresponding to the different percentages of PFA are 0.455, 0.429, and 0.401 m^2/sec, respectively.
iii. The percentage of PFA utilized as a cement replacement in LFC was found to have a negative correlation with the unit weights of the samples itself. The PFA-50 specimen has the lowest dry unit weight value, 1150 kg/m^3, compared to the control sample's 1207 kg/m^3.
iv. The inclusion of higher proportions of PFA resulted in a reduction in water absorption. When comparing the control LFC specimen to the one where 50% of the cement was substituted with PFA, it was observed that the water absorption decreased by 29.6%.
v. The utilization of PFA has been shown to increase the porosity of concrete when used as a replacement material, ranging from 0% to 50%. The control specimen exhibited the lowest recorded permeable porosity, measuring at 63.8%.

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