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The Effects of Palm Oil Fuel Ash on Mechanical and Durability Properties of Sustainable Foamed Concrete

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ABSTRACT In recent years, mortar bricks or autoclaved aerated concrete (AAC), also known as foamed concrete, have been widely used as masonry wall materials. Foamed concrete, like bricks, can be produced by adding a foaming agent to achieve the desired weight and density, while meeting requirements for strength and durability. However, the search for sustainable construction materials has become imperative , including the use of waste materials to partially replace cement. The incorporation of SCM in the production of cement-based materials, such as foamed concrete, has a significant impact on reducing CO_2 emissions and promoting a sustainable environment. POFA, a secondary product derived from the palm oil industry that is typically left on the ground , poses environmental problems. Due to its good performance and pozzolanic reactions, POFA-based construction materials have great potential as alternatives to ordinary Portland cement. Unlike previous studies, this research evaluates the strength and durability of foamed concrete with variations in foam agent dosages, including finer particles of POFA (100μm) as a partial cement replacement. The study produced a total of 6 batches of foamed concrete, measuring compressive strength, porosity, water absorption, and electrical resistivity. Additionally, the research examined the correlation between compressive strength and porosity, as well as compressive strength and electrical resistivity. This study concludes that an ideal content of 10% POFA with a foaming agent-to-water ratio (fa/w) of 1/60 can achieve the best strength of foamed concrete. Furthermore, a partial cement replacement with 20% POFA could potentially increase the compressive strength to levels similar to those of normal foamed concrete (without POFA).

KEYWORDS Foam agent, POFA, Foamed Concrete, Compressive Strength, Porosity, Durability

1 INTRODUCTION

The drive towards sustainability and a sustainable environment has encouraged the use of pozzolanic materials for partial cement replacement in concrete. Reducing the amount of cement used in the production of cement-based materials such as mortar, concrete and foamed concrete can significantly decrease the release of CO_2 emissions during cement manufacturing (Islam et al., 2017). In recent years, fly ash, palm oil fuel ash (POFA), and rice husk ash (RHA) have been used in concrete, clay brick and paving block production due to their significant pozzolanic content (Amran et al., 2021; Dasar and Patah, 2024; Dasar et al., 2024; Ridhayani et al., 2023; Patah et al., 2023, 2022). Utilizing industrial waste materials is a viable solution for sustainability, reducing the manufacturing costs of construction materials, and simultaneously mitigating the environmental impact of the waste.

Foamed concrete is a lightweight concrete, classified as either a cement pastes or mortar. It is created by purposefully including a foaming agent to trap air voids within the mixture. Lightweight concrete is increasingly attracting attention in the contemporary building and construction sector due to its lightweight characteristic of, high fire resistant, and good sound and thermal insulation features (Machdar et al., 2023; Zhang et al., 2022). Several studies have conducted research on foamed concrete, which is a form of lightweight concrete (Bayraktar et al., 2021; Gencel et al., 2022; Gencel, Bayraktar, Kaplan, Benli, Martinez-Barrera, Brostow, Tek and Bodur, 2021; Gencel, Benli, Bayraktar, Kaplan, Sutcu and Elabade, 2021; Sun et al., 2018; Falliano et al., 2018; Gökçe et al., 2019). Sun et al. (2018) investigated the effects of several foaming agents on the workability, drying shrinkage, frost resistance, and pore distribution of foamed concrete in their study. The researchers found that the selection of the foaming agent had a substantial impact on the characteristics of the foamed concrete. Falliano et al. (2018) examined the influence of many factors, such as curing conditions, foaming agent, and dry density, on the compressive strength of foamed concrete. Studies conducted by Gökçe et al. (2019) and Zhang et al. (2022) have examined the impact of mineral admixture, such as fly ash and silica fume, on the physical properties of foamed concrete. It was discovered that these additives had a significant influence on the characteristics of the resulting foamed concrete.

In recent years, there has been a growing interest in the adoption of new supplementary cementitious materials (SCM) that offer improved chemical and physical properties compared to normal concrete. Palm oil fuel ash (POFA) is a type of ash that produced when waste materials like palm kernel shell and palm oil husks are burned (Amran et al., 2021). POFA is typically disposed of in landfills, leading to a growing accumulation of ash deposits each year, which has now become a significant burden (Hamada et al., 2018). Paris et al. (2016) conducted a study to investigate the effects of POFA on the physical and mechanical properties as well as the durability of cement paste. Previous research has studied the usability of POFA in foamed concrete (Lim et al., 2013; Alnahhal et al., 2021; Munir et al., 2015; Alnahhal and Aljidda, 2020). Alnahhal et al. (2021) demonstrated that incorporating a specific percentage of POFA replacement filler into lightweight foamed concretes led to improved strength performance. Also, Munir et al. (2015) reported that foamed concrete with 20% POFA substitution remains suitable for use in non-structural building elements, such as concrete blocks for non-bearing walls, based on its compressive strength. Alnahhal and Aljidda (2020) investigated the effect of POFA (300μm) as a partial replacement for OPC and the ratio of foaming agent to water of 1/25 to produce normal foamed concrete. The study recommends a 20% substitution with POFA as the optimal replacement ratio.

While previous studies emphasized the usability of POFA in foamed concrete, this study specifically examines the effects of variation in foam agent dosages incorporating POFA. Further, earlier studies focused on grinding POFA into smaller particles to enhance pozzolanic reactions as SCM (Wi et al., 2018; Hamada et al., 2023). In this study, POFA with finer particles (150μm) was used as partial cement replacement. Hence, the aim of this research is to analyze the attributes of foamed concrete produced from POFA in terms of its mechanical and durability properties. This study examines foamed concrete properties, including strength, porosity, water absorption, and electrical resistivity. Additionally, it aims to determine the optimal dosages of foam agents with a replacement ratio of POFA to partially replace Portland cement.

2 METHODS

2.1 Materials

The cement utilized for the current study complies with the specifications of Portland Composite Cement (PCC) as defined in the SNI 15-0764-2004. POFA was derived from the combustion of palm oil shells and husks in equal amounts, sourced from Mamuju, West Sulawesi. The dried POFA was subsequently sieved to remove coarser particulates using a No.100 sieve. POFA was employed as a partial substitute for cement, with a range of 0% to 20% in increments of 10% based on the weight of the cement. The PCC and POFA particle morphologies as observed using a scanning electron microscope (SEM) are shown in Figure 1. Table 1 presents the results of the analysis of the physical and chemical oxide concentrations of PCC and POFA. Conforming to the ASTM 618-22 standard, the SiO_2+, Al_2O_3+, Fe_2O_3 value identifies this substance as Type C POFA. The SEM observation showed that the particle size of cement (50μm) was finer than POFA (150μm).

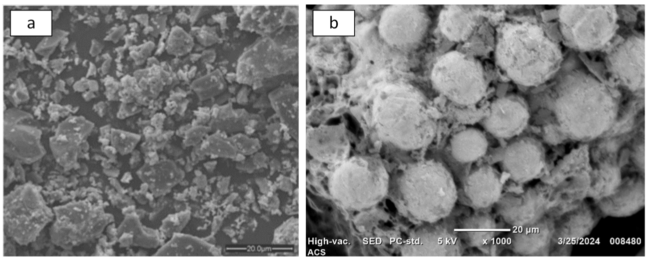

Figure 1 SEM image of (a) PCC and (b) POFA.

Table 1. Physical and chemical compositions of oxides found in PCC and POFA

Material	PCC	POFA
Physical properties		
Specific gravity, kg m^{-3}	3.16	2.84
Maximum particles size, mm	45	150
Chemical composition, %		
SiO_2	20.5	54.32
CaO	62	15.27
K_2O	-	14.13
Fe_2O_3	3.9	9.23
P_2O_5	-	5.38
TiO_2	-	0.617
MnO	-	0.432
SrO	-	0.202
Rb_2O	-	0.166
Al_2O_3	5,5	-
MgO	0.89	-
SiO_3	2.8	-

Fine aggregates (natural river sand with an optimum grain size of 5 mm) were utilized in the preparation of each specimen under saturated surface- dried conditions. The fine aggregate was supplied from a nearby quarry located in Majene Regency, West Sulawesi Province. The gradation limits of the used fine aggregate satisfy the requirements for aggregate use in concrete mixtures (Patah and Dasar, 2021). The material's appearance is displayed in Figure 2. Potable water was used from the laboratory source.

2.2 Mix Design

An in-depth description of the total amount of cement substituted by POFA is listed in Table 2. The test spec-

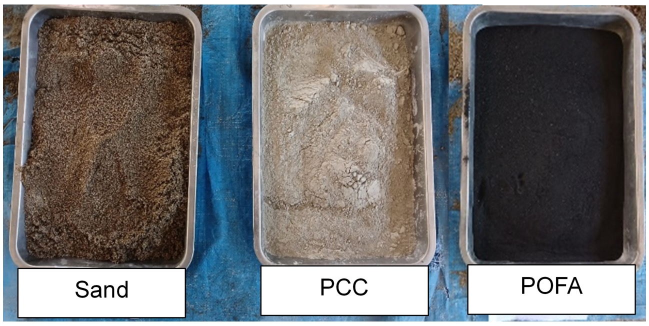

Figure 2 Appearance of Sand, PCC and POFA.

Table 2. Material composition of concrete

MIX ID	Foam agent		Concrete constituent materials (kg m^{-3})					SP (liter)
		liter	Water	PCC	10% POFA	20% POFA	Sand	
POFA0-1/40		5,800	232	580			1233	0
POFA10-1/40	1/40	5,800	232	522	58		1229	3,208
POFA20-1/40		5,800	232	464		116	1224	3,850
POFA0-1/60		3,867	232	580			1233	0
POFA10-1/60	1/60	3,867	232	522	58		1229	3,208
POFA20-1/60		3,867	232	464		116	1224	3,850

imens were produced in cubic molds measuring $50 \times 50 \times 50$ mm. The concrete mix designs were based on the estimated weight of the concrete per unit volume. A total of six concrete mixes were prepared using a water-to-binder ratio (w/b) of 0.4. The foam was produced by diluting the foaming agent with water at volume ratios of 1/40 and 1/60.

The replacement level for the concrete mixtures was established by weight, with the selection of all material contents based on trials. The foamed mortar was produced utilizing the pre-foaming technique, wherein the foam is formed in a separate vessel prior to being mixed into the mortar. After three minutes of combining the PCC, POFA, and sand, the dry mixture was stirred with water for an additional five minutes. Foam was added into the mortar after the mixture had become homogeneous and was subsequently poured into the 50 mm molds. As per the guidelines outlined in ASTM C109-13, the specimens were compacted in a two layers using rod tamping. An additional 10 seconds of vibration was applied using the vibrating table. After 24 hours, the cube specimens were removed and immersed in water for durations of 7, 28 and 91 days. The concrete cubes were used for the purpose of evaluating the compressive strength, electrical resistivity, porosity and water absorption rate.

2.3 Testing Procedures

The dry density of each specimen was determined based on measurements of the specimen weight and volume immediately before the compressive strength test. The density of the specimen was calculated using Equation 1. Where ρ is the density (kg m^{-3}), W_{SSD} is the weight of specimen under SSD condition (kg); and V is the volume of the specimen (m^3).

$$\rho = \frac{w_{SSD}}{v} \tag{1}$$

The compressive strength test was performed by obtaining the average from three cubic samples at different age intervals of 7, 28 and 91 days. The concrete's compressive strength was measured by using a 3000 kN automatic compression machine, according to the guideline in the SNI 1974:2011. The loading rate was established at a rate of 0.15 MPa/s.

For the evaluation of porosity, specimens with dimensions of $50 \times 50 \times 50$ mm were analyzed immediately after being cured for 28 and 91 days, in accordance with the standards outlined in ASTM C 642-97. The method consisted of subjecting the samples to oven drying at 105°C until a consistent weight (W_{AD}) was achieved. After a 48 hours immersion in water, the specimens were taken out, dried, and weighed using a clean fabric or towel to ascertain the saturated surface dry weight (W_{SSD}). The sample weight in water (W_w) was determined by weighing the specimens after they had been boiled for 5 hours and allowed to rest for a minimum of 14 hours. Using Equation 2, the concrete specimen's porosity (P) was measured.

$$P = \frac{W_{SSD} - W_{AD}}{W_{SSD} - W_w} \times 100 \tag{2}$$

The water absorption rate, or sorptivity, was measured 91 days after curing, following parameters outlined in ASTM 1585-20. Specimens with dimensions of $50 \times 50 \times 50$ mm were utilized (Mangngi et al., 2024). The specimens were initially placed in an environmental chamber set at a temperature of 50±2°C and a relative humidity of 80±3% for a duration of three days. Subsequently, for approximately fifteen days, the samples were enclosed in a vessel and maintained at a temperature of 32±2°C. After 15 day, epoxy was applied to all surfaces of the sample excluding the upper and lower parts, and the initial weight was noted. The specimen was sealed using a loosely affixed plastic sheet, which effectively prevented any water from entering it during the measurement process. When the specimens were positioned on a steel rod support mechanism, their surface was subjected to water with a depth ranging from 1 to 3 mm. Recordings were conducted at specific time intervals (0, 5, 10, 20, 30, 60, 120,180, 240 minutes) after the initial water contact. The absorption (I) was determined by utilizing Equation (3),

$$I = \frac{m_t}{a.d} \tag{3}$$

where the variable I represents the absorption in millimeters (mm), mt represents the change in sample mass at specific time intervals in grams (gr), a represents the surface area of the specimen in contact with water in square millimeters (mm^2), and d represents the density of water in grams per cubic millimeters (g mm^{-3}).

The electrical resistivity test was carried out at the age of 91 days. The experiment of electrical resistivity was performed according to RILEM TC154-EMC (Polder et al., 2000). In this, technique, the specimens are placed between two electrodes with moist sponge contact at the interfaces to ensure a proper electrical connection.

3 RESULTS

3.1 Density

The results of density at 28 days with different foaming agent-to-water ratios (fa/w) are shown in Figure 3. According to this study, the density of concrete depends on both POFA content and foam percentage. As a comparison, specimens with fa/w=1/40 for POFA0-1/40, POFA10-1/40, POFA20-1/40 had density values of 2060 kg m^{-3}, 1953 kg m^{-3}, and 1861 kg m^{-3}, respectively. Meanwhile, specimens with fa/w=1/60 possessed slightly higher density values of 2004 kg m^{-3} and 1940 kg m^{-3} for concrete with POFA namely POFA10-1/60 and POFA20-1/60. It is evident that the density of foamed concrete is lighter than that of normal concrete (2400 kg m^{-3}), regardless of the foam agent-to-water ratio (fa/w) being 1/40 or 1/60.

Increasing the concentration of the foam agent leads to a decrease in the density of foamed concrete. This outcome is also in line with the fact that increased density resulted in greater compressive strength. The results indicate an inverse relationship between the amount of the foam agent and the density and compressive strength. This observation corresponds with the conclusion of previous studies conducted by Bing et al. (2012) and Wang and Tang (2012). The reduction in density may be due to air void entrapped in the cementitious matrix and reduced binding system.

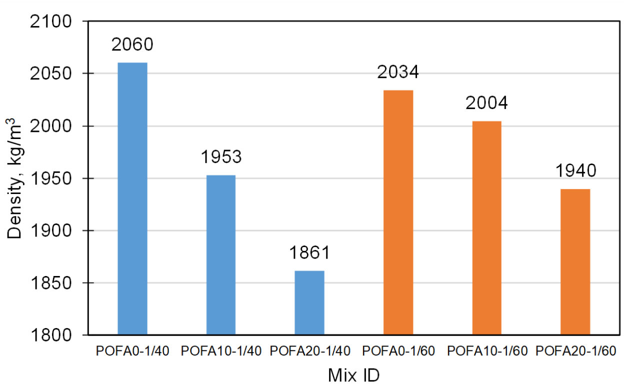

Figure 3 Density at the age of 28 days

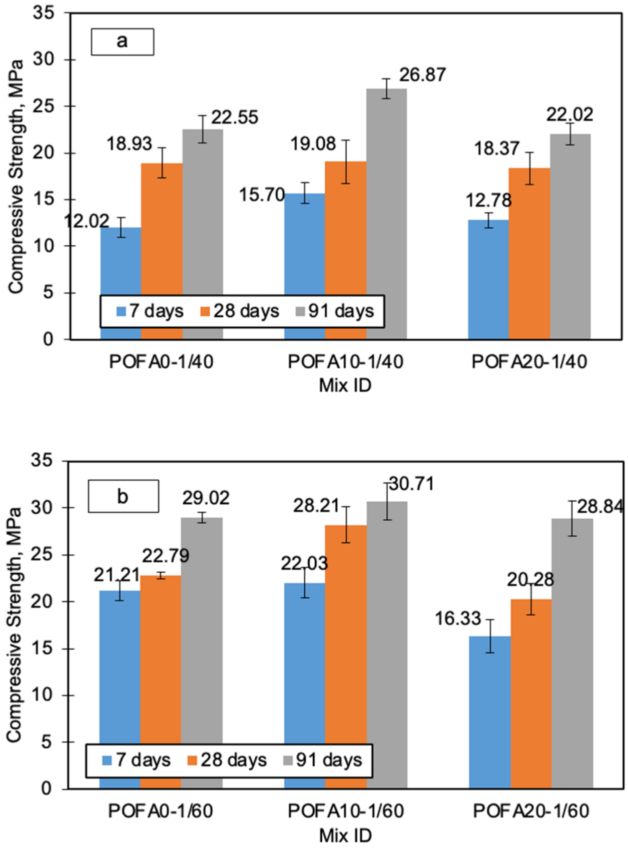

Figure 4 Compressive strength at the age of 7, 28 and 91 days

3.2 Compressive Strength

The results of compressive strength at the age of 7, 28 and 91 days with different foaming agent-to-water ratios (fa/w) are shown in Figure 4. Based on Figure 4, the specimens with 10% POFA (POFA10-1/40) exhibited the highest compressive strength on each of the test days. POFA10-1/40 exhibited maximum compressive strength values of 15.70 MPa, 19.08 MPa and 26.87 MPa at 7, 28 and 91 days, respectively. Figure 4 indicates that the specimens containing 10% POFA (POFA10-1/60) had the highest compressive strength on each of the test days. The POFA10-1/60 exhibited maximum compressive strength values of 22.03 MPa, 28.21 MPa and 30.71 MPa at 7, 28 and 91 days, respectively. The specimens with a foam agent-to-water ratio fa/w=1/60 demonstrate higher strength compared to the concrete with fa/w=1/40 for the same POFA replacement ratio of 10%.

POFA increased the compressive strength more than concrete without POFA in both replacement ratios of 10% and 20% by weight of cement (Aiswarya et al., 2017; Thomas et al., 2017). The primary determinant of strength may be the pozzolanic reaction with the POFA. The silica and alumina in POFA react with CH

Table 3. Porosity

Mix ID	Porosity, %	
	28 days	91 days
POFA0-1/40	22,62	19,82
POFA10-1/40	22,74	19,43
POFA20-1/40	24,53	21,70
POFA0-1/60	21,12	17,09
POFA10-1/60	18,98	14,36
POFA20-1/60	22,46	15,43

to form secondary hydration products, specifically additional calcium-silicate-hydrate (C-S-H) compounds. This process enhances the density and improves the microstructure, resulting in an increase in compressive strength (Thomas et al., 2017). The findings indicate that replacing 10% cement with POFA resulted in a slightly higher compressive strength, which aligns with the findings of a prior study performed by Aiswarya et al. (2017). Further, when the amount of foam agent increased, the compressive strength decreased. The findings suggest that the quantity of foam significantly affects the mechanical strength of foamed concrete. By augmenting the quantities of foams in the binding system, the proportion of cementitious binder diminished. Consequently, there was an increase in the proportion of pores and/or voids in the system, which logically resulted in a reduction in compressive strength (Gencel et al., 2022).

3.3 Porosity

The results from the mortar porosity tests conducted at 28 and 91 days, as shown in Table 3, indicate that concrete with fa/w=1/60 exhibited a lower water porosity than concrete with fa/w=1/40. In particular, samples with fa/w=1/60 resulted in decreased levels of porosity, potentially reducing the total porosity of mortar. Based on Table 3, the porosity values decrease with increasing age. The porosity values at the age of 28 days for the POFA0-1/40, POFA10-1/40 and POFA20-1/40 were 22.62%, 22.74% and 24.53% respectively; and POFA0-1/60, POFA10-1/60 and POFA20-1/60 were 21.12%, 18.98%, and 22.46% respectively. For porosity values at the age of 91 days, the values were 19.82%, 19.43%, and 21.70% for POFA0-1/40, POFA10-1/40 and POFA20-1/40, respectively; and the values were 17.09%, 14.36%, and 15.43% for POFA0-1/60, POFA10-1/60 and POFA20-1/60, respectively. In addition, the dosage of the foam agent leads to an increase in the porosity of the foamed concrete. The foam's structure is intricately linked to factors such as its form, size, spacing between air-voids, size distribution, and volume of micropores (Hilal et al., 2014).

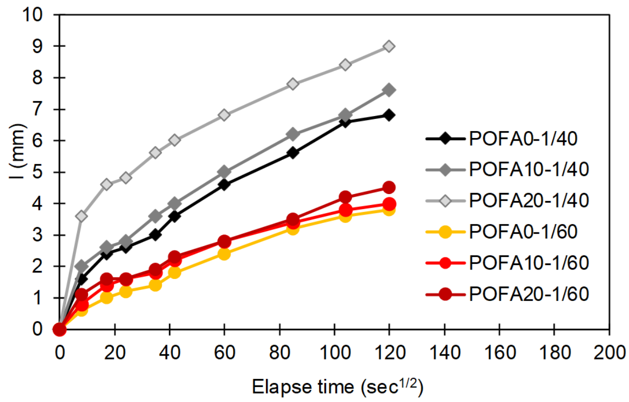

Figure 5 Water absorption rate of mortar at 91 days

3.4 Water Absorption Rate

Pore size influences the water absorption rate of concrete, which is an indicator of surface quality and a measurement of capillary suction. Figure 5 shows the water absorption rate of mortar after a period of 91 days. In general, the water absorption rate exhibited a gradual decline after an initial steep increase during the first six hours according to the ASTM C185. However, the trend becomes visible after 4 hours, at which point the observation ends. The absorption process was initiated by immediately saturating the large pore structures on the immersed face of the specimen, which was then followed by filling the microscopic ones. This study suggests that the water absorption of foamed concrete is influenced by both the level of POFA and the proportion of foam.

As a comparison, specimens with fa/w=1/40 for POFA0-1/40, POFA10-1/40, POFA20-1/40 had water absorption rate values of 6.8, 7.6, and 9, respectively. Meanwhile, specimens with fa/w=1/60 exhibited a slight decrease in water absorption rate values of 3.8, 4 and 4.5 mm for POFA0-1/60, POFA10-1/60, POFA20-1/60, respectively. The results show that the density of the ITZ (interfacial transition zone) between the aggregate and cement matrix changes depending on the amount of foaming agent used. This is shown in the SEM image above. The findings suggest that foam agent dosages have a greater effect on the water-to-binder ratio. Furthermore, the partial replacement of cement with POFA also affects the water absorption rate. A study by Islam et al. (2016) found that concrete with up to 70% POFA absorbs more water. This is because POFA takes time to fully dry and tends to soak up water.

3.5 Electrical Resistivity

Figure 6 shows the results of the electrical resistivity test at the age of 91 days. The primary concept behind electrical resistivity approaches is to quantitatively as-

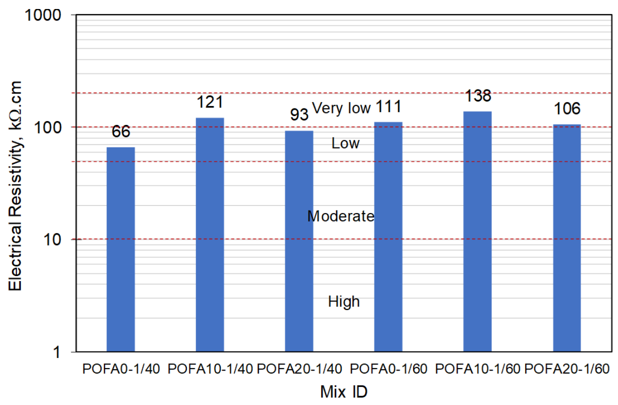

Figure 6 Compressive strength at the age of 7, 28 and 91 days

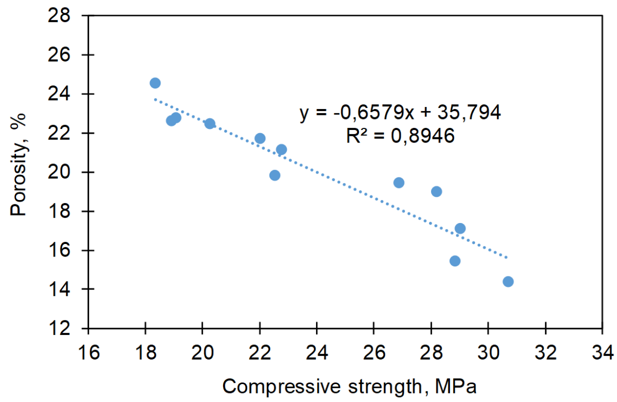

Figure 7 Correlation of porosity with compressive strength

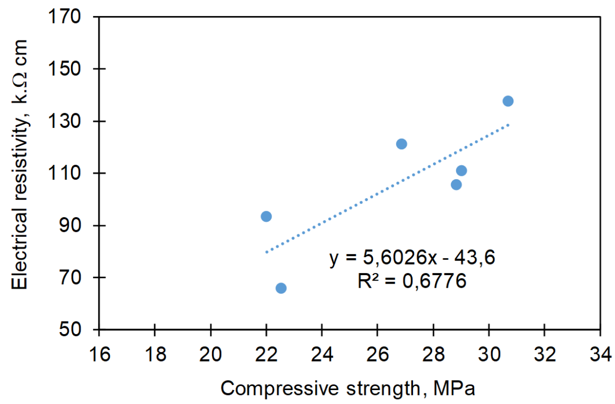

Figure 8 Correlation of electrical resistivity with compressive strength

sess the conductivity qualities of the microstructure of concrete. The corrosion risk was assessed according to a recommendation by the European Concrete Committee (CEB 192). The electrical resistivity of concrete is its ability to impede the movement of ions when subjected to an electric field. The findings indicate that a higher dosage of foam agent led to a reduction in the electrical resistivity of foamed concrete. Within this particular scenario, the utilization of a foam agent affected both the dimensions and the degree of interconnectedness of the pores. A more intricate pore network, characterized by less interconnectivity, results in decreased permeability, which in turn leads to increased electrical resistance. Further, Mohammadhosseini et al. (2017) reported on the durability properties of sustainable concrete consisting of POFA. It was observed that using POFA in concrete helps reduce both water absorption and chloride penetration.

3.6 Correlation for each property

Figure 7 illustrates the relationship between porosity and compressive strength. The findings indicate a significant correlation between the compressive strength of foamed concrete and its porosity. The compressive strength diminishes as porosity increases. Several variables can influence the porosity of solidified foamed concrete, including the components of the job mix design, the type of foam agents and the variety of curing methods. This result is in line with the findings revealed in another study, which indicated that a decrease in water absorption (showing a decrease in porosity) resulted in an increase in the compressive strength of foamed concrete (Sun et al., 2018). Consequently, a rise in porosity signifies an increase in both pore size and the interconnectedness of the pore network within the matrix, resulting in a loss of compressive strength.

Figure 8 illustrates the relationship between electrical resistivity and compressive strength. The durability of concrete is primarily dependent on its compressive strength, which is influenced by factors such as the impermeable matrix of its microstructure, including pore size distribution and interconnection geometry (Layssi et al., 2015). The disparities in chemical and physical characteristics between the binding matrix and the foams in the binder might lead to an unequal dispersion of hydration products in the ultimate bulk specimens. This uneven distribution is believed to negatively affect the compressive strength of the final product (Zhang et al., 2022). Figure 8 shows a linear relationship between compressive strength and electrical resistivity. Higher electrical resistivity indicates that the matrix inside foamed concrete becomes denser and leads to the inside matrix becoming impermeable (Ahmed and Kamal, 2022). Therefore, the greater the permeability of the concrete, the lower its mechanical strength, as well as its resistance against the electric current flow. SCM contributes to pore refinement, restraining its connectivity. This effect directly contributes to the reduction in permeability and increases the resistance against the electric current flow with similar found with Medeiros-Junior and Lima (2016).

4 CONCLUSION

The study examined the impact of varying dosages of foam agent and POFA as a partial substitute for cement on the characteristics of foamed concrete. There was an optimal incorporation of POFA with foaming agent for achieving the highest compressive strength of approximately 10% by weight of cement with a foam agent-to-water ratio of fa/w=1/60. Further, a foam agent-to-water ratio of fa/w=1/60 with 20% POFA replacement resulted in compressive strength, which is similar to foamed concrete without POFA.

DISCLAIMER

The authors declare no conflict of interest.

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