WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.140663

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVIII ISSUE 2 2022

 pp. 627–643

Research paper

Compressive strength and durability of foamed concrete incorporating Processed Spent Bleaching Earth

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Abstract: Foamed concrete incorporating processed spent bleaching earth (PSBE) produces environmentally friendly foamed concrete. Compressive strength, porosity, and rapid chloride penetration tests were performed to investigate the potential application for building material due to its low density and porous concrete. Laboratory results show that 30% PSBE as cement replacement in foamed concrete produced higher compressive strength. Meanwhile, the porosity of the specimen produced by 30% PSBE was 45% lower than control foamed concrete. The porosity of foamed concrete incorporating PSBE decreases due to the fineness of PSBE that reduces the volume of void space between cement and fine aggregate. It was effectively blocking the pore and enhances the durability. Consistently, the

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positive effect of incorporating of PSBE has decreased the rapid chloride ion permeability compared to that control foamed concrete. According to ASTM C1202-19 the foamed concrete containing 30% PSBE was considered low moderate permeability based on its charge coulombs value of less than 4000. Besides, the high chloride ion permeability in foamed concrete is because the current quickly passes through the specimen due to its larger air volume. In conclusion, incorporating PSBE in foamed concrete generates an excellent pozzolanic effect, producing more calcium silicate hydrate and denser foamed concrete, making it greater, fewer voids, and higher resistance to chloride penetration.

Keywords: strength, porosity, chloride resistance, foamed concrete, processed spent bleaching earth

1. Introduction

A pozzolan material, namely Processed spent bleaching earth (PSBE), is derived from processing deoiled spent bleaching earth (SBE) after the oil is recovered. The bleaching earth is excellent powder clay, and its main component is silicon dioxide used for the refining process of palm oil, and its by-product is known as SBE, which is commonly disposed to landfill [1]. The SBE is generated about 240,000 tons per annum in Malaysia due to its refining process of crude palm oil [2]. Among the most prominent palm oil producers globally, Malaysia will produce large quantities of SBE, and it is becoming increasingly difficult to ignore the disposal of SBE when palm oil production increases rapidly. Furthermore, disposal of SBE may lead to a negative impact on the environment if not managed properly. SBE can present potential fire and pollution hazards because it contains 20 to 40% residual oil by weight, metallic impurities, and organic compounds upon its disposal. SBE disposal has been resolved by removing the oil and colouring materials [3] and reuse as material production [4]. The recovery of oil from SBE can be extracted to produce biodiesel [5], and the deoiled SBE has been reused as an adsorbent in wastewater treatment, as a clay substitute in the bricks, blocks, and tile manufacturing [6], and as a filler in asphalts [7]. On the other hand, SBE has been incinerated for cement manufacturing in Japan and Kenya [8]. Partial replacement of Portland cement by PSBE has been proven to be effective in increasing compressive strength of foamed concrete and the use of 30%PSBE enable to exhibit higher resistance from deterioration to against sulphate attack due to the formation of dense microstructure which inhibit the ingress of sulphate ions and reduces the formation of expansive ettringite that leads to reduce the propagation of micro cracks [1]. But, the effect of PSBE on the durability of foamed concrete is limited in the literature. Hence, this research aims to investigate the compressive strength, porosity and rapid chloride permeability of foamed concrete containing 30% PSBE.

Foamed concrete (FC) is the mixing of cement paste and preformed foams and provides lower density, ease of handling, self-compacting [9, 10], and cost savings [11]. It is considered eco-friendly concrete [12–14] and economical because its content has no aggregate, and any supplementary cementitious material can be used as sand or cement in FC. Among the pozzolanic material used as partial cement replacement in FC, fly ash [15, 16], silica fume [17], ground granulated blast furnace slag [18], rice husk ash [19], sewage sludge ash [20], sludge paper mill [21], graphite tailing [22], palm oil fuel ash [23, 24] and soil as sand [25] replacement. Most of the research reported that the positive effects of pozzolanic material in FC enhance the long-term strength, improve durability, economical and eco-friendly due to reducing greenhouse gas emissions, including carbon dioxide, reuse industrial waste, and minimizing cement usage.

The porosity is the measurement of total air voids in the hardened FC, which can be determined by using Vacuum saturation Apparatus as confirmed to ASTM C642-13 [26]. The researchers [27–29] found a linear relationship between porosity and compressive strength of FC. The reduction in porosity increased the compressive strength of FC due to its denser product. The lower porosity indicates the less pores connected, making the strength higher, low water absorption, and permeability. Kersley & Wainwright [30] determined that the reduction in porosity is due to fly ash content increased. It is revealed that the porosity depends on dry density, where the porosity decreased from 67% to 29% when dry density increased from 1000 kg/m^3 to 2000 kg/m^3. Similarly, Yang & Song [31] reported that a density of 1400 kg/m^3 using ground granulated blast-furnace slag (GGBS) with a higher fineness had a lower porosity, fewer unhydrated particles, and a denser surface. It is observed that the porosity of FC containing GGBS decreased as the increased percentage of GGBS in the mix. It has been pointed out that the reactive silica content determines the pozzolanic reaction and specific surface area and mineralogical composition of the pozzolan material leads to a positive effect on the FC properties [32]. This is because the pozzolanic reaction between pozzolan (silica) and the calcium hydroxide (CH) produced additional calcium silicate gel (CSH) that enhanced the strength of FC and increased the durability of FC. The addition of pozzolan can reduce the pore size and reduce the porosity, leading to increased strength.

Chloride permeability is defined as the flow of chloride ions through the pores of FC. The performance of FC against chloride ions is significant because it leads to the corrosion of reinforcement and then causes deterioration of the structure. The rapid chloride permeability test (RCPT) is performed on cylinder specimen by measuring the electrical current passing through a specimen for a standard 6 hours at a standard voltage of 60VDC according to ASTM C1202-19 [33]. The total charge passing through the specimen is measured and expressed in Coulombs. Table 1 presents the chloride ion penetrability based on charge passes. The reduction in total charge value indicates more resistance to chloride ion penetration and lower permeability. The penetration of chloride ions can cause corrosion of concrete and reinforcement due to expansive products produced in the reaction of chloride ions with concrete components, mainly calcium hydroxide ($Ca(OH)_2$). The expansive product, alkaline calcium chloride $Ca(OH)_2{\cdot}H_2O{\cdot}CaCl_2$, increases its volume during crystallization and causes damage to concrete [34]. It has been observed that the chloride permeability of the concrete reduced when incorporating pozzolans compared to decreasing the w/c ratio in the mixture [35]. The chloride ion resistance of concrete depends more on the porosity and interconnectivity of the pore system, and it does not depend much on the chemical bonding capacity of cement [36]. It has been revealed that the charge passing (Coulombs) through the calcined clay specimens decreases with the increase in calcined clay content up to 10%. However, at 12.5% of calcined clay, the charge passing increases with calcined clay content. It indicates the significant chloride ion resistance by replacing cement with calcined clay [37]. Also, there is a relationship between the charge passed and the carbonation depth of concrete. The total charge passed reduces when the increase in carbonation depth increases. It demonstrated that carbonation reduces chloride ion diffusion. It indicates that the carbonation decreases surface porosity after carbonation and has lower chloride ion penetration [38].

Table 1. Classification of flow Chloride ion

Level penetrability	Ion passed (Coulombs)
High	> 4000
Moderate	2000–4000
Low	1000–2000
Very low	100–1000
Negligible	< 100

Hence, incorporating a suitable amount of pozzolan material enhances the strength and durability of FC. The foamed concrete incorporating PSBE is unavailable. This research focuses on the effect of PSBE as partial cement replacement in FC on compressive strength, porosity, and chloride permeability. Besides, less usage cement content can promote waste materials, reduce CO_2 emissions, and conserve energy and resources.

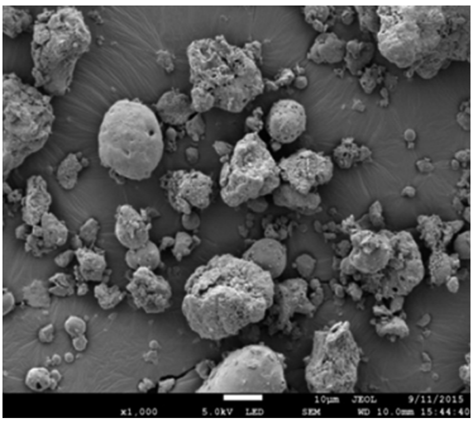
2. Research methodology

2.1. Properties of materials

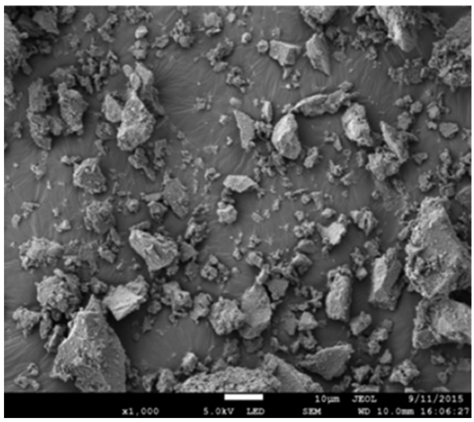
The properties of FC making materials have been discussed accordingly, including a foaming agent, silica sand, pozzolan material, cement, and water. LCM Technology Sdn. Bhd. manufactured the hydrolyzed protein foaming agent. Bhd. Kuantan is conforming to ASTM C796-19 [39]. The foaming agent is not hazardous and meets the requirements of ASTM C869-16 [40]. Johor Silica Industries Technology Sdn manufactured silica sand. Bhd with a 425 µm sieve (No. 425 ASTM) conforming to BS EN 12620 [41]. The Eco Innovation Sdn.Bhd. provided the pozzolan material, namely processed spent bleaching earth (PSBE). Table 2 provided pozzolan material's chemical composition and physical properties and ordinary Portland cement (OPC). Based on ASTM C618-12 [42], PSBE was classified as Class N Pozzolan and conformed to BS Specification for Pulverized-Fuel for Portland cement use, BS EN 450-1 [43]. Fig. 1a shows that PSBE is spherical in shape, porous and smooth surface compared to OPC, which is angular and irregular in shape as presented in Fig. 1b. The function of water in this study is for mixing concrete and curing the specimen.

Table 2. Properties of PSBE and OPC

Composition (%)	PSBE	OPC
Silicon oxide	55.82	16.05
Aluminum oxide	13.48	3.67
Calcium oxide	6.6	62.28
Ferrous oxide	8.24	3.41
Magnesium oxide	5.94	0.56
Sulfur trioxide	1.05	4.10
Total of SiO_2+Al_2O_3+Fe_2O_3	77.54	–
Loss on Ignition	0.18	1.2
Surface Area (BET) m^2/g	8.484	4.459
Specific gravity	2.44	3.1



(a) PSBE



(b) OPC

Fig. 1. Particle shape of PSBE and OPC

2.2. Production of foamed concrete

The production of FC consists of the mixing process, casting of specimens, and curing conditions. The control FC specimen, which contained only cement, sand, water, and foam, was set as a reference and the PFC specimen is the mixture that contains 30% PSBE as partial cement replacement. The mix proportion in Table 3 was constantly set up for water-cement ratio, sand cement ratio, dilution ratio, and percentage of foam dosage at 0.5, 1.5, 1:25, and 25%, accordingly [44, 45]. Fig. 2 shows the process flow of making FC. Firstly, the mixer drum prepares the mortar or cement paste by dry mixing of cement, silica sand,

and PSBE. Water is added after a few minutes and mixed them homogeneously. Next, before the preformed foam is added to the mixer, the density and workability of the mortar were measured. A mortar density is obtained by weight of 1 L of its paste in the beaker. Secondly, the preformed foam is prepared based on its dilution ratio, which dilutes 1 L of a foaming agent and 25 L of water. Before being added to the mixer drum, foam density is measured and controlled at 50 kg/m^3. The foam is added to the mixer and mixed well until no bubbles come up. Again, a density of FC is obtained by weight of 1 L of the mix until 1600 kg/m^3 is desired. Finally, the slurry of FC is used to cast cube specimen size $100 \times 100 \times 100$ mm and cylinder size diameter 100×200 mm height. After 24 h, demolded all specimens. Due to different curing methods, all specimens were cured and tested at various ages of 7 days, 28 days, 3 months, 6 months, and 1 year. In this study, the specimens were subjected to five different curing regimes such as air curing (AC), water immersion (WI), natural weather (NW), 7 days water immersion, and then followed by air curing (7 AC) and 7 days water immersion and then followed by natural weather curing (7 NW). All the equipment, materials, and procedures in producing foamed concrete have been implemented were by ASTM C796-19 [39].

Fig. 2. Process flow of making FC

Table 3. Mix proportion of foamed concrete

Mix	Density kg/m^3	Cement kg/m^3	PSBE kg/m^3	Sand kg/m^3	Water kg/m^3	Foam kg/m^3
FC	1600	535.9	–	803.8	270.9	250
PFC	1600	375.1	160.8	803.8	280	250

3. Testing method

3.1. Compression strength test

This present research has prepared 100×100×100 mm cube specimens for compression testing of FC followed by ASTM C513-11 [46] to determine the compressive strength of FC. All specimens were cured and tested at 7 days, 28 days, 3 months, 6 months and 1 year. The average compressive strength and maximum load are obtained by three specimens tested. The compression test was performed using a 2000 kN UTM machine with a loading rate of 3 kN/s. The compressive strength, σ, was calculated by using Equation (3.1).

$$\sigma = \frac{P}{A} \tag{3.1}$$

where: σ – the compressive strength of concrete, P – the maximum load applied, A – cross sectional area.

3.2. Porosity test

The porosity test set-up was prepared as shown in Fig. 3 according to ASTM C642-13 [26]. The cube specimens have been prepared, cured and tested due to the curing

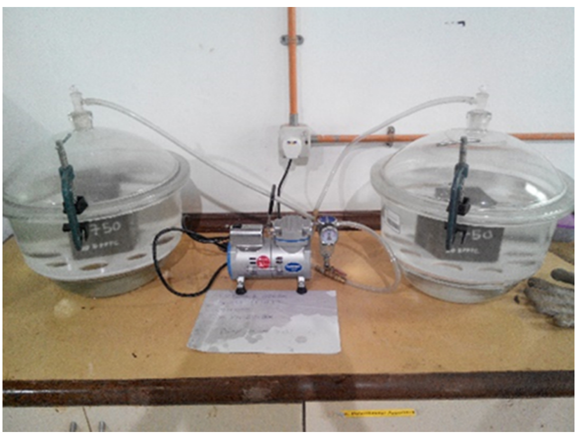


Fig. 3. Porosity test set up

age. The average porosity of FC is obtained by three specimens tested. The porosity was calculated by using Equation (3.2).

$$P = \left(\frac{m_{\text{sat}} - m_{\text{dry}}}{m_{\text{sat}} - m_w} \right) \times 100\% \tag{3.2}$$

where: P – is the porosity in %, m_{sat} – mass of saturated specimen in gram, m_{dry} – mass of the oven dry specimen in gram, m_w – apparent mass in water/buoyancy of specimen in gram.

3.3. RCPT test

The Rapid Chloride Permeability Test (RCPT) was set up according to ASTM C1202-19 [33]. The RCPT was done to investigate the ability of specimens to resist chloride ion penetration by measuring the electrical current passing through a specimen for a period of standard 6 hours at a standard voltage of 60VDC. The specimen's cylinder diameter 100×200 mm height was prepared and cured in water curing for 1 year. Fig. 4 shows the equipment, accessories, and the setting up for the Rapid Chloride Permeability Test.

Fig. 4. Rapid Chloride Permeability Test set up

4. Results and discussion

4.1. Compression strength

Fig. 5 and Fig. 6 show compressive strength development for foamed concrete (FC) and foamed concrete containing 30% PSBE as partial cement replacement (PFC) specimen due to different curing conditions for up to 1 year. It clearly shows that the compressive strength development trend increases from 7 days to 365 days of curing age for both FC and

PFC subjected to different curing conditions. The growing trend of compressive strength was due to the hydration process that promotes the continuing production of CSH gel due to the reaction of cement and water subjected to curing conditions. Based on results, the average compressive strength of FC was a range between (5.3 MPa to 7.8 MPa), (7.5 MPa to 10.5 MPa), (8.2 MPa to 11.4 MPa), (8.5 MPa to 12 MPa), and (8.7 MPa to 12.2 MPa) at 7 days, 28 days, 90 days, 180 days and 365 days while the results for PFC with 30% PSBE was a range between (10.8 MPa to 14.9 MPa), (18 MPa to 24 MPa), (19.8 MPa to 26.2 MPa), (20.8 MPa to 27.5 MPa) and (21.4 MPa to 28.1 MPa) at 7 days, 28 days, 90 days, 180 days and 365 days. Compared to control FC, the PFC shows the higher compressive strength subjected to all curing conditions, as shown in Fig. 6. This result was the effect of the pozzolanic reaction of PSBE, where the chemical reaction of the PFC specimen had developed a strong particle bond between PSBE and gel matrix to increase the compressive strength. The incorporating PSBE in FC produced higher compressive

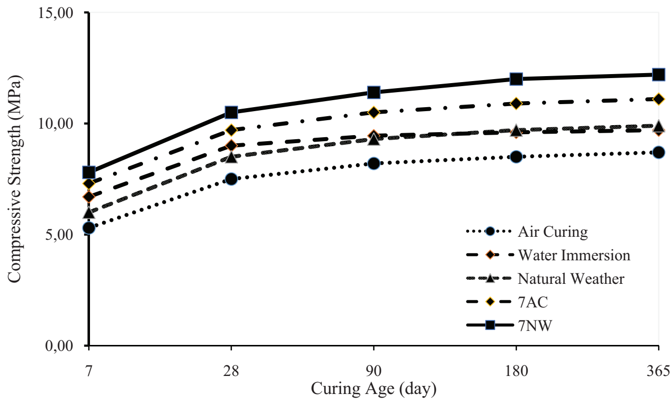


Fig. 5. Development of compressive strength for FC specimen up to 1-year age

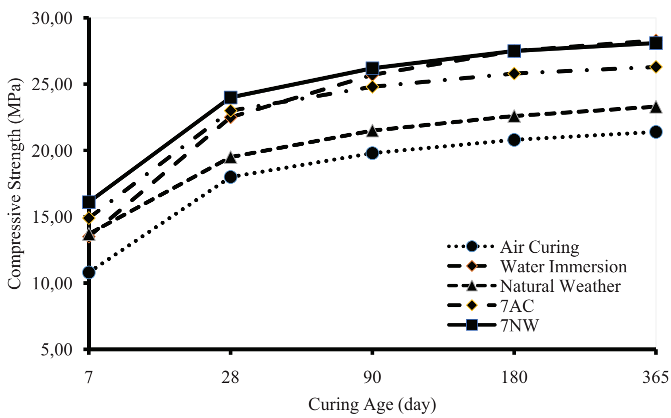


Fig. 6. Development of compressive strength for PFC specimen up to 1-year age

strength than FC because PSBE has a positive effect in generating more calcium silica hydrate due to its higher silica and alumina. On the other hand, PFC is denser than FC because it has fewer voids due to the pozzolanic effect, which more CSH produced denser specimens since FC is a porous structure. A similar influence of pozzolan material on the strength of foamed concrete was reported by [17, 47–51].

On the other hand, the compressive strength of PFC was 56% higher than FC at 28 days subjected to 7 NW due to the curing condition. It should be noted that the 7 days of initial water curing seemed to produce early hydration and led to increased strength development of foamed concrete. Yetgin & Çavdar [52] also found that a combination of water and air curing methods increases the strength of foamed concrete as the ages increase, which leads to the achievement of the ultimate strength. Similarly, Rahman [53] reported that cured in water following cured in air produces higher strength than a specimen cured in water or air exclusively. According to Falade et al. [54], the lower strength exhibited by water-cured specimens might be due to the dilation of cement gel by the adsorbed water, which reduces the forces of cohesion of the solid particles. Also, based on the result obtained, the compressive strength cured in 7 AC was 4% lower than 7 NW, which can also be the suitable curing condition due to sufficient moisture maintained to continue the hydration of cement.

As mentioned earlier, results indicate that 30% PSBE significantly improved the strength of PFC compared to control FC cured in 7 NW curing, which specimen has been 7 days of initial water immersion and then followed by natural weather to achieve the highest strength compared to others. It is proven that, by 7 days of initial water curing, it has produced early hydration and increased strength compared to other specimens cured in different conditions. The microstructure of the specimen PFC and FC for 28 days and 1 year subjected to 7 NW were observed by SEM morphology in Fig. 7 and Fig. 8, respectively. The formation of hydration products like calcium hydroxide (CH) and calcium silicate hydrate (CSH) are presented in SEM morphology. From observation, the inclusion of PSBE has led to pozzolanic reaction resulting in the production of more CSH gel and blocking the voids in the PFC, making PFC denser and more robust. The SEM morphology has revealed that PSBE improves the internal structure of PFC and makes it denser than the control FC specimen. Fig. 7 shows the effect of PSBE, where the crowded tiny of cotton shaped represent the additional CSH in the PFC is more than control FC for 28 days. On the other hand, fewer CH crystals that have been presented by hexagonal plate and more CSH leads to its greater strength.

Fig. 8 shows that the tiny cotton appeared more in PFC due to age of curing increases, representing CSH formation in the hardened specimen. It revealed that the inclusion of PSBE gained more CSH due to the pozzolanic effect. Furthermore, the excellent effect of PSBE has to make PFC denser, which leads to greater strength compared to FC specimen. Besides, a few tiny cotton-shaped pieces appear in the FC specimen because CaO in FC generates CH, and since there is no pozzolanic effect, the CH cannot consume. Similar researches [48, 55] reported that incorporating pozzolan materials in FC provides more CSH, leading to higher compressive strength. The excellent effect of pozzolan materials is due to the reaction with the CH, which produces more CSH during the pozzolanic

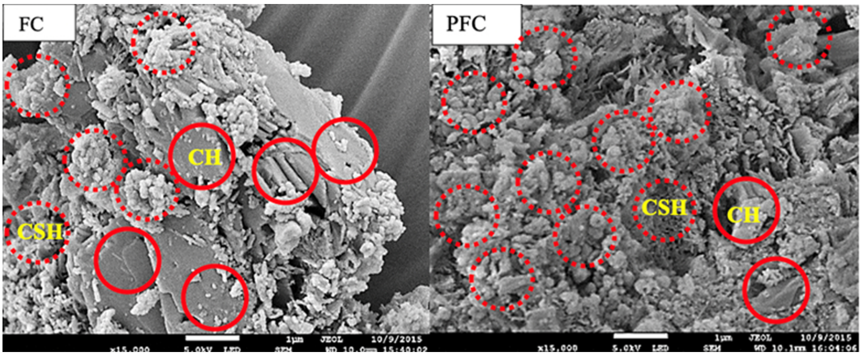


Fig. 7. SEM for hydration product of FC and PFC at 28 days (7 NW curing)

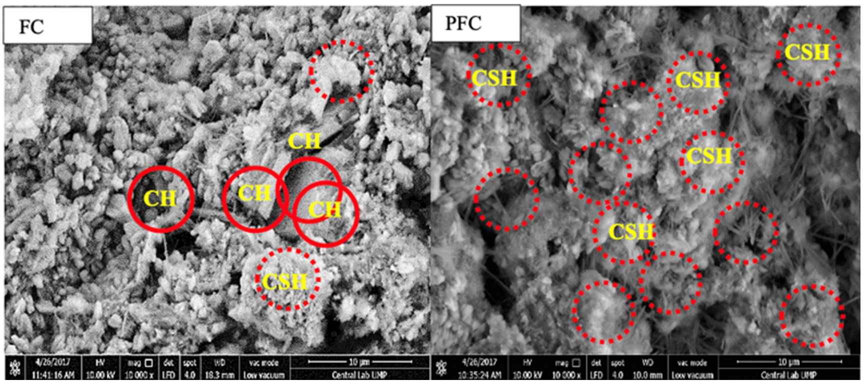


Fig. 8. SEM for hydration product of FC and PFC at 1 year (7 NW curing)

reaction [56, 57]. This mechanism is similar to concrete or mortar incorporating pozzolan materials, which their hardened concrete is denser and less porous due to the formation of CSH during the pozzolanic effect [58–60].

4.2. Porosity

The porosity of foamed concrete incorporating 30% PSBE (PFC) and control specimen FC was shown in Fig. 9 and Fig. 10. From the graph, it can be seen that both FC and PFC specimens cured in 7 NW (which is 7 days water immersion and then followed by natural weather) presented the lowest porosity compared to others. The lowest porosity was between 21.5% to 12.5% at 7 to 365 days for FC and 13% to 6.9% at 7 to 365 days for PFC. Meanwhile, the highest porosity result was observed in air curing in the range between 29.2% to 21.5% at 7 to 365 days for FC and 18.2% to 12.8% at 7 to 365 days for PFC. It discovered that the porosity trend decreased due to curing age increasing from 7 days up to 1 year for both FC and PFC specimens. The decreasing porosity trend indicates the reduction of pore space within the paste due to the hydration process that promotes the continuing production of CSH gel. It is observed that the porosity of the specimen produced by PFC was in the range of 45% lower than FC at every age of all curing conditions. It confirmed that the excellent effect of incorporating PSBE in PFC decreased the porosity compared to that control specimen FC. It consistently revealed that the 7 NW curing is the effective method to reactivate pozzolan in the hydration process and significantly reduce the porosity. The high porosity in FC corresponds to the larger volume of air voids or pore space in the concrete making it less dense.

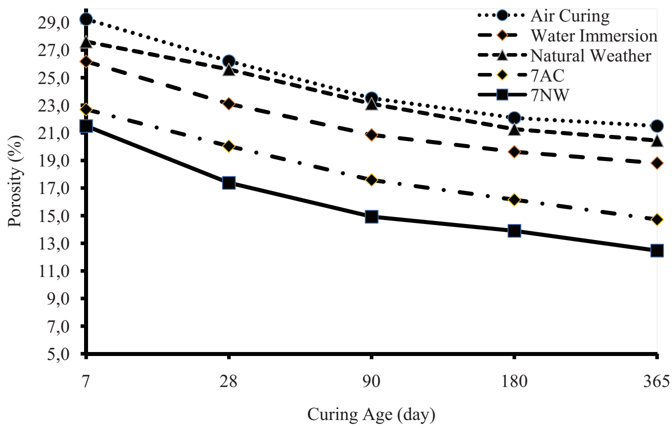


Fig. 9. Porosity of FC

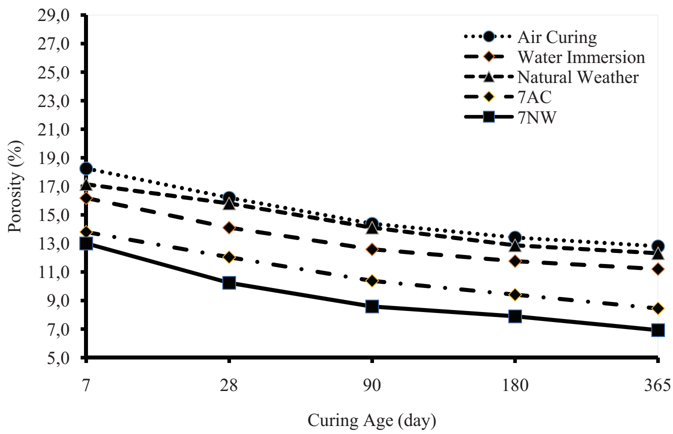


Fig. 10. Porosity of PFC

According to Yang & Song [31], the porosity of foamed concrete containing GGBS was decreased due to the fineness of GGBS and the denser surface. The particle size of pozzolan can reduce the volume of void space between cement and fine aggregate [61]. It confirmed that the porosity of PFC was decreased because the fineness of PSBE effectively blocks the pores and enhances the durability. Also, in the pozzolanic reaction, by combining the PSBE with the calcium hydroxide (CH) producing the additional CSH gel, CSH will close the voids and make the foamed concrete denser and more durable. Walker & Pavía [62] recommended that the particle size of pozzolan should be finer than cement to achieve better performance in porosity. As Kearsley & Wainwright [30], the lower porosity indicated, the fewer pores connected that make the strength higher, low water absorption and permeability and frost resistance will be better but higher in thermal conductivity.

4.3. Rapid chloride penetration

This study reported the performance of PFC and FC specimens towards chloride ion penetration by determining the amount of charge electrical current passing through a specimen for a period of standard 6 hours at a standard voltage of 60VDC in terms of Coulombs. The lower charge value represents the excellent resistance towards chloride ion penetration and lower permeability. The total charge of chloride ions in coulombs for PFC and FC specimens was presented in Fig. 11. According to the results, the charge in coulombs that passes through the specimen of FC was higher than PFC. Consistently, it shows that the excellent effect of incorporating PSBE has lower the chloride ion permeability than control FC. Furthermore, the rapid chloride iron permeability trend of PFC decreased due to the curing age from 7 days up to 1 year. Referring to ASTM C 1202-19 [33], the foamed concrete incorporating 30% PSBE was considered low moderate permeability based on its charge coulombs value less than 4000. While the control FC was classified as higher permeability based on its ion permeability above 4000 coulombs from 7 days up to 1 year.

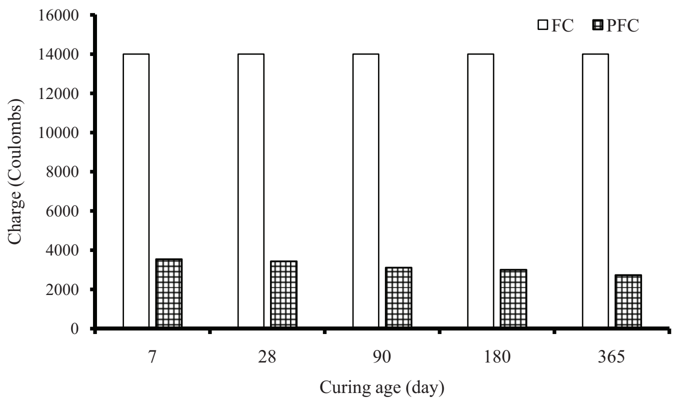


Fig. 11. Rapid chloride permeability of FC and PFC

The high chloride ion permeability in FC indicates low chloride resistance because the current quickly passes through the specimen, corresponding to the larger volume of air voids or pore space within the internal cell structure that makes it less dense. While the reduction in the chloride ion permeability in the PFC indicates that reduction of capillary pores and connectivity due to the particle size of PSBE, which is finer than cement, caused a better particle packing and led to a denser harden phase. The use of PSBE as a replacement for cement is highly effective in improving foamed concrete's resistance. It caused a significant reduction of chloride ion permeability in PFC due to reducing pore space within the paste. Hossain et al. [63] reported that the pozzolans in mortar and concrete improved rapid chloride ion permeability resistance. Further, as mentioned earlier, the rapid chloride iron permeability with the PSBE trend was decreased as the curing period increased from 7 days to 365 days of curing age compared to FC. Besides the pozzolanic materials can be more effective in improving concrete durability due to pozzolanic reaction continuing at a higher rate for a more extended period [35].

5. Conclusions

Incorporating PSBE in foamed concrete generates superior compressive strength, porosity, and chloride permeability. The findings of this study reveal many beneficial effects of PSBE in foamed concrete from exterior to interior hydrated compounds. The specimen subjected to 7 days of initial water immersion followed by natural weather curing is the effective method to reactivate pozzolan in the hydration process. The PFC exhibited higher compressive strength and durability with 45% lower porosity. Regarding chloride penetration, foamed concrete with 30% PSBE is classified as low, moderate permeability, and FC as higher permeability based on its charge coulombs value of more than 4000. In conclusion, incorporating PSBE in foamed concrete as a replacement for cement enhances the compressive strength, porosity, and chloride permeability. In the future, an investigation of the structural performance containing PSBE with other pozzolan ash should be conducted.

Acknowledgements

This study was supported by the Malaysian Ministry of Higher Education and University Malaysia Pahang under the research grant (RDU/UMP) vote number RDU200349.

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Received: 16.12.2021, Revised: 08.02.2022