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ORIGINAL ARTICLE

Bottom ash as a solid waste of the palm oil industry turned into a high-value cement replacement for sustainable cement-based materials

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Abstract

Bottom ash needs a pre-treatment process to produce the finer particles until it is like cement material and has a good reactivity as pozzolanic material. This research investigates the effect of using bottom ash on the durability performance of concrete. The modified process was applied to bottom ash to produce finer particles that can improve the durability performances of concrete. The concrete used in this study is self-compacting concrete (SCC) due to its convenience. The bottom ash was pretreated by mechanical grinding before being used as supplementary cement materials (SCM), later called ground bottom ash, and applied from 10% to 50% as the partial replacement by the weight of cement. BA30 showed the highest compressive strength with an increasing percentage of 32% and had a similar value to BA0. The porosity of all mixtures was under 15%. The water absorption of all mixtures was under 10%. BA10, BA20, and BA30 reduced the permeability of the SCC, while BA50 increased the permeability of the SCC. BA30 had the lowest value of RCPT as 916.22 C. The results show that bottom ash positively affects the durability performance of SCC and can be used as an SCM to produce more sustainable cement-based construction materials.

Keywords Bottom ash · Supplementary cement materials · Durability · Sustainability

Introduction

Coal was burnt at high temperatures to produce thermal energy and generated solid waste in various sizes, such as fly ash and bottom ash. The quality of the bottom and fly ash depends on the coal quality and the combustion temperature [1]. High temperatures will produce both bottom ash and fly ash with a lower carbon content compared with the combustion process using low temperatures. Fly ash is one of the coal combustion by-products more often used in the concrete industry than bottom ash. Generally, fly ash and raw or calcined natural pozzolan are classified into three classes, namely, class N, class F, and class C. The classification is based on chemical calculations, as stated in ASTM C618.

The size of the bottom ash and fly ash materials in each combustion process in any industry will always be different. Bottom ash is coarser than fly ash and is deposited at the furnace's bottom. Meanwhile, fly ash forms and floats on the top side of the stove, because the grain size is smaller than the bottom ash. The coal used as an energy source for almost 40% world-wide in the industries, so that the environmental issues were also present as the effect of bottom ash generation as the municipal solid waste incineration in this industry. As far as known, disposing of the bottom ash as landfilling is the one of solutions to treat the waste [2–4]. The bottom ash, often disposed of without proper treatment, will cause soil and groundwater contamination and threaten the environment.

Conversely, it affects biodiversity degradation and vast consumption of land spaces. Research has concluded bottom ash is a non-toxic waste material, better than fly ash [5–7]. Some studies found that there was a pathway to accomplish the high volume of bottom ash. The problem

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breaker used bottom ash as the construction material, which was adequate to solve the environmental issues. That topic has been a popular focus of research in recent years. The concept of using bottom ash as a construction material is known as solidification. Solidification is a method to block metalloids leaching and compacting the existing raw materials and produce more safe material than before [8–10]. Solidification of waste, such as fly ash and bottom ash, is more often used as construction material. This solidification is considered able to lock in chemical contents supposed to exceed the normal limit range. With this concept, the material resulting from solidification will have a shape and provide added value from waste material.

The utilization of the bottom as partial or entirely replacement as fine aggregate in the mortar was observed by the previous research in the range from 20% up to 40% [11, 12]. The results showed that using bottom ash as a fine aggregate harms these materials' porosity and water absorption properties. Thus, several studies applied pre-treatment to bottom ash, such as washing, thermal, and alkaline treatment, using dry mixing method, and adding SCM (supplementary cement materials) [13–15]. Previous research found the possibility of using bottom ash as SCM. Further research states that bottom ash modified in particle size can be used as SCM with a range of 10–40% of the weight of cement used in concrete mixtures. The results stated that 30% bottom ash with a particle size that is finer than ordinary bottom ash can optimally increase concrete's compressive strength [16].

Bottom ash and fly ash have similar compositions with cement [17]. The results of previous studies on the effect of silica and alumina content of fly ash showed that the content can bind the remaining compounds from cement hydration and become cementitious material in concrete mixtures. The percentage of the amount of silica and alumina content in bottom ash is similar to fly ash. Thus, the same reaction is expected when bottom ash is used as a partial substitute for cement in concrete mixtures [18–20]. This research focuses on using bottom ash as supplementary cementitious materials with a variation range of 10%, 20%, 30%, and 50%. The modified process was applied to bottom ash to produce finer particles that can improve the durability performances of concrete. The bottom ash used in this research comes from the palm oil industry, which differs from previous studies that used bottom ash from power plants. Differences in combustion processes and temperatures between the palm oil industry and power plants will cause variations in characteristics. This research provides new insight into the feasibility and efficacy of using solid waste from the palm oil industry as a partial replacement for cement. In addition, this research can show new opportunities in developing high-value and environmentally friendly construction materials from palm oil industry waste.

Experimental programs

Materials

This study used ordinary Portland cement, bottom ash, fine aggregate, coarse aggregate, and superplasticizer materials. Ordinary Portland Cement (OPC) was used as the binder, and bottom ash was set as supplementary cement materials in proportions. Bottom ash was obtained from the palm oil industry and modified to gain finer particle size using a ball mill machine. The grinding process was carried out for 4 h with 6 kg of bottom ash and 30 kg ball mill balls, after 24 h of dried operation at 100° C [21]. After grinding, the ground bottom ash was pulverized until it passed through 75 µm in mesh diameter. This grinding process is expected to increase the surface area of the original bottom ash. The contact between the bottom ash particle and cementitious materials increased as the surface area increased. This condition leads to more opportunity for pozzolanic reaction between bottom ash and calcium hydroxide, a by-product of cement hydration, to form additional cementitious compounds. Furthermore, grinding bottom ash can be a form of mechanical activation. Applying mechanical forces during the grinding process can change the bottom ash's crystal structures, promoting reactivity and improving its ability to react with calcium hydroxide [16].

Previous research also carried out a grinding process, but it was carried out for silica sand. The grinding process changes the material's character to become more active when ground silica sand turns to gray like silica fume. The reactivity testing process to see the material's activity as a cement substitute shows that modified silica sand may be used as a partial replacement for cement in a concrete mortar if seen from the resulting compressive strength [22].

The chemical composition of bottom ash and ground bottom ash was similar, with SiO_2 as the highest amount, followed by Fe_2O_3, Al_2O_3, CaO, MgO, Na_2O, and K_2O. Its chemical compositions differed from OPCs (Ordinary Portland Cement), where CaO was the highest, followed by SiO_2. The XRF results of bottom ash, ground bottom ash, and OPC are listed in Table 1.

Based on ASTM C618, the value of $SiO_2 + Al_2O_3 + Fe_2O_3$ must meet the requirements. It must be equal to 70%. This provision is applied if you want to use other materials, such as pozzolanic material, in concrete mixtures. From the table above, the ground bottom ash is fulfilled as the pozzolanic materials. Bottom ash from other studies has a total content similar to the ground bottom ash used in this study. The value of $SiO_2 + Al_2O_3 + Fe_2O_3$ in OPC, refer to the other studies, was almost 50% lower than the ground bottom ash used

Table 1 Chemical composition

Oxides (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	$SiO_2 + Al_2O_3 + Fe_2O_3 \geqq 70\%$
Ground Bottom Ash	51.70	12.11	15.04	5.05	2.32	0.55	0.56	78.85
Bottom Ash[a]	47.25	17.64	11.30	9.46	5.10	0.92	0.92	76.19
OPC[c]	20.90	4.80	3.40	63.30	1.30	0.30	0.40	29.10

[a]Wulandari et al. (2021), [b]Celik and Ascuru (2020), and [c]Pormmoon et al. (2020)

in this study. The CaO content in OPC helps accelerate the hardening process in concrete mixtures, and the value is higher than that of ground bottom ash. Therefore, the amount of ground bottom ash used needs to be checked further to find the suitable composition for concrete and does not reduce the performance of normal concrete that uses cement.

Compared to OPC, the ground bottom ash has a smaller specific gravity, and the specific gravity of ground bottom ash is 2.94 g/cm^3, while OPC is 3.14 g/cm^3. Some previous studies stated that the specific gravity of bottom ash is in the range of 2.2–3.2 g/cm^3, while fly ash has a specific gravity of 1.9–2.55 g/cm^3 [23–25]. This shows that the specific gravity of bottom ash, fly ash, and OPC is not much different, so the additional specific gravity of concrete, when produced using bottom ash and fly ash, will not be far apart from normal cement concrete. After the modification process, the average particle size of ground bottom ash is 6.12 µm, while the bottom ash has a large particle size (4.75 mm to 150 µm). The microstructure of the bottom ash before and after the modification process is delivered in Fig. 1. The magnification of microstructure imaging is using an electron microscope with a magnification of 1000 times to see the difference in size from the surface view of bottom ash and fly ash.

The figure above shows the angular shape with low sphericity particles as the bottom ash and ground bottom ash particles. Fly ash has a well-rounded shape with high sphericity particles, and OPC has an angular shape with high

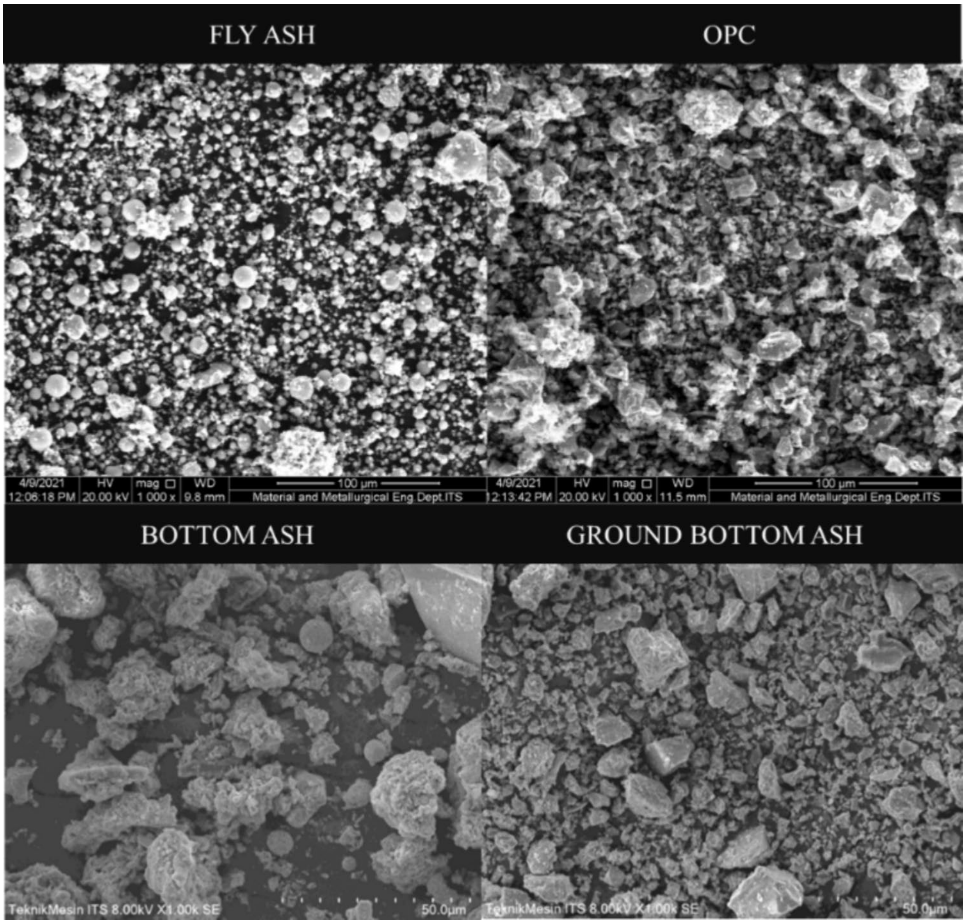


Fig. 1 Micrograph (1000 × magnification) of fly ash, OPC, bottom ash, and ground bottom ash

sphericity particles. Previous research results show that the particle's size and shape affected the strength of itself [26, 27]. The spherical particles of fly ash produce a ball-bearing effect with good flowability and workability to concrete mixtures [28]. The fine particle size of fly ash can fill the small gaps in the concrete mix, increasing the density of concrete, making it impenetrable, more resistant to abrasion, and reducing concrete shrinkage. In the previous studies, in a certain amount with sufficient moisture, the content of silica and alumina compounds in fly ash bind the remaining compounds resulting from cement hydration that cannot bind, namely calcium hydroxide, into new compounds that are cementitious and can increase the compressive strength of the concrete produced. The use of fly ash more than 30% weight of cement can reduce the compressive strength of concrete [17, 18, 29].

In addition, fine and coarse aggregates used in this study have maximum size. They were 4.75 mm and 20 mm, respectively. It has a specific gravity of 2.6 g/cm^3, while the coarse aggregate used is crushed stone with a specific gravity of 2.4 g/cm^3. High-Range Water Reducer (HRWR) Sika Viscocrete 3115N was used as a superplasticizer to reduce the water consumption in the SCC mixtures. This type of superplasticizer is the most suitable for SCC concrete mixture. It does not change the characteristics of the concrete produced but rather facilitates the process of working concrete, even though it uses a small water-to-cement ratio.

Mix proportions, casting, and test methods

The mix design of SCC based on ACI 237R-07 was applied in these experimental steps. Bottom ash, as SCM, substituted the cement with 10% (BA10), 20% (BA20), 30% (BA30), and 50% (BA50), proportions by weight. The requirement of slump flow was set up at more than 650 mm, powder content in 550 kg/m^3, and water-to-cement ratio (w/c) in 0.3. The HRWR to binder proportion used in this mixture is 1.5%. HRWR was added at the end of the mixing process. Materials requirements can be seen in Table 2.

The concrete specimens were conducted as cylindrical shapes with a diameter of 10 cm and a height of 20 cm. Moist-curing was applied to all samples immediately after the 24-h casting period. Some investigations were used to obtain the durability properties of the SCC incorporating ground bottom ash as SCM, including compressive strength, porosity, water absorptions, permeability, and rapid chloride penetration test. The concrete compression, permeability, and rapid chloride penetration tests were applied according to ASTM C39, ASTM D5408, and ASTM C1202, respectively. At the same time, porosity and water absorption tests were conducted based on ASTM C642. Compressive strength is related to concrete mechanical properties. At the same time, the physical properties of concrete would be indicated by porosity, water absorptions, permeability, and rapid chloride penetration test. All physical properties were related to the mechanical properties of mixtures.

Results and discussion

Compressive strength

Compressive tests were observed at the 7-day and 28-day age of concrete specimens. These tests were related to concrete mechanical properties. This test aims to obtain the strength development between 7 and 28 days of samples. The results are listed in Table 3.

The test results show that the compressive strength for normal mixtures BA0 is 41 MPa for 7-day age and 53.84 MPa for 28-day age, with 31% strength development. BA10, BA20, and BA50 have compressive strength below the normal mixture of BA0 at 7-day age. BA50 has the

Table 3 Compressive strength results

Sample code	Compressive strength (MPa)		Percentage of strength development
	7 days	28 days	
BA0	41.00 ± 1.31	53.84 ± 1.59	31%
BA10	28.27 ± 0.07	44.72 ± 0.71	58%
BA20	38.23 ± 2.41	46.97 ± 0.75	23%
BA30	41.97 ± 1.89	55.34 ± 1.42	32%
BA50	19.74 ± 0.18	31.36 ± 0.18	59%

Table 2 Mix proportions

No	Materials	Materials requirement per m^3 (kg)				
		BA0	BA10	BA20	BA30	BA50
1	Cement	550	495	440	330	275
2	Bottom ash	0.00	55.12	110	165	275
3	HRWR	8.14	8.14	8.14	8.14	8.14
4	Water	138	138	138	138	138
5	Fine aggregate	952	9512	952	952	952
6	Coarse aggregate	822	822	822	822	822

lowest 7-day compressive strength of 19.74 MPa, followed by BA10 and BA20, at 28.27 MPa and 38.23 MPa, respectively. At the same time, BA30 has a higher strength than the compressive strength of the BA0. This shows that BA30 produces a chemical reaction that can increase compressive strength at an early age, with values close to the compressive strength of normal mixtures. Adding ground bottom ash in other mixtures can be considered slower in increasing compressive strength at an early age.

At 28 days, there is an increase in compressive strength compared to the results at 7 days. BA0 has a compressive strength of 53.84 MPa, while BA10, BA20, and BA50 still have the same trend as the previous result at 7 days old, with compressive strength rising to 44.72 MPa, 46.97 MPa, and 31.36 MPa, respectively. BA50 remains the mixture with the lowest compressive strength at 28 days when viewed from the overall data. The same trend also occurs in BA30, which still has compressive strength values at 28 days, higher than the normal mixture of BA0. Observations at 7 and 28 days showed that increased compressive strength occurred in the entire mix of specimens, but only BA30 had compressive strength the same as the normal mixture BA0. The graphic of strength development is delivered in Fig. 2.

Generally, Fig. 2 describes strength development, which happens to the specimens at all variations along their ages. BA50 has the highest strength development, followed by BA10, BA30, BA0, and BA20. B10 and BA 50 had above 50% strength development, but the compressive strength was under the BA30 all. BA20 has 23%, the middle result for strength development, but the compressive strength is still higher than BA10 and BA50 at all observation times. In the data above, the percentage of increasing compressive strength conducted from 7 to 28 days shows that BA50 and BA10 have significant increases of 59% and 58%. BA20 has a rise in compressive strength percentage of 23% lower than BA0.

Meanwhile, the percentage increase owned by BA30 is similar to the normal mixture of BA0, which is 32%. A considerable percentage increase in BA10 and BA50 indicates that the use of ground bottom ash as SCM with an amount of 10% and 50% of the weight of cement can cause a significant increase in compressive strength from 7 to 28 days. However, the strength value is still below the normal mixture of BA0. The 32% increase that occurs in BA30 mixtures similar to BA0 shows that the use of 30% bottom ash as SCM can be an alternative solution to reduce the use of OPC as a pozzolan material in concrete but with better compressive strength results than normal concrete mixtures with the same age in SCC mixtures.

The statistical approach was used to find the correlation between variation of cement substitutions by bottom ash (BA) and compressive strength. The analysis uses a polynomial regression approach to capture potential non-linear relationship between both of them. The polynomial regression model for this relation is expressed as

$$\begin{aligned} \textit{Compressive Strength} = {} & -0.0036\,BA^3 + 0.2018\,BA^2 \\ & - 2.8025\,BA + 54.318. \end{aligned}$$

As the result, the correlation between porosity and compressive stress can be addressed as Fig. 3.

The R-squared value obtained from analysis is 0.9568, which indicates that approximately 95.68% of the variability in compressive strength can be explained by the polynomial equation, suggesting a reasonably good fit. The quadratic coefficient implies the effect of BA on compressive strength and accommodate the non-linearity relationship between both of them.

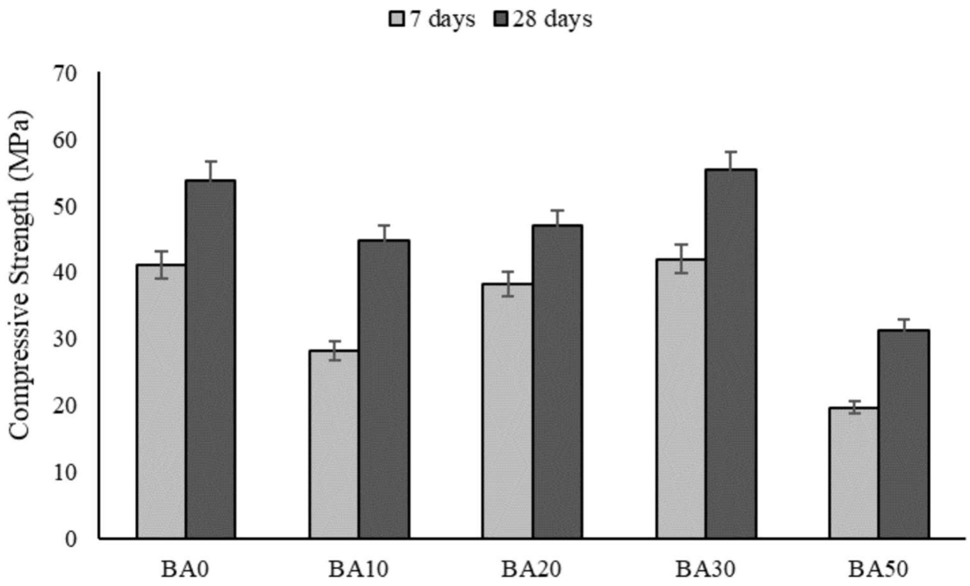


Fig. 2 Strength development of mixtures

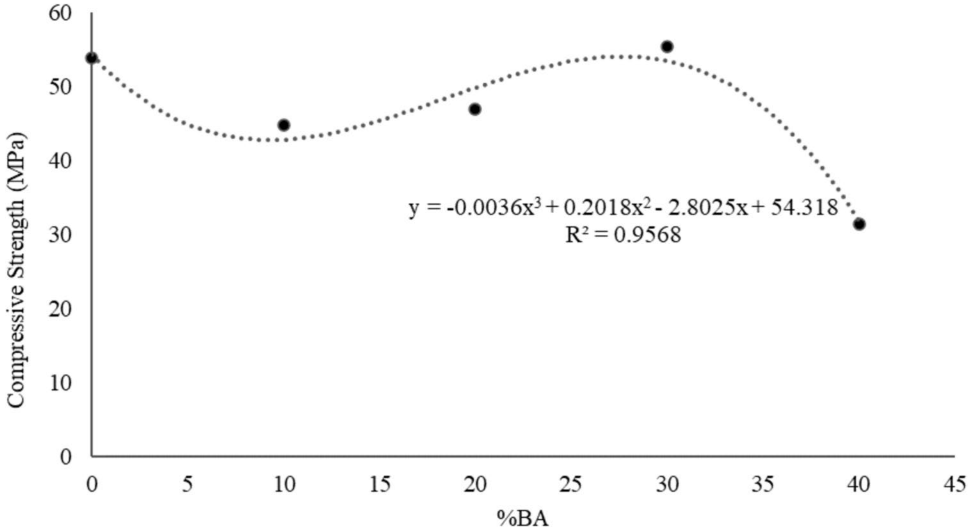


Fig. 3 Correlation between percentage of cement substitution by bottom ash and compressive strength

Porosity test

Concrete pores between 1 nm and 1 mm that were filled with air or water were defined as porosity. Pores were formed along the hydration phase as gas bubbles between the solid crystals. Porosity has two categories, namely closed porosity and open porosity. In this study, the porosity referred to is the total porosity without comparing the amount of closed and open porosity. In previous studies, the resulting porosity category can affect the durability of the concrete produced [30–32]. More closed porosity can help increase compressive strength rather than open porosity. Open porosity will affect the compressive strength of the test object. The shape of porosity can be influenced by the character of the raw materials in a concrete mixture. The interfacial zone is denser, and the microstructure is more uniform than that of normal concrete, which is the characteristics of SCC [33]. The results of the porosity test at 28 days of concrete are delivered in Fig. 4.

Generally, Fig. 4 shows the porosity was under 15% for all mixtures. Previous research concluded that the SCC formed the porosity in ranges from 8 to 15% [34]. The porosity of SCC is related to the increasing amount of ground bottom ash. The silica on the bottom ash reacts with CH and produces calcium silicate hydrate (C–S–H gel) as a result [35]. The amount of C–S–H will improve the concrete microstructure, concrete strength, chloride ion diffusion, permeability, porosity, and resistance to freezing and thawing [10, 32, 36, 37]. According to the data, normal mixtures of BA0 have 8.49% porosity. BA30 has the lowest porosity, and BA50 has the opposite result. The high amount of porosity was influenced by the significant volume of additional ground bottom ash, and it would be associated with the precipitation of additional calcium–silicate–hydrate (C-S-H) gel and calcium–aluminum–silicate–hydrate (C–S–A–H) bonds [38]. Increasing the porosity of concrete when incorporating 50% of bottom ash can also happen due to the high carbon content of the material. Bottom ash contains residual carbonaceous

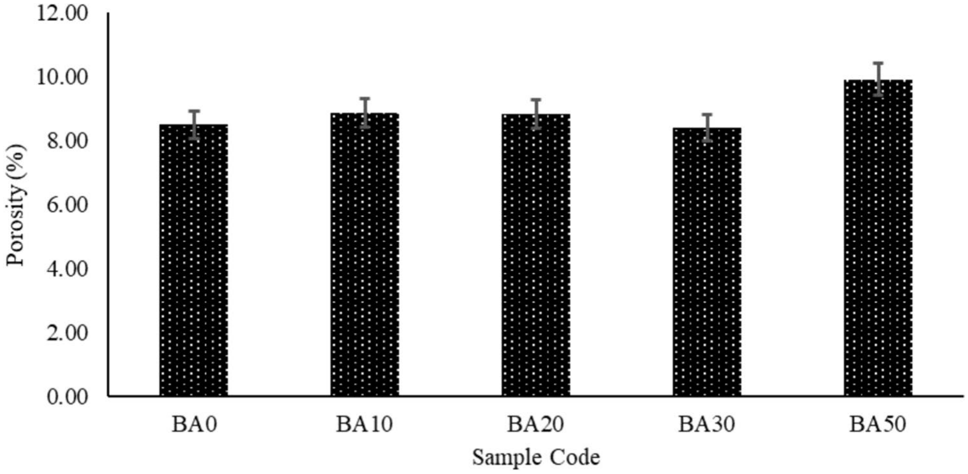


Fig. 4 Porosity of mixtures

material when it is taken from the coal combustion process. This increased carbon content leads to void and air pockets forming, which can contribute to higher porosity.

The statistical approach was used to find the correlation between porosity and compressive strength. The analysis uses a polynomial regression approach to capture potential non-linear relationship between both of them. The polynomial regression model for this relation is expressed as

$$Porosity = 0.0013\,Compressive\,Strength^2 - 0.1707Compressive\,Strength + 14.035.$$

As the result, the correlation between porosity and compressive stress can be addressed as Fig. 5.

The R-squared value obtained from analysis is 0.9973, which indicates that approximately 99.73% of the variability in porosity can be explained by the polynomial equation, suggesting a reasonably good fit. The quadratic coefficient implies the effect of compressive strength on porosity and accommodate the non-linearity relationship between both of them.

Water absorption test

Water absorption tests were obtained at 28-day age of mixtures, which coincided with porosity test. These test results are shown in Fig. 6.

The test results relate to previous research that the water absorption of concrete does not exceed 10% [38]. According to the results above, BA0 has 4.14% water absorptions as a normal mixture. While water absorption for BA10, BA20, BA30, and BA50, is 4.53%, 4.43%, 4.22%, and 5.44%, respectively. From the data mentioned above, the mixture using ground bottom ash as SCM increases the overall water

Fig. 5 Correlation between porosity and compressive strength

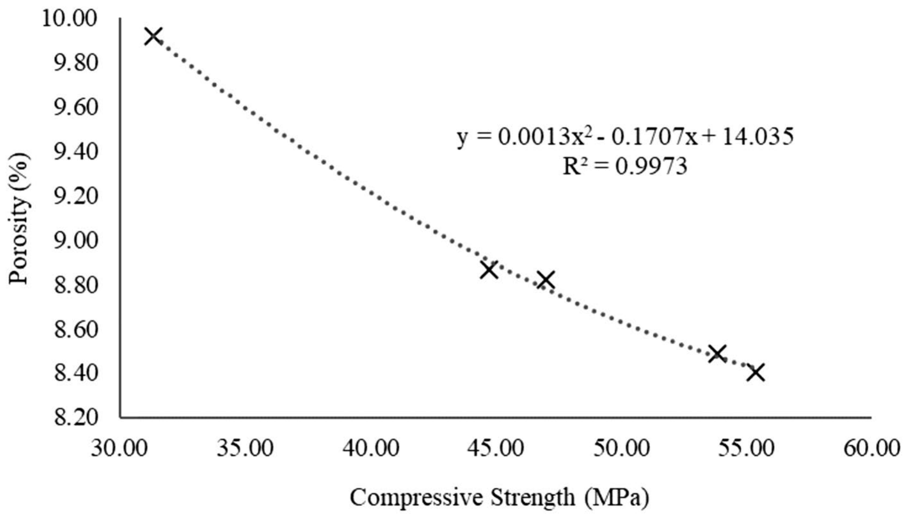
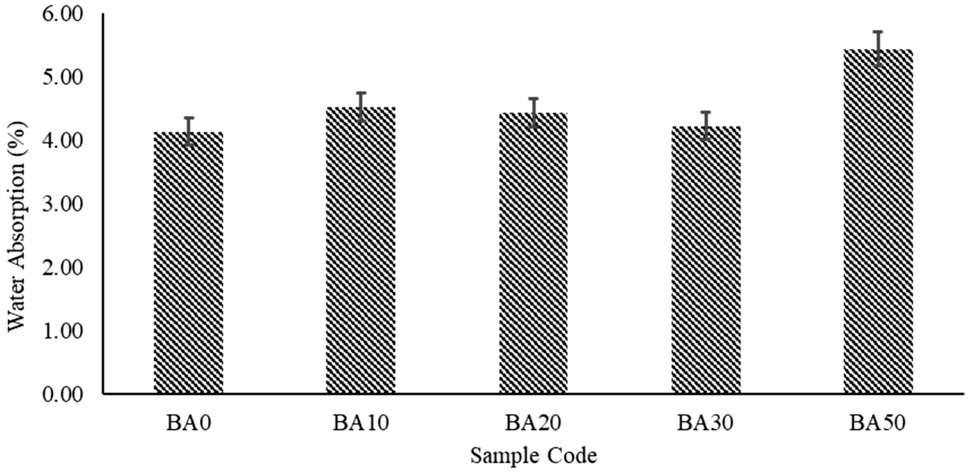


Fig. 6 Water absorption of concrete



absorption ability of SCC. 50% replacement of OPC with ground bottom ash increases the water absorption ability of concrete mortar by 1.30% compared to normal mixture BA0. The same increase occurred in BA10, BA20, and BA30, namely by 0.39%, 0.29%, and 0.08%, respectively. BA30 is the least mixture with increased water absorption ability compared to the normal mixture BA0.

Ground bottom ash as a fine particle inside the concrete mixture reduces the concrete's total porosity and capillary pores and produces a denser structure than normal concrete [31]. The rising water absorption was caused by the rising porous concrete resulting from the high volume of ground bottom ash. Thus, water quickly spreads through the porous structure [32, 39, 40]. The characteristics of its raw materials can influence the ability of water absorption possessed by a concrete mixture, the size of material particles, the chemical content of the material, the chemical reactions that occur in it, and the shape of the pores produced by chemical reactions inside. The results between porosity and water absorption show that the more significant the pores generated, the more linear water absorption increases. Porosity and water absorption were measured to evaluate the moisture properties, which can affect the durability of concrete [41, 42].

Permeability test

Permeability is a parameter of concrete durability [43, 44]. As a parameter, durability and permeability are benchmarks that affect other physical parameters, such as compressive strength, porosity, water absorption, and chloride permeability.

Permeability testing was carried out on specimens that have 25 mm as minimum height. This study used the 28-day age of concrete as a permeability test specimen. Before the permeability test, the coating process was applied to the test object's side. The coating process aims to inhibit the pressurized water from passing through the concrete side pores. The concrete samples were given 5 bar water pressure for 3 days. The main concern when carrying out the permeability test is to lower the water level in the permeameter and continuously monitor whether a pressure of 5 bar does not penetrate the test object. The results of the permeability test can be seen in Table 4.

The test results show the permeability coefficient for BA0, BA10, BA20, BA30, and BA50, is 6.617×10^{-11} m/s, 6.238×10^{-11} m/s, 6.200×10^{-11} m/s, 2.079×10^{-11} m/s, and 9.452×10^{-11} m/s, respectively. The high permeability coefficient means that the concrete has many pores, and the water can pass through the pores. The result of the permeability test can be seen in Fig. 7.

Figure 7 describes that the 50% volume of ground bottom ash in BA50 produces the highest permeability, which means that there are many porous, and the liquid can pass through the porous due to high-volume fine. BA30 has the lowest permeability, which means that BA30 has a dense structure inside the mixture due to the addition of 30% ground bottom ash as the SCM. BA30 produces the filler effect, reducing the distance between the particles, increasing the solidity of concrete, and decreasing its permeability. The nature of the pozzolan indicates that the finer the pozzolan used, the permeability will decrease [43]. Otherwise, BA10 and BA20 have quite similar permeability, which is smaller than BA0s. The result means that the additional ground bottom ash affects the concrete permeability. 10%-30% additional ground bottom ash can reduce the permeability, but 50% supplementary increases the concrete permeability.

Table 4 Permeability test results

Sample code	Coefficient of permeability (m/s)
BA0	6.67×10^{-11}
BA10	6.24×10^{-11}
BA20	6.20×10^{-11}
BA30	2.08×10^{-11}
BA50	9.45×10^{-11}

Rapid chloride permeability test (RCPT)

The rapid chloride penetration test (RCPT) method aims to determine the ability of concrete to penetrate chloride with the help of electric acceleration. Based on ASTM C1202, the criteria for concrete depend on how much the load passes during the test. The specimens used in this test have a diameter of 10 cm and a height of 5 cm. The samples were coated using Sikadur 732 to prevent the passing of the NaCl and NaOH solutions that were injected with electricity through the concrete pores. The test was conducted with a voltage of 60 Volts flowing through 2 cells containing NaCl and NaOH. Figure 8 shows the specimens and schematic view for the RCPT test.

Current data are recorded every 30 min for 6 h. The charge yield through porous concrete is related to the chloride permeability of the concrete. The ability of concrete to resist the penetration of chloride ions is an essential parameter in determining the service life of reinforced concrete structures exposed to salts or marine environments [44]. RCPT test results are listed in Table 5.

Charge passed (Qs) obtained at BA0, BA10, BA20, BA30, and BA50, are 3023.19 C, 2298.75 C, 1104.66 C, 916.22 C, and 1393.82 C, respectively. BA0 and BA10 have moderate chloride permeability values according to ASTM C1202 requirements. BA30 is categorized as having very low chloride permeability. BA20 and BA50 are classified as having low chloride permeability. RCPT has a linear

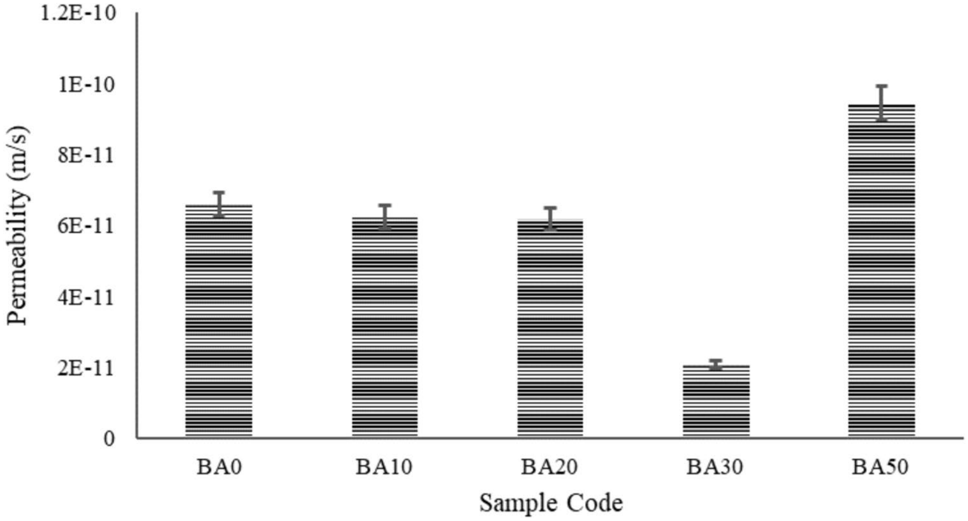


Fig. 7 Permeability of concrete

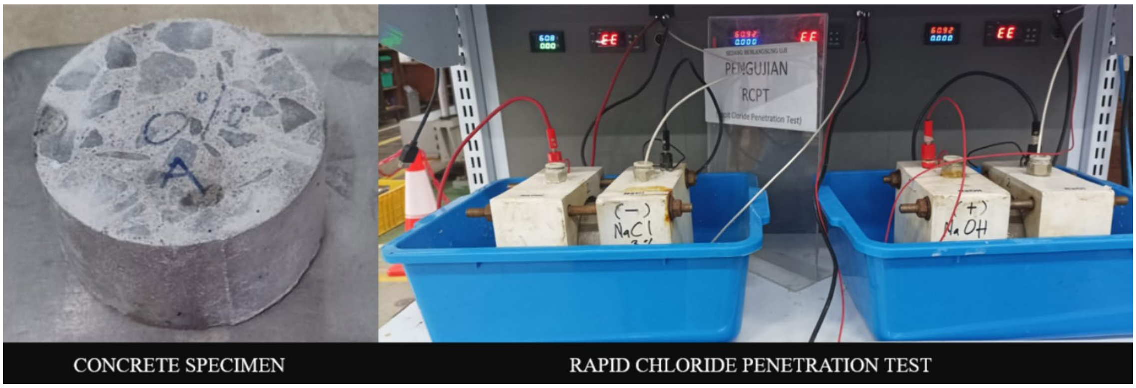


Fig. 8 Specimen and rapid chloride penetration test

Table 5 RCPT results

Sample code	Charge passed Qs (Coulomb)	Notes
BA0	3023.19	Moderate
BA10	2298.75	Moderate
BA20	1104.66	Low
BA30	916.22	Very low
BA50	1393.82	Low

correlation between passing loads and temperature increases [45]. The 28-day age specimens at all variations show that the ground bottom ash affects the chloride permeability.

Figure 9 shows that the concrete incorporated with ground bottom ash as a supplementary cement material has a lower charge passed than the normal mixture of SCC. These results were supported by previous research, namely High-Volume Fly Ash (HVFA) concrete with 50% substitution has a charged passed of 874 C, which is less than normal concrete (4660 Coulomb) [46]. Using SCM materials and strict moist-curing will significantly reduce the chloride permeability of concrete, especially at the 28-day age of concretes [47]. The low chloride permeability in SCM materials happened due to the minor porosity or capillary permeability, because the material reacts slowly with incoming chloride [48].

The result of porosity, water absorptions, permeability, and compressive strength have a relation to each other. The finer particle size of bottom ash used in this study as SCMs for SCC with various replacement percentages. The concrete specimens were observed until 28 days of age, and the results show that the particle size affects the durability performance of SCC. The results represent the increase of compressive strength, decrease of porosity, and decrease in water and chloride permeability as the effect of additional ground bottom ash as SCMs in SCC until 30% cement replacement. However, the novel result found that above 30% of cement replacement with ground bottom ash brings out the opposite effect. Porosity was increased, water and chloride

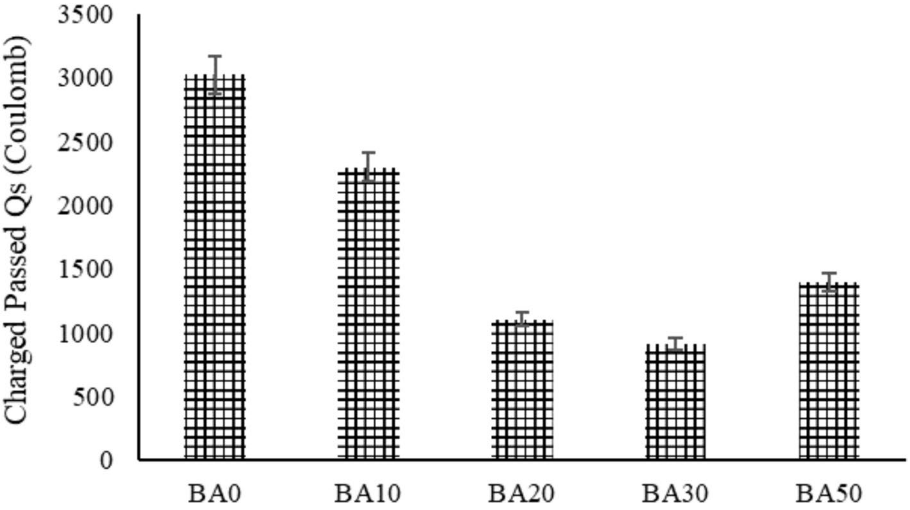


Fig. 9 RCPT results

permeability were decreased, and it affected the decreasing of compressive strength. The high amount of ground bottom ash as finer particle SCMs detruded the durability performance of SCC. The 28 days of observation of the concrete specimens to obtain the durability performance was too early to conclude, and it was in tune with the previous research. This research delivered that the concrete with SCMs needs more than 28 days to generate the compact concrete structure, and it was related to chemical reactions inside the mixtures [49–51]. Bottom ash–cement binder mixtures have a CSH with a lower Ca/Si ratio than those of fly ash–cement pastes, and they started to active from 28 days age forward along the curing period. However, the result of this study can be the prior data for the following research to observe the development of the durability performance of concrete along the various maturity periods. The results of the tests that were carried out show that the use of BA30 significantly influences the mechanical performance of concrete. Apart from that, reducing the use of cement also affects the total cost of materials needed in concrete production. Replacing cement with bottom ash by 30% can save $8,356 for every 1 m3 of concrete, equivalent to a cost savings of 7.8% to meet total material cost requirements, with better quality than normal concrete.

Conclusions

Using ground bottom ash with finer particles than bottom ash as supplementary cement materials influence the durability of SCC, including compressive strength, porosity, water absorptions, and chloride permeability. The compressive strength of BA30 increased by 32% and showed values that were close to BA0. Compared to the BA0, all the mixtures of BA10, BA20, BA30, and BA50 increased the water absorptions by 0.39%, 0.29%, 0.08%, and 1.30%, respectively. Adding bottom ash of 10%, 20%, and 50% tends to reduce the porosity values by 4.36%, 3.89%, and 16.84%, respectively, compared to BA0. Only BA30 can reduce the porosity by 1.06% compared to BA0. The highest permeability coefficient is owned by BA50 followed by BA0, BA10, BA20, and BA30, respectively, at 9.452×10^{-11} m/s, 6.617×10^{-11} m/s, 6.238×10^{-11} m/s, 6.200×10^{-11} m/s, and 2.079×10^{-11} m/s. From the RCPT test, the Charge Passed (Qs) values for BA0, BA10, BA20, BA30, and BA50 were found to be 3023.19 C, 2298.75 C, 1104.66 C, 916.22 C, and 1393.82 C. BA30 gave the smallest Charge passed values even when compared with BA0. A 30% cement replacement using ground bottom ash has an optimum compressive strength, porosity, water permeability, and chloride permeability compared to normal mixtures of SCC and other cement replacement percentages in this study. Bottom ash has potential advantages as an SCM for concrete materials.

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