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Performances of concrete containing coal bottom ash with different fineness as a supplementary cementitious material exposed to seawater

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ABSTRACT

Concrete structures are seriously deteriorated under marine environment because marine water is aggressive in nature; it contains salts of sulphate and chloride and others. These salts deteriorate the plain and reinforced concrete structures. However, most of previous research was investigated on concrete performances exposed to single solution, such as sulphate or chloride attack, even though the actual conditions are the combination of both. Therefore, the object of this study is to evaluate the performances of concrete containing coal bottom ash (CBA) with different fineness as a supplementary cementitious material (SCM) exposed to seawater. This study considered 10% ground CBA as a SCM in concrete. The original CBA was ground in a ball mill for 20 and 30 h, to get different particle fineness. Initially all specimens were cured in normal water for 28 days as to achieve targeted strength and then half of the specimens were shifted into seawater for further 28, 56, 90 and 180 days and other specimens were kept in normal water. The particle fineness of CBA influence on the concrete performances was assessed in terms weight variations, compressive strength and chloride permeability. Experimental results demonstrated that concrete strength with CBA of fineness 3836 cm^2/g (type-A) delivers around 11.9% and 8.5% higher than control mix in water and seawater respectively at 180 days. Subsequently, concrete strength with CBA fineness of 3895 cm^2/g (type-B) brings about 12.7% and 5.8% greater than control mix in water and seawater respectively at 180 days. However, it was also detected that concrete with CBA-type-A and CBA-type-B exhibits around 45.4% and 42.4% reduction in chloride penetration as compared to control mix at 180 days. Hence, it was concluded the strength performances of CBA-type-B is superior than the control mix at 28 days. However, CBA-type-A gives the better performances at later ages of 90 and 180 days. Hence, CBA-type-A is suggested for the future studies, based on strength performances and resistance to chloride penetration. This study encourages the use of ground CBA in concrete as SCM in normal as well as in marine environment.

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1. Introduction

Seawater is typically containing high level of salts concentration with major portion of sodium, chloride, and sulphate. It is aggressive in nature for concrete, due to the presence of $MgSO_4$, $MgCl_2$, NaCl, and other dissolved salts [1]. Therefore, the performances of concrete structures exposed to the seawater have been given serious attention for a long-time. However, most of previous research was conducted on the deterioration of concrete under single solution of sodium sulphate [2–5] or sodium chloride [6,7] even though the actual conditions are the combination of both and others. Therefore, this study considered concrete performances exposed to seawater, this approach could consent more realistic evaluation of concrete containing CBA as cementitious material under aggressive environment. Since long, concrete under seawater exposure is a subject of interest and most of previous research was carried out on the concrete structures underwater, structures in tidal zone or in environments closer to the sea [8–10]. According to the reported of Suprenant [11] concrete structures exposed to seawater could deteriorate much faster because of combined actions of physical and chemical processes, i.e. Sulphate attack, leaching of lime, alkali-aggregate growth, salt crystallization

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through wetting and drying cycle, freezing-thawing, reinforcement corrosion, erosion and abrasion from waves [11]. These effects could be decelerated by reducing penetrability because lower penetrability retains the aggressive salts out of the concrete, slows leaching of soluble materials such as lime, and limits the depth of carbonation, better corrosion protection. Recently, construction sector intended to resolve the problems associated with concrete in seawater through two steps; one is the addition of supplementary cementitious materials, which is more important according to the durability point of view, and second is; to improve design standards for deterioration resistance and life of concrete [12]. It was generally observed that seawater is highly concentrated with salts, almost 3.5% of salts, which means that every kilogram (one liter by volume) of seawater has approximately 35 g of dissolved salts, these salts are predominantly contains chloride and sodium. Subsequently, it was noticed from pie-chart as shown in Fig. 1, the significance amount of chloride, sodium and sulphates salts concentration present in seawater [13].

Therefore, the concrete structures erected in the seawater environment need to be monitored for its performances. Considering the significance of seawater effects on the concrete structures, research work has long been known on this issue. Following studies were conducted to resolve the issues associated with concrete;

Jaya et al. [14], investigated the influence of rice husk ash (RHA) on the concrete specimens, immersed in seawater for 3, 7, 28, 56, 90 and 180 days at the laboratory conditions. They found that the concrete containing 20% RHA exhibited a significant increase in compressive strength and increased resistance to seawater attack compared with normal mix concrete and concrete containing 10, 30 and 40% RHA for 56 days. However, at the age of 90 and 180 days, concrete containing 10% RHA significantly improved in strength compared with the other proportions. Whereas, the chemical characteristics of seawater particularly collected from Malacca Straits, Malaysia are provided in Table 1. Generally, Seawater pH values ranges between 7.5 and 8.4, however seawater of Malacca Straits, Malaysia were recorded pH value 7.9–8.20 [12].

Argiz et al. [15], considered fly ash and coal bottom ash as cementitious material in concrete to improve its durability aspects. They mentioned that fineness of cementitious material has great influence on the pozzolanic activity and pore filling action in the concrete and recommended 10% use of ground CBA as replacement of cement in the concrete under chloride conditions.

Khan & Ganesh [16] also suggested that ground CBA has good potentiality to replace the ordinary portland cement, but the optimum performances could be achieved at 10% replacement. However, it could also reduce the cost of construction and reduction in the carbon dioxide (CO_2) emissions produced through the manufacturing of cement.

Table 1
Characteristics of Malaysian seawater [12].

Parameter	Unit	Range
Sodium (Na^+)	ppm	2002–2402
Potassium (K^+)	ppm	375
Calcium (Ca^{2+})	ppm	285
Magnesium (Mg^{2+})	ppm	1055
Chloride (Cl^-)	ppm	16618–18020
Sulphate (SO_4^{-2})	ppm	1098
pH	ppm	7.90–8.20
Temperature	°C	26.5–32.0

Chindaprasirt et al. [17], studied the fly ash particle fineness influences on the concrete performances, they were used two type of fly ashes having sizes 19.1 and 6.4 μm with surface area 3000 and 5100 cm^2/g and declared that fly ash having 5100 cm^2/g gives the higher compressive strength and lower porosity than the coarser fly ash. It shows that the particle fineness of cementitious material has great influence to improve the performances of concrete. Therefore, current work is focused to utilize ground CBA with different fineness, which could improve the strength as well as durability performances of concrete exposed to the normal as well as in aggressive environment like seawater.

However, seawater is mainly composed of sodium, magnesium, chloride, and sulphate as shown in Table 1. Due to presence of these aggressive salts in seawater, it is being considered as dangerous for concrete structures. However, concrete attributed to the reaction of magnesium sulfate with calcium hydroxide, resulting in the formation of gypsum and magnesium hydroxide [14]. The resulting gypsum reacts with calcium hydroxide and forms ettringite. This phenomenon leads to strength development at early ages but decreases with the long-term presence in seawater. Therefore, to handle this problems, supplementary cementitious materials are introduced, those offered dual mechanisms. First, hydroxide is transformed into additional calcium silicate hydrate (C-S-H) gel; this change brings strength development of blended cement. Second advantage is reduction in the penetrability of sulphate and chloride ions, which causes the corrosion in the reinforcement.

The performance of concrete exposed to seawater is the important aspect. Most of the concrete structures exposed to seawater are partly or exclusively situated so that they are sometimes immersed in seawater and sometimes exposed to the atmosphere [18]. It was observed during the seawater collection for this study, a real example of reinforced cement concrete (RCC) column deterioration was detected as shown in Fig. 2 which displays that the concrete is more vulnerable in the seawater exposure, particularly in submerged, tidal and splash zone, it was physically observed that atmospheric zone has less chances of damage. However, foundation is the main part of the RCC structures; if it is damage then super structure could not survive. So, this study provides experi-

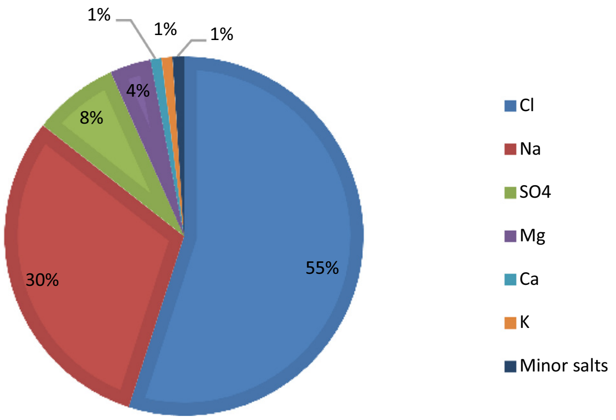

Fig. 1. Typical seawater concentration [13].

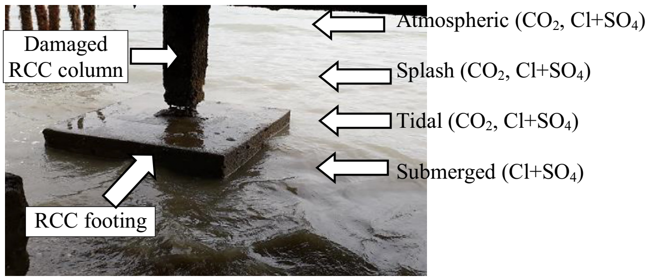

Fig. 2. Concrete erected on seashore, Batu Pahat, Malaysia.

mental outcomes on the concrete submerged into the seawater at laboratory conditions because continuous submerged conditions provide a uniformity of environment like temperature and moisture content [18].

Furthermore, the deterioration of concrete could be classified into three groups, physical, mechanical and chemical from which durability issues such as steel corrosion is initiated and developed [19] Summary of recent studies are provided in Table 2. Furthermore, it was perceived that considering the environmental concerns, the selection of sustainable construction material is stimulating aspect [20]. The selection of construction material should be such that it has high durability and adequate strength properties and it can be conceivable through utilizing industrial by-products [21]. There is a broad consent about the strength advantages of SCM in concrete over the OPC and there is an extensive debate regarding their durability performances. It was also declared in previous research [22] that there are four main problems in durability of concrete including alkali–aggregate reaction, sulfate attack, steel corrosion and freeze–thaw. Bjegovic et al. [20] recommended the use of different cementitious materials other than the cement in concrete, which leads towards durable concrete structures in aggressive environments.

The literature as mentioned in Table 2 indicated that the performances of concrete under aggressive environment are the most important issues associated with the concrete structures, which can counterfort by addition of pozzolanic material like RHA, F.A, and CBA as a supplementary cementitious material (SCM) [22]. However, the pozzolanic activity is also depends on the particle fineness of the SCM [17,23]. Therefore, in this study ground CBA is adopted as a SCM with different fineness and this study selected 10% proportion of ground CBA to replace ordinary portland cement in concrete by weight, because it was also recommend as optimum replacement level in the previous studies [16,26–28]. Hence, the objective of this study has been set forward, to evaluate concrete performances with ground CBA as a SCM exposed to seawater.

Table 2
Issues associated with concrete performances and solutions proposed by researchers.

Ref.	Issues	Recommendations
[12]	Strength and durability of concrete exposed to high sulfate environment	20% fly ash as a cement replacement material provides the good strength and durability.
[14]	Performances of concrete under aggressive seawater environment.	Concrete with 10% and 20% RHA shows excellent durability performances in seawater.
[18]	Concrete under seawater exposure	Pozzolanic materials
[19]	Durability and Sustainability	Utilization of more industrial waste
[21]	Strength and durability performance to develop eco-friendly concrete	coal bottom ash (CBA) and blast furnace slag (BFS) with different fineness to enhancing performances of concrete
[20]	Chloride penetration and corrosion of reinforcement	Use of blended cement
[22]	1) Durability issues; alkali aggregate reaction, sulfate attack, steel corrosion and freeze–thaw; 2) Durability of concrete in seawater 3) coupling effects of mechanical load and environmental factors on concrete	Use cost-effective pozzolanic materials
[23]	Concrete strength and penetrability	Different fineness of RHA could improves the engineering properties of concrete
[24]	Chloride penetration and corrosion of reinforcement	Fly ash and w/b ratio greatly influences the chloride permeability in concrete; higher fly ash and lower w/b ratios produced well chloride resistance concrete under a marine environment
[25]	Concrete structures erected in the coastal areas suffering from durability problems	The performances of concrete could be influenced by type of cement, W/C ratio and quantity of cement, proposed slag cement.
[26]	Concrete under sulphate and chloride	Use of 10% ground CBA in concrete was recommended as cementitious material to reduce the sulphate and chloride affects.

2. Experimental setup

2.1. Ingredients

Ordinary portland cement (OPC) was used as a main binding ingredient, which meets the MS 522 and BS EN 196-1 [29]. The coal bottom ash (CBA) was transported from Kapar Energy Ventures power plant, Selangor, Malaysia. The original CBA is coarser in size as shown in Fig. 3. The collected CBA was first dried in oven at a temperature of 110 ± 5 °C for 24 h, at first stage Los Angeles machine was used to grind original CBA for 2 h. Furthermore, CBA passed through 300-μm sieve was placed into secondary grinder (ball mill) for 20 and 30 h which produced powdered CBA as shown in Fig. 4, as comparable to the OPC. The particle fineness of CBA type-A, CBA type-B and OPC fineness is provided in Fig. 5, which indicated that both type of CBA have almost similar particle fineness and comparable to the fineness of OPC. The chemical characteristics of CBA as presented in Table 3 shows that it mainly composed of SiO_2, Al_2O_3 and Fe_2O_3. It's collective proportion is more than 70%, and CBA categorized as Class-F ash as described in ASTM C618 [30]. The details about CBA and OPC characteristics are listed in Tables 3 and 4.

2.2. Proportioning of concrete mixes

In this study three types of mixes were prepared; one is the control mix without coal bottom ash (CBA), second mix containing 10% CBA of type A (M1) and third mix were prepared with 10% CBA

Fig. 3. Original CBA.

Fig. 4. Ground CBA.

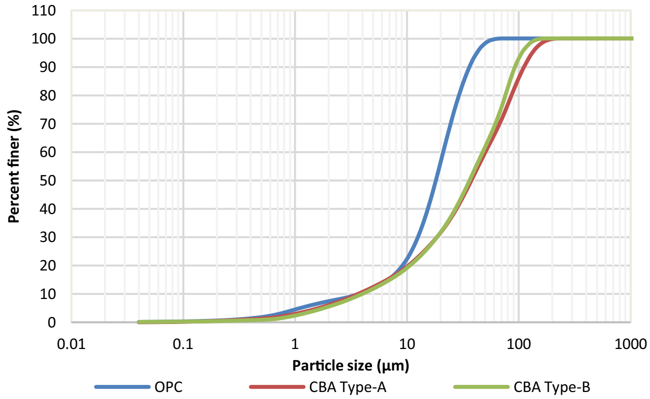

Fig. 5. Particle fineness of ground CBA compared with OPC.

Table 3
Chemical characteristics of CBA and OPC.

Properties	CBA	Class F ash Prerequisite as per ASTM C618 [30]	OPC
SiO_2	52.50	70% (min) $SiO_2 + Al_2O_3 + Fe_2O_3$	20.61
Al_2O_3	17.65		3.95
Fe_2O_3	8.30		3.46
CaO	4.72	–	63.95
MgO	0.58	–	1.93
SO_3	0.84	5% (max)	3.62
TiO_2	2.17	–	0.20
Loss on ignition	4.01	6% (max)	2.18

of type B. The detail of concrete mix proportions is provided in Table 5. The fine aggregates passing from sieve size of 4.75 mm and 10 mm size of coarse aggregate was used. The amount of ingredients was selected based on ACI concrete mix design.

2.3. Collection of seawater

In this study, the seawater was collected from Pantai Minyak Beku, Batu Pahat, situated in the straits of Malacca, Malaysia and just 31 km from UTHM. After collection of seawater, it was placed in to plastic tanks at the laboratory conditions, similar method was also previously adopted by Jaya et al. [14]. Beside that 3 representative samples were taken for the evaluation of salts concentration and test results of seawater are provided in Table 6. Due to stagnant position of seawater in the tank, major changes in pH value and salt concentration were observed, due to that seawater was replaced in the tank on monthly basis.

2.4. Specimens preparation

This study involved 100 mm size cubes for the concrete casting. Over-all 90 samples were prepared, 18 cylinders for rapid chloride permeability test (RCPT) and 72 concrete cubes for compressive strength test performances.

After de-moulding all specimens were cured in water for 28 days as to attain designed compressive strength, then 36 specimens were shifted in seawater at laboratory conditions, rest of specimens were kept in normal water. Moreover, 18 cylindrical specimens of size 100 mm in diameter and 200 mm in length were cast to evaluate RCPT at 28 and 180 days. The list of specimens for the study is provided in Table 7.

2.5. Testing procedure

The weight of all specimens was recoded at the time of shifting from normal water to the seawater as to compare the variation in weight at 28, 56, 90 and 180 days. Concrete cubes were evaluated for compressive strength at the exposure period of 28, 56, 90 and 180 days as per BS EN 12390-3 [31]. At the designated age of testing, specimens were takeout from water and seawater and kept for a while to get surface dry positions and weight was recorded and well saturated specimens were further proceed for the compressive strength test under the compression machine having a loading capacity of 3000 kN. A constant loading rate 7 kN/s is applied till the specimen fails.

After the compressive strength test, representative samples from the crushed specimen were collected for the scanning electron microscopy (SEM) investigations at the age of 56 days, as to understand the inside behavior concrete with and without ground CBA and the influence of seawater on the performances of concrete.

Moreover, rapid chloride permeability test (RCPT) considered concrete cylinders 100 mm (diameter) and 200 mm (length). These cylinders were cut at 50 mm from each end. These core pieces were saturated in water for 18 ± 2 h until fully saturated and then allowed to surface dry in air for 1 h. Then suitable epoxy (silicon) was placed and complete coating of all surfaces was ensured. One side contained 3.0% NaCl solution and other side 0.3 M NaOH solution. The current in ampere-second was noted at every 30-min up-to 6 h, the detail about experimental arrangements is provided in Fig. 6. According to the charge passed, concrete permeability rating was evaluated with reference to ASTM C1202 [32] standard.

3. Results and discussion

3.1. Fresh mix properties of concrete

One of the important fresh mix property of concrete is the workability, which was evaluated as per ASTM C143 [33]. The workability results for control mix without CBA (M1), concrete with 10% CBA of type-A (M2) and concrete containing 10% CBA of type-B (M3) are provided in Table 8. The outcome of the test shows that workability decreases as the CBA added in the concrete. The decrease in workability indicated that CBA absorbed more water

Table 4
Physical characteristics OPC and CBA.

Properties		OPC	CBA-Type-A	CBA-Type-B
Grinding period		Original	20 h	30 h
Specific surface area (cm^2/g)		4871	3836	3895
60% Particle Size Range (μm)		21.15	50.45	47.78
Specific gravity		3.10	2.41	2.44
Cement paste		OPC	10% CBA-Type-A + 90% OPC	10% CBA-Type-B + 90% OPC
Standard consistency water requirement (%)		30	32	32.5
Setting time (Min)	Initial	90	110	105
	Final	270	280	280

Table 5
Concrete mix proportions (kg/m^3).

Materials	Control Mix (M1)	Concrete with CBA-Type-A (M2)	Concrete with CBA-Type-B (M3)
Cement (kg/m^3)	440	396	396
CBA (%)	0	10	10
Fine aggregates (kg/m^3)	805	805	805
Coarse aggregates (kg/m^3)	828	828	828
Water (kg/m^3)	220	220	220
Water to binder ratio	0.5	0.5	0.5

in the mixture, resulting in the drop of workability. it was also agreed by Khan & Ganesh [16]. Subsequently, variation in fresh mix density of concrete was also noticed, density decreases as the amount of CBA added in the concrete mix. It was also previously declared that the addition of palm oil biomass clinker as a sand replacement reduces the concrete workability due to porous nature of particles which absorbed more water [34]. It was observed that the fineness of CBA particles also influences the workability and fresh mix density of concrete. More fineness gives higher reduction in workability because more the fineness higher the surface area which absorbed more available moisture in the mixture [35].

3.2. Weight variations

Concrete specimens' weight was measured before and after seawater exposure. The weight variation for control mix (M1), concrete with 10% CBA of type-A (M2) and concrete with 10% CBA of type-B (M3) were recorded at the exposure period of 28, 56, 90 and 180 days and results are presented in Fig. 7. Weight variation of specimens was calculated with reference to the initial weight of specimens before the seawater exposure.

Results show that concrete with or without CBA has significant influence on the weight variations, noticeable weight variations were recorded in concrete without CBA. The maximum weight was noticed in M1 at the exposure of 28 days and at the same conditions lesser weight gain was noticed in M2 and M3. It is demonstrated that concrete containing ground CBA decreases the salts permeability. These outcomes also agreed by Xu et al. [36], they were found that concrete specimens gain its weight when exposed to sulphate conditions. It shows that formation of more hydration products like ettringite and gypsum resulting in weight growth. Similarly, seawater is rich in the sulphate, therefore, more formation of hydrations products expected in the control mix. However, the addition of pozzolanic materials like CBA in concrete could decrease the permeability of salts because finer particles of CBA could fill up the free pores inside the concrete [23,37]. This showed that in CBA presence, condenses the process of hydration and decreases the salts penetrability in concrete; this advantage of CBA reduces the salts intrusion which is the potential cause of corrosion in reinforcement and failure of concrete structures. Hence, in general the ground CBA utilization in concrete could improves the resistance against aggressive environment like marine environment.

3.3. Compressive strength performances

The compressive strength test results for control mix concrete (M1), concrete containing 10% CBA-type-A (M2) and concrete containing 10% CBA-type-B (M3) exposed to normal water and seawater is provided along with standard deviation values in Fig. 8, outcomes shows that at early 28 days, M3 and M2 performed well as compared to M1 in normal as well as in seawater. The compressive strength of M1 concrete were recorded as 46.8, 50.8, 52.1 and 53.6 MPa, M2 gives 43.8, 53.2, 58.0 and 60.0 MPa and M3 gives 48.9, 52.6, 58.8 and 60.4 MPa at the age of 28, 56, 90 and 180 days

Table 6
Seawater characteristics, Pantai Minyak Beku, Batu Pahat Malaysia.

Month of collection	pH value	Salinity (NaCl) (mg/l)	Electric conductivity (millisiemens/cm)	Temperature (°C)
May-2018	8.50	26,900	44.4	28.3
	8.52	26,700	44.6	28.4
	8.51	26,500	44.6	28.3
June-2018	8.44	24,700	36.4	24.4
	8.46	24,800	36.3	24.3
	8.45	24,800	36.4	24.4
July-2018	9.13	26,400	44.5	24.0
	9.14	26,240	44.3	24.4
	9.18	26,350	44.4	24.1
August-2018	9.46	22,600	38.3	26.7
	9.44	22,500	38.3	26.6
	9.42	22,600	38.4	26.6
Sept-2018	9.13	27,460	43.5	25.1
	9.14	27,380	43.2	25.4
	9.18	27,450	43.4	25.2

Table 7
Specimens prepared for the study.

Specimen detail	Notation	Exposure period (days)	Exposure conditions		Samples for RCPT Test
			Water	Seawater	Water
Control Mix without CBA	M1	28	3	3	3
		56	3	3	–
		90	3	3	–
		180	3	3	3
Concrete with 10% CBA-Type A	M2	28	3	3	3
		56	3	3	–
		90	3	3	–
		180	3	3	3
Concrete with 10% CBA-Type B	M3	28	3	3	3
		56	3	3	–
		90	3	3	–
		180	3	3	3
	Total prepared specimens		72 (cubes) + 18 (cylinders) = 90		

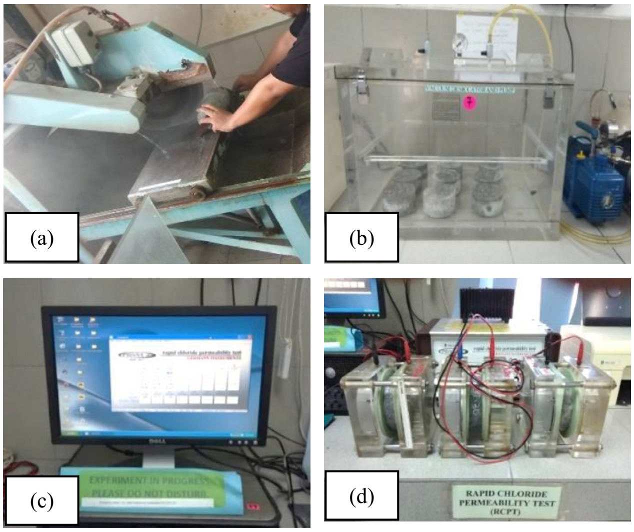

Fig. 6. RCPT apparatus arrangement (a) cutting of specimens, (b) specimens in vacuum desiccator, (c) data logger, (d) specimens under testing.

Table 8
Properties of fresh mix concrete.

Mix description	Notation	Slump (mm)	Fresh mix density (kg/m^3)
Control Mix	M1	56	2340
Concrete with CBA-Type-A	M2	50	2312
Concrete with CBA-Type-B	M3	48	2285

in normal water. Considering the maximum exposure period of 180 days, the performance of M2 and M3 is 11.9 and 12.7% higher than the M1 concrete respectively. However, M2 and M3 also give the adequate performances as related to that of M1 in seawater for early and later ages. This shows that presence CBA helps to reduce the seawater effects on the concrete. When concrete exposed to the seawater, pozzolanic reaction could be motivated, because seawater comprises chloride, sulphate and sodium, once they entered in the concrete, could activated the pozzolanic reaction [38] and resulting in the reduction of pore sizes in the concrete and ultimately gives better strength performances [38]. However, it was agreed earlier that the pozzolanic reaction spent calcium hydroxide and makes denser concrete, though seawater is rich in sulphate which cause the development of ettringite [39]. But, CBA contains lower portion of calcium oxide, it could reduce the production of ettringite. Experimentally outcomes validated that concrete with finer CBA provides the satisfactory compressive strength performances and less affected in seawater exposure at early ages. The highest compressive strength value (60.4 MPa) was recorded with concrete containing M3 exposed to seawater for 180 days, which gives almost 12.7% higher compressive strength as compared to that of M1.

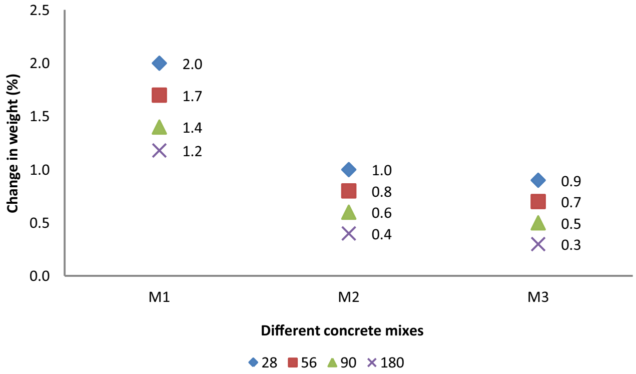

Fig. 7. Weight variation of concrete exposed to seawater.

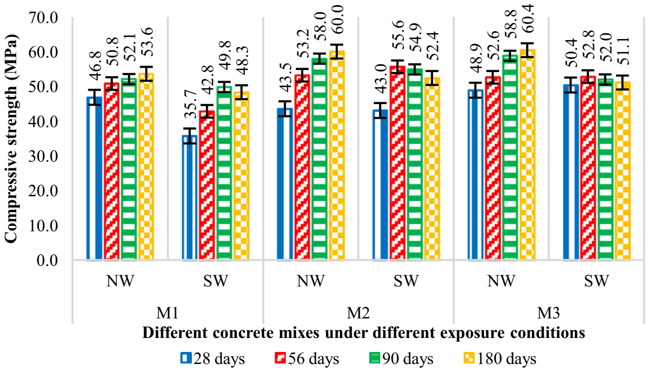

Fig. 8. Compressive strength performances of concrete with and without CBA exposed in normal water and Seawater.

3.4. Variation in compressive strength performances

The percentile variations of compressive strength were calculated through the compressive strength comparison of M2 (concrete containing CBA-Type-B) and M3 (concrete containing CBA-Type-B) with reference to the M1 concrete (control mix) at different exposure period of 28, 56 and 90 days and calculated results are presented in Fig. 9. The experimental findings revealed that concrete containing finer CBA has more resistance against the seawater and its strength is significantly higher than the control mix concrete. However, it was also noticed that fineness has slight positive influence to resist saline environmental conditions. The concrete performances in terms of compressive strength of M2 exposed to the seawater was found to be satisfactory, which gives 20.5, 30, 10.2 and 8.5% increment in compressive strength as compared to that of M1 at the exposure period of 28, 56, 90 and 180 days respectively. At 56 days high increate was observed, it indicated that numerous hydration products has been produced which make the concrete denser and resulting in the higher compressive strength. But later ages harmful hydration products like ettringite affects the concrete performances and resulting in the reduction of compressive strength. However, M3 concrete exposed to seawater also gives the 41.1, 23.4, 4.4 and 5.8% rise in compressive strength as compared to the M1 at the exposure period of 28, 56, 90 and 180 days respectively. Similar behavior was recorded with M2 concrete.

Moreover, considering the energy consumption scenario, producing more fine particles, requires more energy. It was noticed that at the early 28 days, the performances of concrete with 10% CBA-type-B are superior than the control mix and CBA-type A. However, CBA-type-A gives the better compressive strength performances at later exposure periods of 90 and 180 days. Hence, this study recommended CBA-type-A, based on compressive strength performances under seawater and energy consumption point of view.

3.5. Chloride permeability performances

The concrete chloride permeability performances were evaluated in terms of rapid chloride permeability test (RCPT) for control mix specimens (M1), concrete specimens with 10% CBA-type-A (M2) and concrete specimens containing 10% CBA-type-B at the age of 28 and 180 days. This test involves two different fineness of CBA, to assess the influence of particle fineness on the chloride resistance performances of concrete. However, based on the charge that passed through the samples, a qualitative rating was made by ASTM C1202 [32], which categorized the specimens based on the charge passed; high (>4000), moderate (2000–4000) and low (1000–2000). The test results of RCPT test for the concrete with and without CBA at the age of 28 and 180 days are provided in Fig. 10. The results demonstrated that M1, M2 and M3 are under the high-risk category at 28 days. Risk has been recovered as the curing age increased [35]. At the age of 180 days 3584 and 3780 C charge passed through the concrete containing 10% of CBA-type A and CBA-type B respectively.

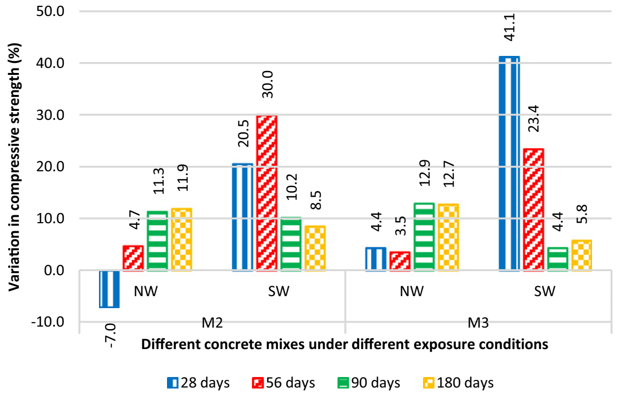

Fig. 9. Compressive strength variations in concrete containing CBA with different fineness compared to the control mix exposed in normal water and Seawater.

However, it was observed that less charge passed through concrete containing 10% ground CBA of type-A (M2) as compared to that of control specimens (M1) and concrete containing 10% ground CBA of type-B (M3). It shows that performances of CBA type-A, exhibits less charge passed through the modified concrete. It can clearly be observed from experimental results that CBA-type-A gives around 45.4% and CBA-type-B gives around 42.4% reduction in chloride penetration with reference to the control mix at the age of 180 days. Yigiter et al. [25] also confirms that the blended cements (slag cement with ordinary portland cement) could improves the resistance against chloride penetration, which is of great importance in terms of corrosion protection of steel reinforcement embedded in concrete. They used slag cement which contains 54% steel slag and particle fineness 4940 cm^2/g with a specific gravity of 2.96. However, current study involves two type pf ground CBA particle fineness around 3836 and 3895 cm^2/g, both type of fineness delivers the better resistance to chloride penetration in the concrete. It was also validated by Yang & Chiang [40] and also agreed by Singh & Siddique [41] that CBA as sand replacement in concrete could also shows the better resistance to chloride penetration and the cumulative charge passed through all concrete containing CBA was lower than control specimen at 28 days and onward.

3.6. Scanning electron microscopy analysis

The scanning electron microscopy (SEM) investigations were considered control mix and concrete with coal bottom ash (CBA) exposed to normal water and seawater at 56 days. The SEM images are provided in Figs. 11–16, SEM images clearly shows the inside behavior of OPC in presence of CBA and influence of seawater. The pozzolanic activity was observed in the CBA-concrete, reaction among calcium-hydroxide and CBA was perceived in the CSH gel shape. The C-S-H gel formation was also detected in the concrete with CBA even in seawater exposure. Based on the previous studies [26,35,42,43] it was assumed that bright matter in the images indicated the CSH gel, white crystal needles indicated the formation of ettringites, while solid matter represents Friedel's salts (calcium aluminium chloro-hydrate) and dark oxide mineral indicated portlandite (calcium hydroxide). However, abundant formation of hydrated products were observed such as ettringite, portlandite (calcium hydroxide) and CSH, beside that Friedel's salts were noticed in the concrete containing CBA under seawater exposure, because seawater presence of major amount of NaCl in the seawater [44].

Fig. 11 shows the well formation C-S-H get and no any sign of cracks which indicated that no more ettringite development in normal water conditions. Beside that Fig. 12 indicated the crack

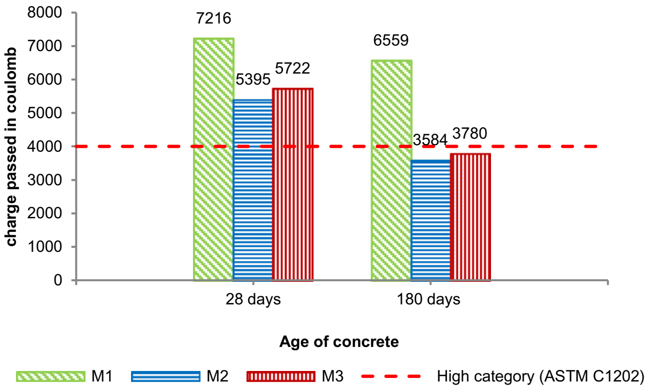

Fig. 10. RCPT performances of concrete with and without CBA.

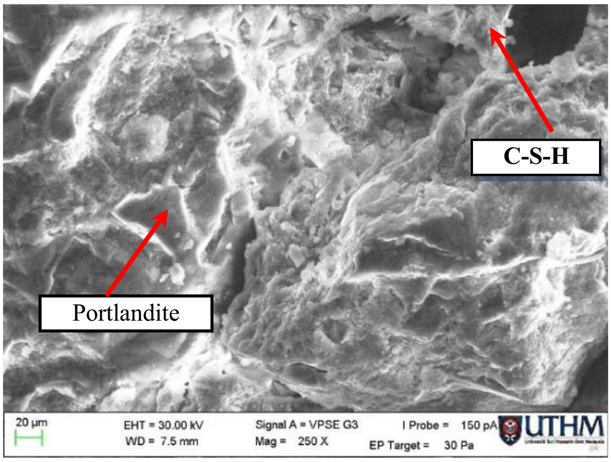

Fig. 11. Control mix concrete exposed to normal water for 56 days.

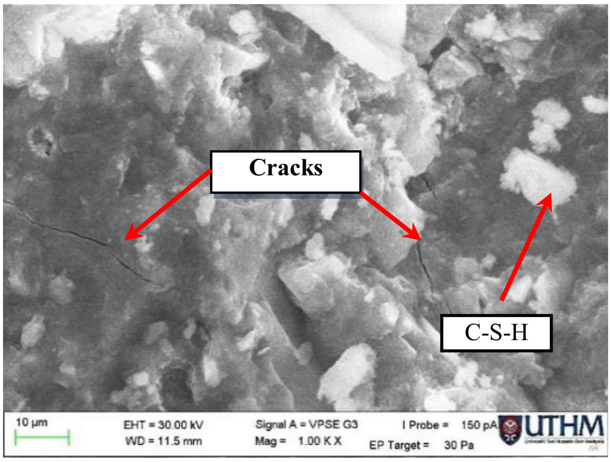

Fig. 12. Control mix concrete exposed to Seawater for 56 days.

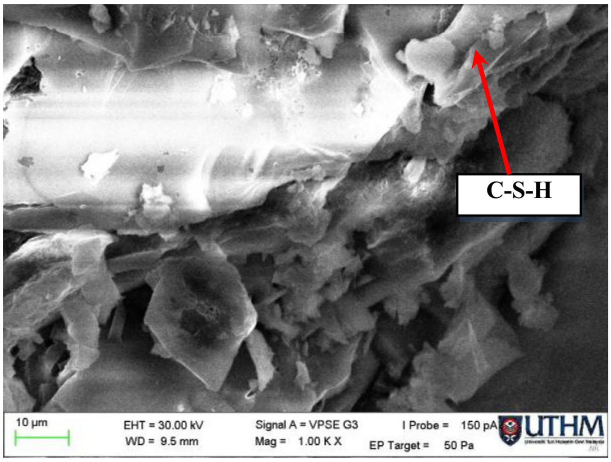

Fig. 13. Concrete containing CBA type-A exposed to normal water for 56 days.

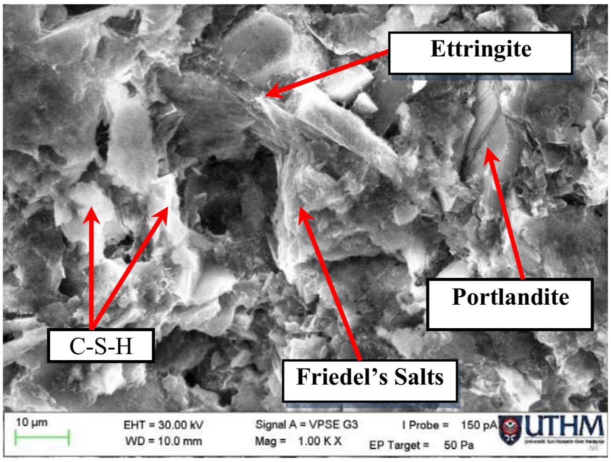

Fig. 14. Concrete containing CBA type-A exposed to Seawater for 56 days.

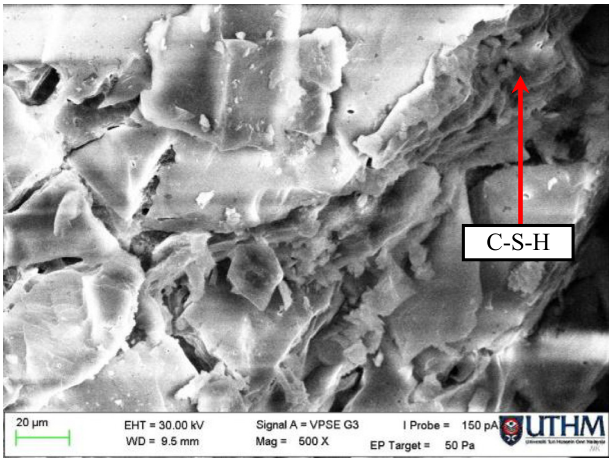

Fig. 15. Concrete containing CBA type-B exposed to normal water for 56 days.

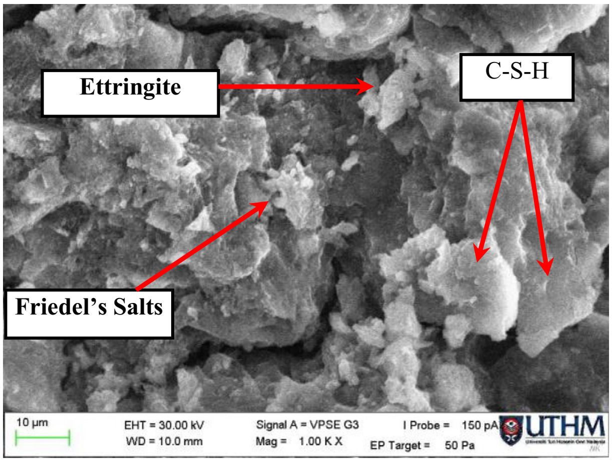

Fig. 16. Concrete containing CBA type-B exposed to Seawater for 56 days.

development in the control mix concrete (M1) due to seawater effects, which trigger the formation ettringite, cause cracks development [44]. Moreover, Figs. 13 and 14 represent the concrete containing CBA type-A and CBA type-B in normal water respectively. It shows the formation of well shape C-S-H gel and no any cracks were observed. It was observed that CBA is rich in aluminium and ordinary cement paste is rich in calcium carbonate, which creates reaction among these two compounds and form tricalcium aluminate (C_3A) and gives the adequate strength development at age 56 days. The development of ettringites (white crystal needles) formation gives the good early strength because volume of voids were occupied by the ettringites [34] but for later ages it could be harmful, cause the crack development and reduction in compressive strength. However, this kind of crack development was protected through the addition of fine particles of CBA in concrete, as Figs. 14 and 16 shows the abundant formation of hydrated products were observed such as ettringite, portlandite (calcium hydroxide) and CSH, beside that Friedel's salts were observed in sample because major amount of NaCl present in seawater.

4. Conclusions

The fineness is important aspect of supplementary cementitious materials. However, grinding period of 20 and 30 h does not produced significant variations in fineness. Less variation in fineness not greatly influences the concrete performances. Thus, considering the outcomes of the experimental study, following conclusions can be drawn;

i. It was observed that concrete containing CBA-type-A with fineness 3836 cm^2/g gives the 11.9% and 8.5% higher compressive strength in normal water and seawater at exposure period of 180 days respectively. Beside that concrete containing CBA-type-B with fineness 3895 cm^2/g gives the 12.7% and 5.8% higher compressive strength in normal water and seawater at the exposure of 180 days respectively.
ii. It was experimentally perceived that at the early 28 days, the performances of CBA-type-B is superior than the control mix and CBA-type-A, but CBA-type-A also delivers the better strength performances at later ages of 90 and 180 days. Hence, CBA-type-A is suggested, based on compressive strength performances under seawater and energy consumption point of view, because more energy is required to produce finer CBA particles.
iii. Concrete containing CBA exposed to seawater gain its weigh less than the control mix. Because, CBA addition reduces the rate of hydration and decreases the penetrability of salts. Thus, concrete containing finer CBA gains less weight. Hence, ground CBA reduces the salts permeability.
iv. It was observed through the RCPT test that less charge passed through concrete containing 10% ground CBA of type-A (M2) as compared to that of control specimens (M1) and concrete containing 10% ground CBA of type-B (M3). However, CBA-type-A gives around 45.4% and CBA-type-B gives around 42.4% reduction in chloride penetration as compared to that of control mix.
v. Overall, it was observed that the use of CBA as a cementitious material carries satisfactory performances in normal water as well as in seawater.

Hence, the idea to replace cement with ground CBA expands the concrete performances, and it also reduces the environmental pollution caused by the improper dumping of CBA, in general it is leading importance in sustainable development. Therefore, it is recommended for the future studies; to extend the investigations on the concrete performances with CBA as SCM exposed seawater under wetting-drying cycles.

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