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IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Experimental Study on Cement and Fine Aggregate Replacement with Coal Bottom Ash in Seawater-Mixed Concrete

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DOI: https://doi.org/10.30880/ijie.2022.14.09.029
Received 29 August 2022; Accepted 24 October 2022; Available online 30 November 2022

Abstract: An experimental study was carried out to study the properties of concrete made with seawater as total mixing water, ground coal bottom ash as binary cement and coal bottom ash as sand replacement. The first stage mixes were prepared with three percentages (0, 10, 20 and 30) of ground coal bottom ash as partial replacement of binder. The second stage mixes involved 10 percent of ground coal bottom ash with 25%, 50%, 75% and 100% of coal bottom ash replacing natural sand. Properties investigated were materials properties, binder chemical composition, concrete hardened density, compressive strength, and SEM. Test on hardened density was conducted on 7 and 28 days. Ground coal bottom ash was identified as Class F, while coal bottom ash has low specific density and high-water absorption compared to natural sand. Concrete density and compressive strength decreased on use of coal bottom ash as fine aggregate. Compressive strength was seen to decrease as CBA percentage rose, with the maximum value being 44.4 MPa for combination of 10 percent ground coal bottom ash and 25 percent coal bottom ash. Series with 10% CBA (ground coal bottom ash) reduces by roughly 51% while maintaining a sufficient structural strength value. The findings of this investigation showed that it is possible to produce seawater-concrete, which incorporates coal ash in concrete.

Keywords: Coal bottom ash, compressive strength, seawater-concrete, binary-binder

1. Introduction

Conventional concrete is made from freshwater, cement, fine and coarse aggregate. As part of concrete making, the demand for freshwater is also divided into mankind, agricultural industry, and fauna. According to the United Nations World Water Development Report 2019, the freshwater supply in 2050 estimated that over 570 cities with 685 million people will have limited freshwater ability by the increased human population in cities and urbanization. Its depletion of freshwater is also caused by climate change. It is also estimated that 10% of freshwater reduction is caused by climate change due to the greenhouse effect. Thus, the rise of the human population which increases the freshwater demand also deals with global warming-sector such as drought and climate change. In Malaysia, the water demand rose in domestic and industry sectors with 4.8 billion from 2000 to 9.5 billion in 2020 [1]. United Nations [2] reported the

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Corresponding author: nurazuwa@uthm.edu.my estimation of population of the world will keep growing from 7.7 billion in 2020 in the middle of July to 9.7 billion in a medium variant of the year 2050. In Asia, the population estimation will be increased from 4.6 billion in 2020 to 5.2 billion in 2050. Meanwhile in Malaysia, the population will rise from 32 million in 2019 to 40.5 million in 2050.

From this statistic, the development of domestic houses, industrial areas, and all the activities that involve human life will increase to fulfil human needs. It can cause an increasing usage of other concrete materials such as river sand and cement. The usage of river sand keeps bringing bad effects on the environment. Sand quarrying from the riverbed may cause a rapid change in bed configuration in response to the changes in inflow. Quarrying operations cause material damage, groundwater depletion, loss of fertile topsoil, deforestation, loss of aquatic biodiversity, and harm to public health [3]. Natural sand is being used as fine aggregate in concrete making and is referred to as fine aggregate. It is mostly mined from the riverbeds and indiscriminate mining of sand has caused damage to the environment. The dependency on this source has led to high material costs also and scarcity of natural sand. Due to this shortage of good quality natural sand and heavy dependency on this for concrete manufacturing, there has been seen the usage of poor-quality natural sands for construction. Thus, it becomes almost obligatory to find alternatives to natural sand and evaluate these alternatives for use in concrete production. Meanwhile, the manufacturing of cement releases carbon dioxide gases (CO_2) due to the furnace process of cement leading to fossil fuels ignition and it involves indirect greenhouse gas emissions. Cement manufacturing entails several health-related concerns. It is poisonous by nature and contributes significantly to environmental inequality and poses a risk of air pollution [4]. Every year more than 4 billion tonnes of cement are produced, and it contributes to 8% of world emissions [5] while Malaysia produces 2,254 thousand tonnes in last 2020 rather than 1,417 thousand in last 2019 [6].

Therefore, under the current situation of such huge consumption of freshwater, river sand and cement, the revolution of the concrete industry is inevitably promoted. Seawater is seen as the alternative to be used for mixing water in concrete. It is well known that the earth covers 75% of its surface with water which is divided into seawater about 97.6 % and freshwater about 2.4 % [7]. Seawater concrete has been introduced since the Rome Empire, and this building still survived for more than 2000 years against chemical attacks and wave force underwater [8]. Seawater had the same chemical component compactable as the replacement of freshwater in concrete such as chloride and sulfate presented [9]. Concrete with seawater can make concrete obtain good mechanical properties, drying shrinkage behaviour and microstructures, which can undoubtedly reduce carbon emissions [10]. Moreover, the 58 MPa in compressive strength at 28 days by using seawater at the water-cement ratio of 0.39 has been reported [11]. All these results show that the use of seawater in the concrete mixture can be done successfully with the positive result presented. However, it has been discovered that adding seawater can increase early compressive strength and a loss in workability, whereas using seawater can lead to a decrease in later strength [12].

The coal used for electricity in Malaysia leads to producing the amount of coal ash with available data disclosing that about 83% of electric power in Malaysia will be by fossil fuels (58% coal and 25% gas) in 2024. It implies that coal consumption as a fossil fuel for producing electricity will jump from 43% in 2014 to 58% in 2024 [13]. Hence, coal ash production (such as bottom ash, BA) will increase due to the increased coal consumption, and it required an immediate solution to solve the problems. Thus, the use of coal bottom ash as a sand replacement and cementitious can minimize the amount of waste in the damping site and save the environment. A large proportion of the bottom ash is fine particles that comprise 50–90% of bottom ash falls into the A-1-a class and well-graded sand groups of the AASHTO and USCS classification systems [14]. Coal bottom ash (CBA) has a lighter weight and is more brittle as compared to natural river sand. It has low specific gravity because of the porous texture that readily degrades under loading or compaction [15] The compound in CBA helps the concrete more feasible because it contains silica, iron alumina, and a little sulfate, magnesium, calcium, and another compound in it. CBA with porous structure and low specific gravity tends to reduce the concrete self-weight and can absorb more water. The sand replacement to CBA is suitable because it is usually a well-graded material, and its particle size distribution is like that of river sand with the interlocking characteristic [13]. CBA also can reduce the salt permeability and reduce the hydration rate in concrete. However, the utilization of CBA as a lightweight aggregate will induce strength reduction in lightweight concrete. CBA when grinded into micro-size as cementitious material is known as ground coal bottom ash (GCBA). GCBA has good pozzolanic qualities when CBA was grinded up to 40 hours to boost its fineness and pozzolanic reactivity significantly [16].

Based on prior research, it is an important approach to study the replacement of freshwater with seawater and river sand with coal bottom ash. Also, it is necessary to investigate the use of GCBA at microscale binary blended pozzolans binder to improve the strength of seawater-concrete. Therefore, it is of great significance to explore the mechanism of microscale GCBA on physical, chemical, and strength in producing structural strength seawater concrete This study will improve resources shortage and achieve sustainable material.

2. Experimental Study

2.1 Materials Preparation

CBA was collected from a power plant in Tanjung Bin, Johor, Malaysia. The process to make CBA as a binder is shown in Fig. 1. It started with the CBA being dried in an oven at a temperature of 110 ± 5^0C for 24 hours. After cooling the oven-dried CBA, the grinding process took place using a Los Angeles machine for six hours. Upon completion, the CBA was sieved and passed a 75-micron pan and named ground coal bottom ash (GCBA), see Fig. 2. For the sand replacement, CBA was sieved and passed a 5 mm sieving pan. Meanwhile, seawater was taken from Pantai Sungai Lurus, Batu Pahat, Johor, Malaysia. Seawater was collected at approximately 10 meters from the seashore and replaced freshwater totally in the mix design. Other conventional materials were ordinary Portland cement (OPC), river sand and crushed aggregate (passing sieve 20 mm). Selected materials were tested for specific density (ASTM D854-14 and BS 812-2:1995), water absorption (BS 20290-1:2019) and sieve analysis (BS EN 12620:2002 +A1:2008 and BS EN 933-12-2012). Determination of GCBA classification, chemical oxide element composition, including silica oxide (SiO_2) content, and loss of ignition (LOI) was determined through x-ray fluorescence analysis.

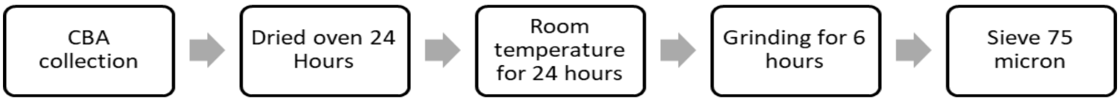
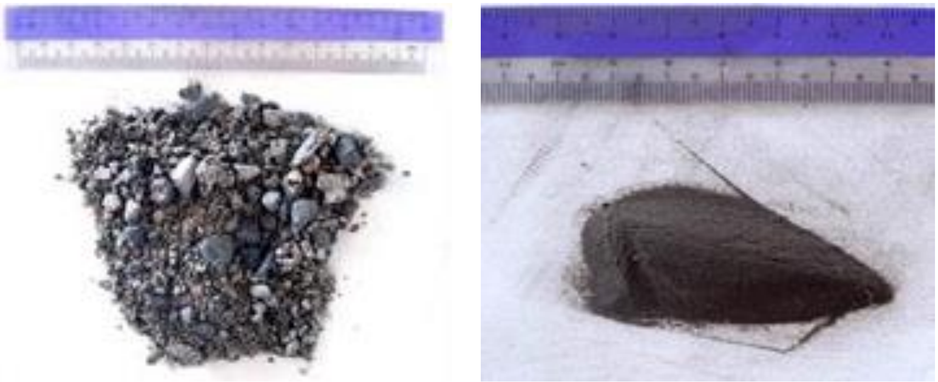


Fig. 1 - Process for making ground coal bottom ash from coal bottom ash



(a) (b)

Fig. 2 - Coal ash (a) bottom ash (b) ground bottom ash

2.2 Preparation and Testing of Specimens

There were nine series of the mixture, and the process was divided into two stages. The first stage consists of five mixture series with GCBA only and control specimens with and without seawater. The aim was to determine the optimum of GCBA by conducting a compression test on the specimen with 10%, 20% and 30% of GCBA as a replacement to OPC by weight. Target compressive strength was 40 MPa. A result from stage 1 was carried forward to stage 2. This second stage involves four series of mixtures with the substitution of CBA as a sand replacement at 25%, 50%, 75% and 100% by volume. All specimens were cast in 100 mm x 100 mm x 100 mm cube mould and compressed using the universal testing machine at 7 and 28 days. The mix design was fixed to a water-to-cementitious ratio of 0.39, see Table 1 and Table 2.

Table 1 - The description of specimens

	Series	Description
Without CBA	Control - FW	Freshwater + OPC + sand + coarse aggregates
	Control - SW	Seawater + OPC + sand + coarse aggregates
	SW-10GCBA	Seawater + 90% OPC + 10% GCBA + sand + coarse aggregates
	SW-20GCBA	Seawater + 80% OPC + 20% GCBA + sand + coarse aggregates
	SW-30GCBA	Seawater + 70% OPC + 30% GCBA + sand + coarse aggregates
With CBA	SW-10GCBA-25CBA	Seawater + 90% OPC + 10% GCBA + 75% sand + 25% CBA + coarse aggregates
	SW-10GCBA-50CBA	Seawater + 90% OPC + 10% GCBA + 50% sand + 50% CBA + coarse aggregates
	SW-10GCBA-75CBA	Seawater + 90% OPC + 10% GCBA + 25% sand + 75% CBA + coarse aggregates
	SW-10GCBA-100CBA	Seawater + 90% OPC + 10% GCBA + 0% sand + 100% CBA + coarse aggregates

Table 2 - Concrete mix proportion

Series	Freshwater	Seawater	OPC	GCBA	Sand	CBA	Coarse Aggregate
	kg/m³						
Control - FW	195	0	500	0	705	0	975
Control - SW	0	202	517	0	705	0	975
SW-10GCBA	0	202	465	52	705	0	975
SW-20GCBA	0	202	413	103	705	0	975
SW-30GCBA	0	202	362	155	705	0	975
SW-10GCBA-25CBA	0	202	465	52	529	176	975
SW-10GCBA-50CBA	0	202	465	52	353	353	975
SW-10GCBA-75CBA	0	202	465	52	176	529	975
SW-10GCBA-100CBA	0	202	465	52	0	705	975

3. Results and Discussion

3.1 Chemical Composition of OPC and GCBA

The chemical composition of the OPC and GCBA were analysed using XRF analysis. Based on the result data shown in Table 3, the GCBA was classified as Class F (ASTM C618) where the total of SiO_2 + Al_2O_3 + Fe_2O_3 is 85.8%. Thus, it achieved the minimum requirement chemical composition for Class F which is 70%. The lime (CaO) value for GCBA was far lower than an OPC which contributes to 28 days and later strength development, however, potassium (K_2O) at 1.87% can cause strength decrement after 7 days compared to OPC at 0.16%. The loss of ignition of GCBA is greater than that of OPC, indicating that a combination containing GCBA requires more water during mixing.

Table 3 - The chemical composition of OPC and GCBA

	Oxide composition (mass %)								
Materials	Al_2O_3	SiO_2	Fe_2O_3	CaO	K_2O	MgO	Na_2O	SO_3	LOI[b]
OPC	3.57	16.4	3.51	68.9	0.16	2.46	-	3.66	1.5
GCBA	18.6	57.2	10.00	6.49	1.87	1.66	1.03	0.5	2.62

[b] Loss of ignition

3.2 Material Specific Gravity, Water Absorption and Particle Distribution

The density of each material is presented in Table 4. Seawater has a somewhat greater density than freshwater by 1.04 g/cm³. Meanwhile, GCBA has a density of 2.89 g/cm³ which is slightly higher than OPC. The density of CBA as a sand substitute was 1.95 g/cm³, which is lower than sand and has a high-water absorption rate (31.39%), indicating that CBA is porous and has a propensity to absorb free water during mixing. Sand water absorption should also be taken into consideration. To guarantee proper concrete preparation, it is crucial to make sure all aggregates are prepared under saturated surface dry (SSD) conditions. Table 5 summarizes the sieve analysis results for both fine aggregate and CBA. Overall, the sand and gravel were within the % passing limitations specified by the standard. CBA, on the other hand, has a coarser size than the fine aggregate, therefore special consideration must be given when using CBA in a mixed design. Similar findings were observed by [17], [18].

Table 4 - Materials specific density and water absorption

Materials	Specific Density (g/cm³)	Water Absorption (%)
Freshwater	1.00	-
Seawater	1.04	-
OPC	2.81	-
GCBA	2.89	-
Sand	2.52	7.46
CBA	1.95	31.39
Gravel	2.58	1.11

Table 5 - Aggregate size distribution

	Percentage passes						
Sieve size	**37.5 mm**	**28 mm**	**20 mm**	**14 mm**	**10 mm**	**5 mm**	**FM^a**
Recommended nominal size passing (A.M Neville)	100	90 - 100	40 - 80	30 - 60	0 - 20	0 - 10	-
Cumulative (%) Passed (coarse aggregate)	-	-	78.81	42.39	20.54	2.00	-
Sieve size	**5.0 mm**	**2.36 mm**	**1.18 mm**	**600 µm**	**300 µm**	**150 µm**	**FM^a**
Recommended nominal size passing (A.M Neville)	89 - 100	80 - 100	70 - 100	55 - 100	5 - 70	0 - 15	-
Cumulative (%) Passed (sand)	97.92	93.75	77.08	37.5	18.75	2.08	2.72
Cumulative (%) Passed (CBA)	85.42	72.92	54.17	31.25	6.25	2.08	3.47

[a] Fineness modulus

3.3 Concrete Hardened Density, Compressive Strength and SEM Image

The density test results of (A) freshwater-mixed, (B) seawater-mixed concrete with GCBA only, and (C) seawater-mixed concrete with GCBA and CBA as sand replacement are given in Fig. 3. In the (B) section, density increased when FMK was introduced at 10% and subsequently decreased when GCBA was replaced at 20% and 30%. The density reduced further when sand was substituted with CBA from 10% to 50%, as shown in section (C). In comparison to the Control 1 specimen ((A) section), the 28 days density was reduced by roughly 9% at 50% CBA replacement. Fig. 4 provides further information on the density reduction percentage in comparison to Control 1 specimens. Compressive strength at 7 and 28 days are presented in Table 6. Control 1 specimen reached 52 MPa at 28 days and began to decrease when the combination was mixed with seawater and GCBA. 28-days strength loss was clearly seen at 10%, 20%, and 30% GCBA replacement, with the maximum strength among this replacement being 10% GCBA at 49 MPa (6% loss). Therefore, 10% GCBA was considered to be the leading substitute for GCBA. This is comparable with the results reported by Mangi et al. [19]. In stage 2, 10% GCBA was further mixed with CBA at sand replacement levels ranging from 25% to 100%. Concrete attained strength of 44.4 MPa, 29.8 MPa, 28.6 MPa and 25.4 MPa at 25%, 50%, 75% and 100% CBA replacement, respectively. It was observed that the compressive strength decrease as CBA percentage increased, with highest value was 44.4 MPa (10GCBA-25CBA) which was much higher than that reported by Rafat [20] due to higher cement content in the mix. When compared to Control 1 specimen, series with 100% CBA (10GCBA-100CBA) lowers by around 51%, yet it still maintains an adequate structural strength value. The strength values corresponded to those reported by Bheel et al. [21] at 28 days age of curing. Futher reduction in compressive strength versus coal bottom ash content in seawater-mixed concrete containing ground coal bottom ash are shown in Fig.5. SEM image of seawater -mixed concrete with 10% GCBA and 25% CBA, 50% CBA, 75% CBA and 100% CBA are shown in Fig. 6.

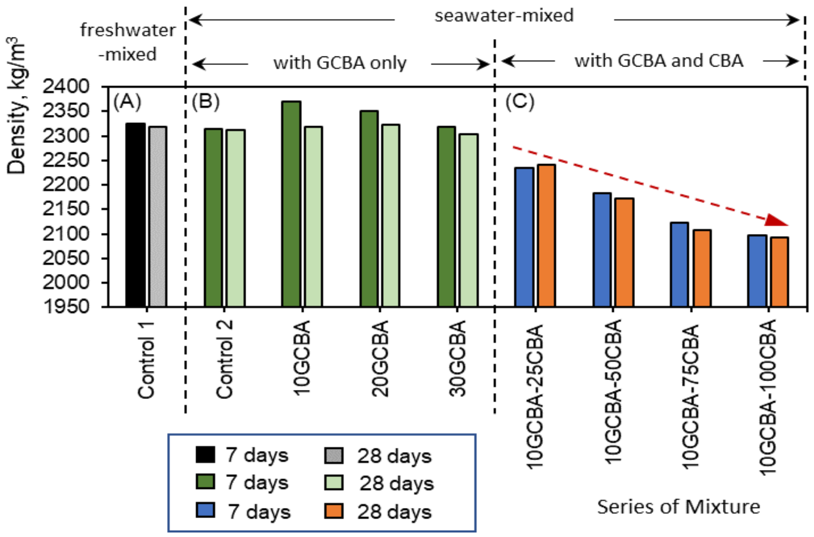


Fig. 3 - Hardened density for seawater-concrete with CGBA only, and seawater-concrete with GCBA and CBA

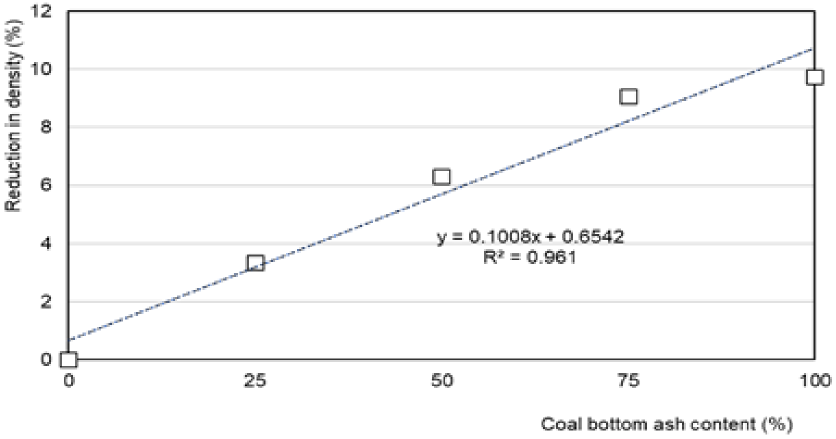


Fig. 4 - Reduction in density versus coal bottom ash content in seawater-mixed concrete containing ground coal bottom ash

Table 6 - Compressive strength for seawater-concrete with GCBA and CBA

Mix	Replacement Material	Series ID	Compressive strength (MPa)	
			7-days	28-days
Freshwater-mixed	-	Control 1	43.7	52.0
Seawater-mixed	-	Control 2	43.5	41.5
Seawater-mixed	GCBA only	10GCBA	33.8	49.0
		20GCBA	38.6	40.9
		30GCBA	33.0	37.1
	10% GCBA and CBA	10GCBA-25CBA	39.3	44.4
		10GCBA-50CBA	24.9	29.8
		10GCBA-75CBA	22.1	28.6
		10GCBA-100CBA	21.9	25.4

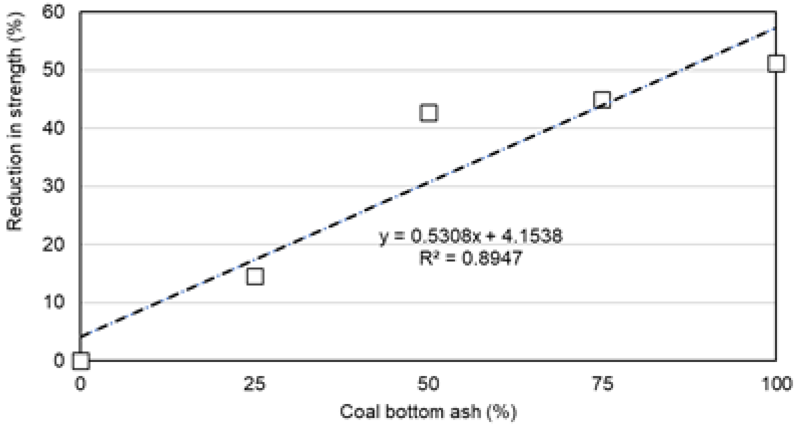
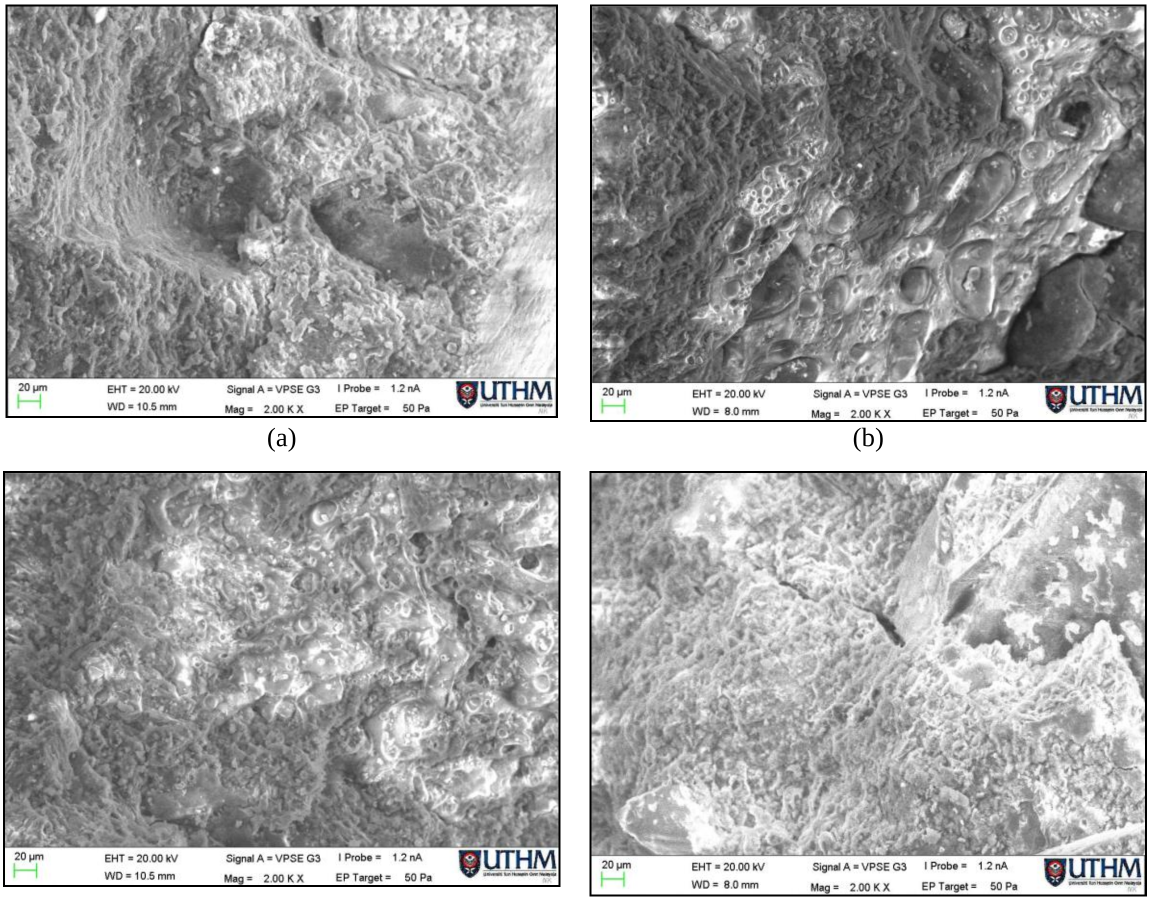


Fig. 5 - Reduction in compressive strength versus coal bottom ash content in seawater-mixed concrete containing ground coal bottom ash



(a) (b)

(c) (d)

Fig. 7 - SEM image of seawater -mixed concrete with 10% GCBA with (a) 25% CBA; (b) 50% CBA; (c) 75% CBA, and; (d) 100% CBA

4. Conclusion

The results of the experimental study with seawater, GCBA at 10%, 20%, and 30% of cement replacement and CBA as a sand replacement at 25%, 50%, 75% and 100%. Based on the result, these are the following summaries can be concluded:

- The GCBA is categorized as class F according to ASTM C618-05.
- The density of the hardened normal concrete is roughly similar with the seawater concrete mix of 10% to 20% GCBA without CBA. When CBA was added, the density of the specimen decreases when the volume of CBA increases.
- The optimum GCBA was at 10% replacement which was 49 MPa at 28 days.
- With the substitution of CBA, the strength pattern was declining by around 51% for series with 100% CBA (10GCBA-100CBA).
- The highest strength was recorded at 44.4 MPa for seawater-mixed concrete with 10% GCBA and 25% CBA.

Acknowledgement

Communication of this research is made possible through monetary assistance by Universiti Tun Hussein Onn Malaysia and the UTHM Publisher’s Office via Publication Fund E15216. This research was also supported by Universiti Tun Hussein Onn Malaysia (UTHM) through GPPS (Vot H710).

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