

INFLUENCE OF BOTTOM ASH AS A SAND REPLACEMENT MATERIAL ON DURABILITY OF SELF-COMPACTING CONCRETE EXPOSED TO SEAWATER

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Abstract

Concrete strength and durability performance under marine environment have been considered as challenging issue for many decades because seawater contains aggressive salts and it could affect the service life of concrete structure that is expected for the marine environment, such as offshore, harbour and coastal structures. Therefore, this study investigated the strength and durability performance of self-compacting concrete (SCC) containing Bottom Ash (BA) exposed to seawater under wetting-drying cycles. The exposure period for seawater was considered up to 180 days. Concrete mix incorporated BA from 10% to 30% by weight of sand with fixed water to binder ratio 0.4 with superplasticizer to produce 40 MPa concrete at 28 days. The performance of SCC was evaluated based on compressive strength, rapid migration test and depth of carbonation test. SCC with 10% BA gives satisfactory compressive strength and exhibits good resistance to chloride migration rate and it gives around 4.5% reduction in carbonation depth as compared to control mix at 180 days. The microstructural study also indicated that 10% BA form well shape calcium silicate hydrate gel, which delivers adequate compressive strength development. It was concluded that 10% BA as a sand replacement was found to be optimum, provides satisfactory strength and durability performance.

Keywords: Carbonation, Compressive strength, Rapid chloride migration, Self-compacting concrete.

1. Introduction

The concrete strength and durability performance under marine environment have been considered as challenging issue for many decades, because seawater contains aggressive salts and it could affect the service life of concrete structure that is expected for the marine environment, such as off-shore, harbour and coastal defence structures [1]. The concrete exposed to seawater has long been employed in the construction, even first structures were built by Romans was exposed to seawater on the coast of the Mediterranean Sea [2].

According to Suprenant [3], concrete structures that exposed to seawater can be grouped into three zones; submerged zone, splash zone so-called tidal zone and atmospheric zone. The submerged zone is immersed in seawater, splash zone or tidal zone is continuous under wetting and drying. Whereas atmospheric zone is just above the splash zone, it receives sprays of seawater occasionally. Concrete exposed to all three zones is cause damage due to marine contact. It was previously declared that concrete under splash zone (wetting-drying cycle) is more dangerous and fast deterioration will take place and leading towards a reduction in strength and ultimately failure of structure [4]. The deterioration of concrete occurs due to wetting and drying cycles, which creates a destructive condition for concrete due to chloride ions movement and concentration in pores of concrete [5].

On the other hand, Khan et al. [6] and Matsagar [7] indicates that chloride ions are primarily responsible for the corrosion of reinforcement. Due to corrosion of reinforcement, the concrete structure becomes deteriorated. It requires more cost to repair and replace the damaged involved millions of dollars. Therefore, concrete requires immediate attention to bring new ideas through research and development to enhance concrete performance. Conventional concrete needs a profound renovation process to avoid objectionable appearance due to seawater exposure. One of the current innovations is incorporating bottom ash (BA) into concrete since it has the same chemical composition as pozzolanic material. Domone [8] conducted a case study relating self-compacting concrete (SCC) comprises data about material selection, mixture proportion and properties of concrete. However, SCC was developed in Japan in 1980 [9].

This type of concrete is proficient to strengthen only under its self-weight and suitable in complex formwork. In reinforced concrete structure during execution, vibration is very much problematic, which sometimes causes bleeding and segregation [10]. Therefore, SCC does not require any mechanical vibration. However, selection of material for the preparation of SCC is very important; sizes of aggregate that considered for the SCC are ranging from 16 to 20 mm; while slump flow in the range of 600-750 mm, to make concrete more viscous, a viscosity modifying agent was used, and a superplasticizer to improving the workability of the fresh properties, the proportion of coarse aggregates is given by median value is about 31.2% by volume and 47.5% by volume for fine aggregate [8]. Hamzah et al. [11] reviewed the cementitious ingredients in self-compacting concrete (SCC). It was noted by them that pozzolanic materials can enhance the deformability and durability without a reduction in the early strength. Memon et al. [12] stated that pozzolanic material can improve the performance of concrete. Since a pozzolan is a siliceous and aluminous material having slightly cementitious properties, but when it was added with cement and in the presence of water, it reacts chemically with calcium hydroxide to form compounds to act as cementitious material [13].

There is a lot of pozzolanic materials that have been incorporated in concrete production, either as partial or total replacement such as fly ash, rice husk ash, ground granulated blast furnace and silica fume, etc.

However, studies on concrete containing bottom ash (BA) as a sand replacement subjected to aggressive seawater wetting and drying cycle are rarely reported. It was also earlier identified by the researchers that BA has a good potential to be utilized as fine aggregate in concrete [14-18]. Moreover, it has been recently recommended that concrete containing BA should be evaluated under the marine environment [19]. However, when BA is used to replace fine aggregate in concrete, it could be a possible solution to minimize the waste material produced by the coal-based powerplants. This approach could also enhance the concrete durability. The aim of this paper is to investigate the influence of BA on strength and durability performance of self-compacting concrete (SCC) exposed to seawater under wetting and drying cycles. This paper brings new knowledge regarding BA utilization in SCC to improve its performance in the aggressive environment such as the marine environment.

2. Materials and Methodology

2.1. Materials

Ordinary Portland cement (OPC) was used as a main binding material in concrete. EFNARC [20] stated that the general suitability in producing SCC is established for cement conforming to MS EN 197-1 [21]. The OPC is most common that is used for general concrete construction [22]. Fine aggregates and coarse aggregates were used in the production of self-compacting concrete. Fine aggregates with particle passing 5 mm sieve was used in the concrete mixture. The size of coarse aggregates used throughout this study is passing from 16 mm sieve and retained on the 10 mm respectively conforming to EFNARC [20]. The sieve analysis was also performed in accordance with CS3 [23].

Figure 1 shows the materials used in the study such as Bottom ash (BA) that was produced by coal operated power plant in Klang, Malaysia, was utilized in this study as shown in Fig. 1(a). After collection, the oven drying method was used to dry it at a temperature of 105 ± 5 °C for 24 hours to eradicate moisture. However, it was also observed that the original BA has 40% moisture content. The dried BA was passed from 5 mm sieve and larger particle than 5 mm were removed before storing in an airtight container to prevent atmospheric humidity contact. The proportion of BA that passed through a sieve of 5 mm could be classified as sand and suitable to use in a concrete mixture.

Subsequently, the concrete mix was prepared with 10%, 15%, 20%, 25% and 30% replacement of sand with BA by weight of sand. The particle size distribution BA is presented in Fig. 2, it indicated that BA particles size falls within the upper and lower limits of fine aggregates and it can be utilized as fine aggregate replacement. However, the chemical and physical characteristics of BA are given in Tables 1 and 2. The chemical contents of BA indicated that it has a major portion of silica oxide (SiO_2) and alumina oxide (Al_2O_3) and ferric oxide (Fe_2O_3), which is approximately 94.07%, which meet the ASTM C494 [24] requirement and categorized a class *F* ash. Moreover, A superplasticizer ADVA 181 was used in this study as shown in Fig. 1(b). This super-plasticizer is chloride free and has been

formulated as per ASTM C494 [24]. A technical data prepared for this type of superplasticizer: Form: liquid, Colour: liquid brown, Specific gravity: 1.09, pH: 5.29, Suitability: all Portland cements.



(a) Bottom ash.



(b) Superplasticizer.

Fig. 1. Bottom ash and superplasticizer used in this study.

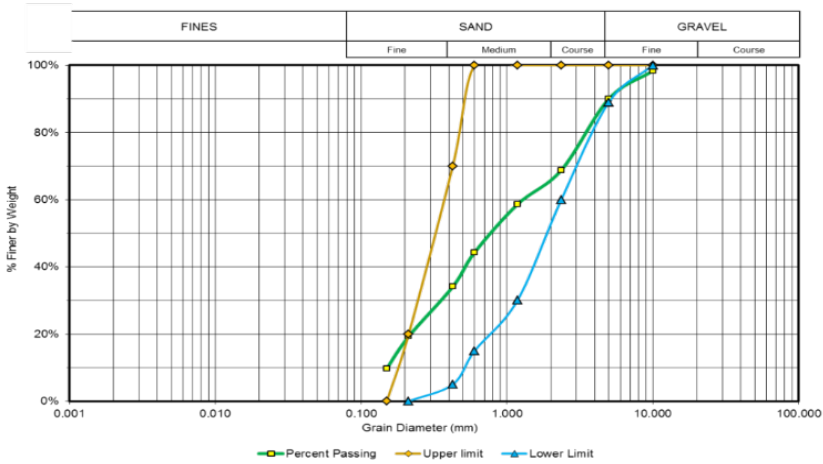


Fig. 2. Particle size distribution of bottom ash.

Table 1. Chemical characteristic of OPC and BA.

| Detail | Chemical characteristics | | | | | | | |
|-------------|--------------------------|--------------------------------|--------------------------------|-------|------------------|------------------|------|-------------------|
| Content (%) | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | K ₂ O | TiO ₂ | MgO | Na ₂ O |
| OPC | 22.00 | 8.35 | 3.92 | 58.93 | 1.01 | 0.72 | 0.52 | 0.26 |
| BA | 68.9 | 18.67 | 6.5 | 1.61 | 1.52 | 1.33 | 0.53 | 0.24 |

Table 2. Physical properties of OPC and BA.

| Description | Physical characteristics | |
|------------------|--------------------------|------|
| | OPC | BA |
| Specific gravity | 3.0 | 1.90 |
| Moisture content | - | 40% |

2.2. Sample preparation and curing conditions

Total six proportions of fine aggregate replaced with BA at the proportions of 10%, 15%, 20%, 25% and 30% by weight method. The mix proportion of self-compacting concrete based earlier study of Jawahar et al. [25] was adopted as presented in Table 3. The BA was thoroughly mixed with cement, sand, coarse aggregate, superplasticizer and water. The water to binder ratio was kept 0.40 for all mix. Superplasticizer was added to the mix to maintain slump flow values. However, the superplasticizer quantity was adjusted as it can be self-compacting. After mixing and casting, concrete specimens were cured in normal water for 28 days to achieve a strength of 40 MPa. After 28 days of curing normal water curing, the specimens were shifted into seawater under wetting-drying cycles.

The seawater was collected from Pantai Punggor, Johor, Malaysia as location shown in Fig. 3. Seawater samples were taken around 3 km from the coast. The average monthly temperature at the site was recorded as 25.9-33 °C. The selection of location for the collection of seawater was based on the availability of open space, good wind circulation, away from walls, trees or other elements [26, 27]. The chemical composition of the collected seawater is provided in Table 4.

Table 3. Concrete mix proportions (kg/m³).

| Sample | Cement | Coarse aggregates | Sand | Bottom ash | Water | SP |
|--------|--------|-------------------|--------|------------|--------|------|
| 0BA | 518.00 | 715.50 | 874.50 | 0 | 207.20 | 1.00 |
| 10BA | 518.00 | 715.50 | 874.50 | 87.45 | 207.20 | 0.80 |
| 15BA | 518.00 | 715.50 | 874.50 | 131.18 | 207.20 | 0.75 |
| 20BA | 518.00 | 715.50 | 874.50 | 174.90 | 207.20 | 0.85 |
| 25BA | 518.00 | 715.50 | 874.50 | 218.63 | 207.20 | 0.90 |
| 30BA | 518.00 | 715.50 | 874.50 | 262.35 | 207.20 | 1.00 |

Table 4. Seawater characteristics.

| Chemical properties | Symbol | Unit | Content |
|---------------------|-------------------------------|------|---------------|
| Sodium | Na ⁺ | mg/l | 2075 - 2415 |
| Potassium | K ⁺ | mg/l | 389 |
| Calcium | Ca ²⁺ | mg/l | 293 |
| Magnesium | Mg ²⁺ | mg/l | 1073 |
| Chloride | Cl ⁻ | mg/l | 16219 - 18310 |
| Sulphate | SO ₄ ⁻² | mg/l | 1201 |
| pH | - | | 7.92 - 8.26 |
| Temperature | - | °C | 25.9 - 33 |



Fig. 3. Location of the seawater collection site.

2.3. Compressive strength test

The compressive strength test was conducted on 100 mm concrete cubes. Total of 90 cubical specimens were prepared for this test. All cubes were tested at the ages of 7, 28, 60, 90 and 180 days. The compressive strength test setup is provided in Fig. 4. However, the data of control specimens were compared with specimens containing BA as fine aggregate. According to British Standard Institution (BSI) [28], BS EN 12390-3, the loading rate was set as constant as $0.6 \pm 0.2 \text{ N/mm}^2/\text{s}$.



Fig. 4. Compressive strength test setup.

2.4. Rapid migration test (RMT)

This test was conducted with reference to NT Build 492 [29]. This test was used to evaluate the chloride penetration depth. The tests were performed on cylindrical specimens having a diameter of 100 mm and a thickness of 50 mm and the surface

of the specimen was coated with epoxy. For this test total, 90 cylindrical specimens were prepared. The testing device basically has a diffusion cell and it consists of two spaces. One side, sodium chloride (NaCl) solution concentration 3.0% and other side sodium hydroxide (NaOH) solution concentration 0.3 N.

A direct current voltage of 30 Volt was applied across two sides and the initial current was measured as shown in Fig. 5. After testing, specimens were split into two portions. A solution of 0.1 M AgNO_3 was sprayed on the concrete surface, and depth of chloride penetration was evaluated. The rate of penetration was calculated through Eq. (1). Chemical reactions happened once silver nitrate solution is sprayed on the specimens; all of these are denoted in white and brownish regions with well-distinguished boundaries. The white region is appeared because of precipitation of AgCl and the brownish region is known as “no chloride zone”.

$$CPR = XD/T*U \quad (1)$$

Whereas; CPR is chloride penetration rate, mm/(v.hr), U is the absolute value of the applied voltage, T is the duration of the test (hour), XD is the average value of the penetration depth in mm. This test was performed at 7, 28, 60, 90 and 180 days.



Fig. 5. Apparatus for RMT [29].

2.5. Carbonation test

This test method was performed according to British Standard Institution (BSI) [30], BS EN 14630, standard to determine the depth of carbonation through new crushed the surface of the concrete. The cylindrical specimens of 100 mm diameter and a thickness of 200 mm were used for this test. Overall, 90 cylindrical specimens were prepared for this test. Each mixed was cast into cylindrical moulds. The sample has been exposed to the cyclic seawater environments by wetting-drying. On a specific day such 7, 28, 60, 90, and 180 days, split tensile test was performed.

A common and simple method to establish the extent of carbonation is by treating a freshly broken surface (split surface) of concrete with a solution of 1% phenolphthalein. The freshly broken surfaces shall be cleared of any dust and loose particles. Then, the phenolphthalein was sprayed on the split surface. After 24 hours, carbonation was measured at three different locations as shown in Fig. 6. The average values were considered as carbonation depth. Unchanged colour zone indicated carbonated portion of concrete when the colour changed into purple shows non-carbonated zone.



Fig. 6. Measurement of depth of carbonation.

2.6. Microstructural analysis

Scanning Electron Microscopy (SEM) was used to evaluate the microstructural behaviour of SCC containing BA exposed to seawater exposure. In this study, NOVA NANOSEM 230 model was used to investigate the inside behaviour of reference mix (with 0% BA) and SCC containing 10%, 15%, 20%, 25% and 30% BA exposed to seawater wetting and drying for the period of 180 days.

3. Results and Discussion

3.1. Compressive strength

The compressive strength test results of SCC with BA under seawater with wetting and drying cycles are presented in Fig. 7. Initially, the compressive strength of SCC was increased at the early days of 7 days and 28 days, and then slowly increased up to 60 days. After 60 days of wetting-drying cycles, strength started to decrease until 180 days. The explanation of the strength decrement is attributed to the reaction of sulphate ions with hydrated cement to form gypsum and ettringite [31]. The strength also could be due to the leaching out of hydration products. As mentioned by Ganjian and Pouya [32], when the specimen is exposed to seawater in cyclic condition, it can affect the crystallization of salts and resulted in the degradation of the protective layer facilitating the ingress of ions.

On the other hand, in Fig. 7, 10% BA delivers substantial increment in compressive strength and were more resistant to seawater as compared to other specimens. The specimen of 10% BA shows that the strength is slightly increased in comparison to a controlled specimen. For instance, at the age of 28 days, the compressive strength of the controlled specimen and 10BA were 55.23 MPa and 56.12 MPa, respectively. However, it was observed that the strength of 10BA had less difference at the age of 60 days up to 180 days, which is showed lower strength than a controlled specimen. Nevertheless, the differences in strength for 0BA and 10BA are not too obvious. However, at the age of 60, 90, and 180 days were observed as 2.87%, 2.17% and 1.58%, respectively. Increase in the age strength resulting in the strength deprivation affects the ettringite formation [33]. However, ettringites are the well-known hydration products produced because of the calcium aluminate (C_3A) reaction, which delivers early strength development.

Consequently, 15BA to 30BA did not show any significant improvement in strength value as compared with the controlled specimen. The compressive strength of 15BA to 30BA decreased in increased of replacement level of bottom ash. The decrement in strength can be attributed to lower specific gravity and porous particles of BA. On replacement of sand with BA in concrete, heavyweight particles are replaced with the lightweight particles. Therefore, it can increase voids in the concrete and resulted in lower strength. In this study, the specific gravity of BA and fine aggregate was recorded as 2.61 and 1.90 respectively. It indicated that BA contained more fine particles than the fine aggregate and resulting in the higher specific gravity than the fine aggregate [34].

It was observed that the specific gravity of sand is higher than BA. However, higher specific gravity delivers dense concrete and resulting in high strength. In this study, the compressive strength with 10% BA was recorded highest as compared to other mixes. The maximum strength was obtained at 10% replacement in the mix, which can be considered as an optimum mix. Kasemchaisiri and Tangtermsirikul [34] and Hamzah et al. [10] stated that SCC containing 10% BA as fine aggregate delivers good strength performance. In this study, it was determined that the incorporation of 10% BA in SCC help to produce the highest strength even though subjected to seawater environment under wetting and drying cyclic conditions.

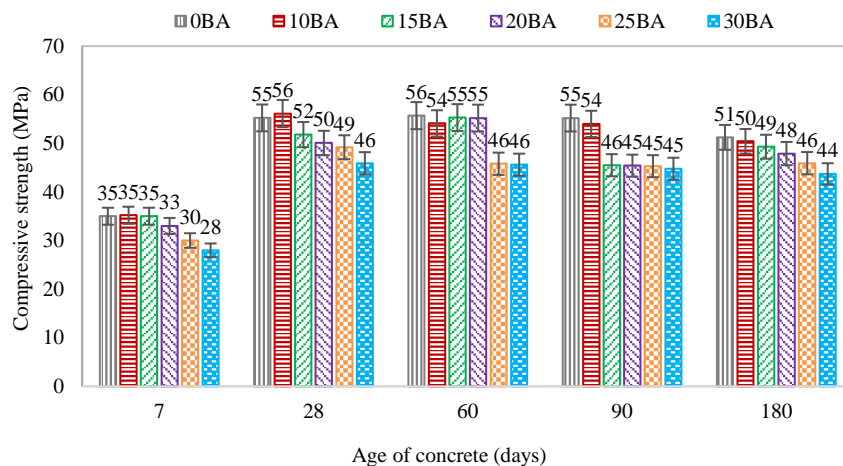


Fig. 7. Compressive strength of SCC with BA exposed to seawater wet-dry cycle.

3.2. Rapid migration test (RMT)

The results of RMT were used to calculate chloride penetration rates for specimens exposed in seawater by repetitive wetting-drying are presented in Fig. 8. It can be observed that BA has a major influence on chloride-ion diffusion in concrete. However, maximum penetration rates noticed in all concrete mixes at 180 days. The rate of chloride penetration was increased with increasing in BA content. BA has high chloride binding due to porous texture and pozzolanic characteristic. However, lowering the chloride penetration is a result of high chloride binding and capillarity of concrete [34-37]. Hydration of cement paste reacts with BA and

creates expansive products because BA mainly contains silica, which reacts with calcium and producing calcium-silicate-hydrate (C-S-H) gels, which fills the capillary pores of the concrete. Therefore, a higher amount of BA in concrete significantly increased the chloride-ion migration.

It was observed through the experiment data that chloride penetration rates were high at early days in all mixes. Inclusion of 30% BA in SCC gives highest chloride penetration rate as compared to others. However, 10% BA delivers the lowest chloride penetration rates. The chloride penetration rates at 180 days for reference mix without BA was noticed as 0.82 mm/(v.hr), while 10% BA, 15 % BA, 20% BA, 25% BA and 30% BA observed as 0.75, 0.86, 1.06, 1.23 and 1.50 mm/(v.hr) respectively. The good resistance of chloride-ion migration rate for SCC exposed to seawater was observed with 10% BA.

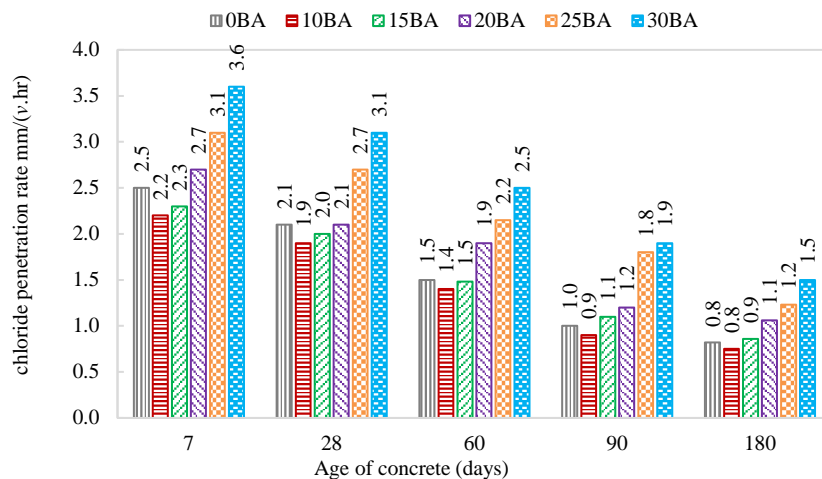


Fig. 8. Chloride penetration rate in SCC with BA exposed to seawater wet-dry cycle.

3.3. Carbonation

In general, concrete of better quality having low carbonation depth although it exposed to seawater. In this study, depth of carbonation was noticed as slightly decreased with the addition of 10% BA in concrete. The depth of carbonation was slightly increased as the amount of BA is increased in the mix as results are presented in Fig. 9. For instance, at an earlier age of 28 days, the carbonation depth of the control specimen (BA) was 3.10 mm. Then, when incorporations of 10% BA, the depth of carbonation value decreased to 3.0 mm. Afterwards, the depth of carbonation started to increase when BA proportion increased from 15% to 30%, which is in the range of 3.20 mm to 4.0 mm. However, the addition on pozzolanic materials in concrete could significantly reduce the carbonation depth [38], the surrounding environment also influences concrete performance particularly for carbonation relative humidity and temperature [37, 38]. Neville [37] stated that carbonation in concrete is due to penetration of atmospheric CO₂, which react with calcium hydroxide at a relative humidity range from 50% and 70%. During the experimental program, the relative humidity was recorded between 60% and 90%.

Besides that, high carbonation in concrete is due to chemical reaction and when BA is introduced in concrete, the chemical composition of cement becomes unstable. Addition of BA increases the amount of silica oxide in concrete, which react with calcium oxide in the presence of water. Therefore, the presence of BA encouraged to form calcium hydroxide ($\text{Ca}(\text{OH})_2$) and react with atmospheric carbon dioxide CO_2 to produce carbonation [39]. When more BA was added in concrete, it reduces the quantity of fine aggregates and resulting in increased depth of carbonation due to increasing of $\text{Ca}(\text{OH})_2$ in concrete [40]. Besides, Kasemchaisiri and Tangtermsirikul [34] reported that penetration of CO_2 greatly depends on the porosity of concrete, it can be reduced by introducing such material, which can reduce the porosity of concrete. The depth of carbonation for SCC containing 10% BA was lower when it was tested for a longer age. However, the pozzolanic reaction densifies the pore structure due to the presence of BA in concrete.

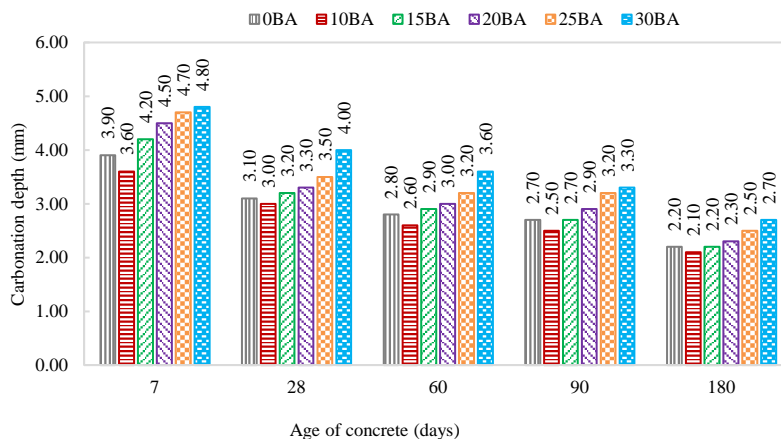


Fig. 9. Carbonation depth of SCC with BA exposed to seawater wet-dry cycle.

3.4. Microstructural analysis

Microstructural analysis was performed through scanning electron microscopy (SEM) before and after seawater exposure. Figure 10 shows the SEM analysis of SCC without BA exposed to seawater under wetting and drying cycle. It was observed that SCC contains irregular particles with micropores and cracking, this is the reason behind the poor performance associated with strength and durability. It was observed through SEM analysis that SSC when exposed to seawater, the reaction products were formed like Friedel's salts, ettringite, gypsum, and C-S-H gel. The identification of these reaction products based on the previous studies [40-42] that ettringite as white crystal needles, C-S-H gel as white bright matter, Friedel's salts as individual white solid particles, portlandite as dark hexagonal plates and gypsum as elongated rod-shaped solids. The presence of Friedel's salts shows the calcium aluminium chloro-hydrate, which forms due to seawater intrusion in concrete since seawater contains the major portion of NaCl [43]. Whereas, portlandite specified the formation of calcium hydroxide. However, more hydration products formation was detected in SCC containing BA.

Figures 11 to 13 indicated concrete containing BA, when exposed to seawater under the wetting-drying cycle has been formed a reaction of magnesium sulphate with calcium hydroxide, which later form the gypsum and magnesium hydroxide. Then, the gypsum compound reacts with calcium hydroxide and produce ettringite in the cement paste as the crystal needles are known as ettringite and portlandite as hexagonal plates also existed. Furthermore, well shape C-S-H gel formation were also observed in SCC incorporated BA. It was observed that strength was increased due to the presence of BA in SCC. It is due to the addition of BA in SCC, which enhances the aluminium, which reacts in presence of water with calcium to form tricalcium aluminate (C_3A) resulting in the strength development [43]. However, it was noticed that strength reduction at the later ages, this is due to the formation of ettringites provides early strength due to filling of free voids by the ettringites [44], but at later ages, it can be damaging in terms of cracks growth and ultimately decrease in compressive strength.

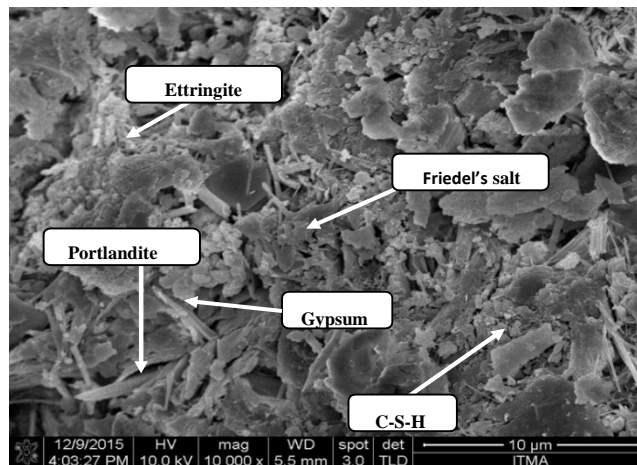


Fig. 10. Microstructure of SCC with 0% BA exposed to seawater wet-dry cycle.

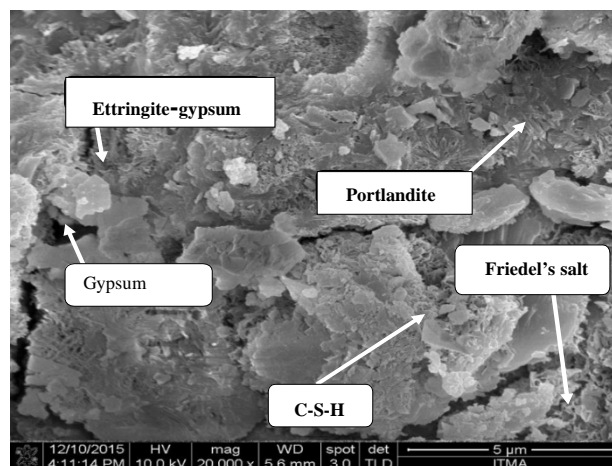


Fig. 11. Microstructure of SCC with 10% BA exposed to seawater wet-dry cycle.



Fig. 12. Microstructure of SCC with 15% BA exposed to seawater wet-dry cycle.

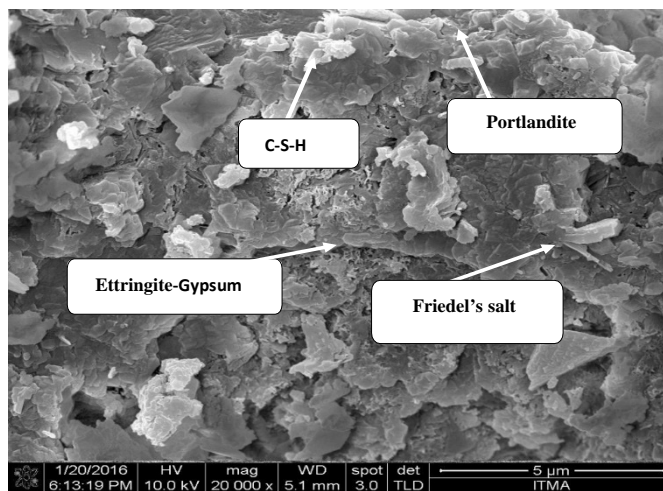


Fig. 13. Microstructure of SCC with 20% BA exposed to seawater wet-dry cycle.

4. Conclusions

Based on the experimental investigations, the following conclusions can be made;

- The experimental results revealed that BA was suitable to replace fine aggregate in SCC. However, its excessive amount could affect the properties of concrete.
- It was observed that 10% BA incorporation in SCC gives satisfactory compressive strength. However, a substantial reduction in compressive strength was observed at the replacement level of 15%, 20%, 25% and 30%.
- Rapid migration test results reveal that the SCC with 10% BA exhibits good resistance to chloride-ion migration rate when exposed to seawater under wetting-drying cycles. Besides that, more chloride penetration depth was noticed at the replacement level of 15%, 20%, 25% and 30%.

- It was observed that SCC with 10% BA gives 4.5% reduction in carbonation depth as compared to a control mix specimen at 180 days. Whereas, the carbonation depth was higher at the replacement level of 15%, 20%, 25% and 30%.
- Microstructural analysis indicated that SCC containing 10% BA displays well shape formation of C-H-S gel, which deliver adequate compressive strength development.
- This study declared that 10% BA as an optimum proportion for the production satisfactory SCC. It delivers substantial improvements in compressive strength, reduction in chloride migration and carbonation depth.

Hence, Bottom Ash (BA) has a good potentiality to be utilized as sand replacement in self-compacting concrete. However, this study recommended 10% proportion of BA as an optimum replacement level with satisfactory performances.

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Greek Symbols

μm Micrometre

Abbreviations

| | |
|-------|--|
| ASTM | American Society for Testing and Materials |
| BA | Bottom Ash |
| BS | British Standard |
| C-S-H | Calcium Silicate Hydrate |
| OPC | Ordinary Portland Cement |
| SCC | Self-Compacting Concrete |
| SEM | Scanning Electron Microscopy |
| RMT | Rapid Migration Test |

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