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Full Length Article

# Short-term effects of sulphate and chloride on the concrete containing coal bottom ash as supplementary cementitious material

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ABSTRACT

Suphate and chloride attacks on concrete are the prominent issues in the field of durable concrete structures. Therefore, this study focused on the influence of ground coal bottom ash on the strength performances of concrete exposed to sulphate and chloride environment. In this study the ordinary portland cement was replaced with 10% of coal bottom ash by weight of cement and same water to binder ratio of 0.5 was used in all concrete mixes. The original CBA was initially ground for 2 h in Los Angeles machine. Subsequently, after passing from 300micron sieve it was further ground for the period of 20 h in a ball mill grinder, to get the similar particles sizes as to ordinary portland cement. After demoulding samples were immersed in a water for the curing period of 28 days. Afterward, specimens were shifted in 5% sodium sulphate ($Na_2SO_4$) and 5% sodium chloride (NaCl) solutions for additional curing periods of 28, 56, and 90 days. The short-term effects of sulphate and chloride on the concrete were evaluated in terms of change in weight, variation in compressive strength and degree of damage. It was observed that the addition of CBA in concrete, gives the significant development in compressive strength, around 11.32% and 13.92% higher strength than that of the control mix in water and 5% $Na_2SO_4$ solution respectively at the exposure period of 90 days. However, the development of compressive strength in 5% NaCl solution was slower, around 6.87% decrease was observed in concrete containing CBA at the exposure period of 90 days as compared to the control mix. This study suggests that 10% of CBA as a supplementary cementitious material in concrete could reduce the negative effects of sulfate and chloride salts. The outcome of this study indicated that application of ground CBA as supplementary cementitious material in concrete increases the resistance against aggressive environment.



## 1. 1. Introduction

Concrete is chief material of construction for the infrastructures development around the globe. However, concrete structures built with ordinary portland cement tend to deteriorate much faster under aggressive environmental conditions such as underground structures, marine structures and structure of wastewater treatment plants [1,2]. Therefore, the performance of concrete structure could be affected due to its surrounding environment. In that case sulphate and chloride attacks are the paramount issues for the strength and durability of concrete structures because marine environments are typically more aggressive which contains high concentrations of chlorides and sulphates [3]. Therefore, it was advised to integrate supplementary cementitious materials (SCM) in concrete construction for the enhancement its strength and durability performances and make it durable and sustainable [4]. Currently, most common supplementary cementitious materials like fly ash [5–7], coal bottom ash [8,9], bagasse ash [10,11] and palm oil fuel ash [12–14] were adopted as partially replacing ordinary portland cement to improve the concrete properties. These materials can be acquired from industrial wastes, which is a suitable option to reduce the cost of concrete production [15]. Coal bottom ash (CBA) is the one of such industrial waste and it was declared as a pozzolanic material [8], CBA can also be utilized as supplementary cementitious material, because it contains high proportion of silica [9]. It was also agreed by Dehwah [16] that the concrete prepared with blended cements are more durable structures exposed under sulfate and chloride solutions. Therefore,

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the utilization of CBA as a supplementary cementitious material could be a viable solution to improve the strength and durability performances of concrete structures. When ordinary cement concrete exposed to sulphate solution, it may suffer from two types of destruction, reduction in strength due to C–S–H gel deprivation, and volumetric expansion leading to cracking [17,18]. This attack also triggers the gypsum precipitation and deformation of C-S-H. The deformation of C-S-H destroys the bonding ability of C-S-H and due to that strength loss in concrete. Consequently, sulphate reaction leads towards volumetric expansion and develop internal stresses which create interruption in concrete [19]. Following recent studies were reviewed on concrete contacting difference supplementary cementitious materials under sulphate and chloride exposure conditions;

Aksogan et al., [4] considered 5% $Na_2SO_4$ for the investigation on the durability performance of concrete prepared with partial replacement of fine aggregate by colemanite and barite, and cement by corn stalk, wheat straw and sunflower stalk ashes. Dewi et al., [20] also studied on sodium sulphate (5% $Na_2SO_4$) and sodium chloride (5% NaCl) effect on concrete containing RHA as a cement replacement.

Maes and Belie [3] considered Blast-Furnace Slag (BFS) as a partial cement replacement material in concrete exposed to sodium chloride and sodium sulphate, they were considered 5% $Na_2SO_4$ and 5%NaCl for the period up to 497 days and declared that Blast-Furnace Slag improves the resistance of chloride penetration and sodium sulphate attack in concrete/mortar.

Indu Siva Ranjani & Ramamurthy [21] stated that according to the ACI-318, 5% $Na_2SO_4$ solution considered to be very severe exposure class. Hime & Mather [22] stated that the sulphate attack can be categorized by chemical reaction of sulphate ions (as the aggressive substance) with the aluminate components and ions of sulfate, calcium and hydroxyl of hardened portland cement. Concrete with portland cement can be influenced by solutions containing sulfates (sodium or magnesium sulfate). It was agreed by Biricik, Aköz, Türker, & Berktay [23] that the strength of concrete could be improved by replacing portland cement with pozzolanic materials. However, the concrete structures exposed to sulfate solutions, generally deteriorate due to formation of gypsum and ettringite and it leads to decrease in compressive strength, weight loss, and change in volume [24].

Demir et al., [25] evaluated the performance of OPC mortar in combination with fly ash, bottom ash, and blast-furnace slag as a partial cement replacement under $Na_2SO_4$ solution for the period up-to 360 days. They were found that the compressive strength of blended cement mortar with 5% Fly ash, 5% bottom ash and 5% blast-furnace slag cured in $Na_2SO_4$ for 360 days was around 2% greater than that of OPC mortar. It was also noticed from their study that all specimens tend to decline or closer to the strength performances of 90 days. Therefore, current study considered 90says exposure period for the sulphate as well as for chloride solutions. However, sulphate attack in concrete considered to be an important issue, and it was validated by Aydin [26] that the incorporation of CBA in a concrete as a partial cement replacement gives the good performances and suggested as a beneficial product for the concrete construction, to enhance its strength and durability. It is generally perceived that the utilization of pozzolanic material in concrete could reduce the calcium hydroxide of cement paste and decrease the penetrability of concrete. This modification enhances the concrete resistance under sulphate and chloride solutions [27]. The summary of previous studies on concrete under sulphate and chloride solutions are provided in Table 1.

Currently there are growing concerns about the strength variation of concrete under sulphate exposure conditions [21]. It was previously agreed by Jaturapitakkul and Cheerarot [8] that compressive strength of concrete increases with the use of CBA as partial cement replacement in concrete, Subsequently, Kurama & Kaya [9] were also validated that the compressive strength increased by 6% while using 10% CBA as partial replacement of cement. It was also agreed by Chaipanich and Wongkeo [35] that replacement of OPC with 10% CBA could improve compressive strength by 13% as compared to the OPC concrete. Furthermore, Khan and Ganesh [36] also confirmed that replacement of OPC with 10% CBA could enhance 14% compressive strength and they were also found that cost of construction could be reduced by 10% and reduction in corban dioxide ($CO_2$) emissions. Hence, the CBA has a good potentiality to be utilized as partial cement replacement material in concrete production and it was agreed by Cheriaf et al., [37] that grinding process could improves the pozzolanic activity of the CBA. The literature review on the utilization of CBA in concrete has been conducted and the summary of key findings is provided in Table 2, which indicated the potentiality of CBA. Therefore, this study focused on the utilization CBA as supplementary cementitious material in concrete, under sulphate and chloride exposure conditions.

Considering the previous ideas as cited in Table 1, majority of researchers considered the 5% of sodium sulphate ($Na_2SO_4$) and 5% sodium chloride (NaCl) for long-term experimental and theoretical studies [42]. It was observed that no any study has been reported yet on the short-term effects of sulphate and chloride solutions on the strength performances of concrete containing ground CBA as a supplementary cementitious material. Moreover, considering the earlier inputs as cited in Table 2, the 10% optimum

**Table 1**
Previous studies on concrete under sulphate and chloride solutions.

| Ref. | Materials and method | $Na_2SO_4$ | NaCl | Exposure period |
|---|---|---|---|---|
| [2] | Ordinary portland cement (OPC) and sulfate-resisting cement (SRC) with 20% fly ash | 10% | 5% | 1 year |
| [3] | Blast-Furnace Slag (BFS) as a partial cement replacement material in concrete | 5% | 5% | 497 days |
| [4] | Concrete with partial replacement of fine aggregate by colemanite and barite, and cement by corn stalk, wheat straw and sunflower stalk ashes. | 5% | | 180 days |
| [16] | OPC with blast furnace slag, silica fume, and fly ash | 1%, 2.5%, and 4% | 5% | 4 years |
| [20] | concrete containing RHA as a cement replacement | 5% | 5% | 180 days |
| [21] | OPC foam concrete of densities ranging from 1000 to 1500 $kg/m^3$ | 5% | | 1 year |
| [25] | OPC mortar with fly ash + bottom ash + blast-furnace slag | 10% | | 360 days |
| [27] | OPC cement with addition of building stone waste | 0.15, 0.90 and 1.35 | | 125 days |
| [28] | Concretes with w/c ratios of 0.35 and 0.45 under continuous immersion and dry-wet cycling | 5% | 3.5% | 150 days |
| [29] | OPC with unprocessed pulverized fuel ash (PFA) Mortar | 5% | | 504 days |
| [30] | Self-compacting concrete (SCC) prepared through OPC replaced with fly ash (FA), granulated blast furnace slag (GBFS), limestone powder (LP), basalt powder (BP) and marble powder (MP) | 10% | | 400 days |
| [31] | Concrete under alternate action of carbonation and single surface sulphate attack | 10% | | 360 days |
| [32] | Mortar with polyethylene terephthalate (PET) | 5% | | 28 days |
| [33] | OPC concrete containing rice husk ash under with drying-wetting cycles | | 5% | 180 days |
| [34] | Rice husk ash as a partial replacement of OPC in concrete | | 5 and 10% | 28 days |

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**Table 2**
Previous key findings on coal bottom ash.

| Ref. | Methodology | Suggested | Benefit | Findings |
|---|---|---|---|---|
| [8] | 10, 20 & 30% Original and grounded CBA replacement of OPC | 20% | Good strength performances | Grinding process is necessary to convert original CBA in to a pozzolanic material. Strength not increased at initial ages, but it was observed 11% increased at 90 days |
| [9] | Ground CBA at 5, 10, 15, 20 & 20% cement replacement in 1:3 mix | 10% | Compressive and flexural strength increased 10% at 56 days | Pozzolanic reaction not initiated at early ages due to that strength was not increased up to the age of 28 days |
| [35] | CBA at 10, 20 and 30% cement replacement along with 5% silica fume | 10% | 13% compressive strength increased at 28 days | CBA concrete gives lower strength without silica fume, but due to addition of silica fume, it gives good strength performances even at early ages. |
| [36] | CBA at 10, 20 and 30% cement replacement in cement sand mortar 1: 3 | 10% | 14% compressive strength increased at 56 days. | Pozzolanic reaction not initiated at first 28 days. But strength was significantly elevated after 56 days. Concrete containing CBA also gives good durability performances in terms of resistance to acid ($H_2SO_4$) attack. |
| [38] | 20 and 40% cement replacement with coal combustion bottom ash (CCBA) | 20% | Strength not increased at the age of 28 days | CCBA was grinded for various grinding periods 4, 15, 30 and 45 min) |
| [39] | Fly ash (10 & 25%); Bottom ash (10 & 25%) as cement replacement with SP 1 to 1.3% | 10% | Reduces chloride migration in concrete | Ground CBA was observed as a new durable supplementary cementing material in concrete construction. |
| [40] | Fly ash (25 & 33%); Bottom ash (25 & 33%) as cement replacement | – | Both provides the resistance to environmental actions | FA and CBA reduce the workability of concrete. FA and CBA exabits the comparable compressive strength performances and gives the similar chloride diffusion coefficient and carbonation resistance |
| [41] | Fluidized bed combustion (FBC) to PCC Fly Ash ratio of 3:1 | – | Adequate strength performance for the long-term | 3 mixes were studied non-cement, partial-cement, and control concrete. Lower compressive strengths for non-cement and partial-cement concretes were observed than the control concrete at early ages. But at 90 and 180 days its strength higher than the control. |

replacement level of ordinary portland cement with ground CBA was advised. Therefore, in this study 10% replacement of ordinary portland cement with ground CBA has been nominated. In addition to that concrete with and without CBA was immersed under 5% $Na_2SO_4$ and 5% NaCl solutions for the short-term exposure period up-to 90 days was considered, to evaluate change in weight, variation in compressive strength and degree of damage. Moreover, crushed concrete samples were further investigated through advanced technique of scanning electron microscopy analysis to support the experimental findings.

## 2. Materials and methodology

### 2.1. Materials

In this study ordinary portland cement (OPC) of Tasek Brand was used, which meet the requirements of Malaysian standard MS 522 and BS EN 196-1 [43]. The Coal bottom ash (CBA) was collected from Sultan Salahuddin Abdul Aziz power station, Selangor, Malaysia. It was visually observed that original CBA is mostly coarser, porous in nature and in appearance like a volcanic material as shown in Fig. 1. The SEM image of CBA as presented in Fig. 2, shows that it has irregular, sharp, spherical and porous particles and mix of multi texture. The collected CBA was dried in an oven at 110 ± 5 °C temperature for 24 h, after that it was grinded in Los Angeles machine for the period of 2 h, after passing from 300micron sieve, it was further grinded in a ball mill grinder for the period of 20 h, to get more fine particles like to portland cement. The chemical properties indicated that CBA mainly contained $SiO_2 + Al_2O_3 + Fe_2O_3$ and its sum is more than 70%, thus it can be classified as Class F ash in accordance with the ASTM C618 [44]. The chemical and physical properties of CBA and OPC are provided in Tables 3 and 4 respectively.

### 2.2. Mix proportions

Two types of concrete mixes were prepared; first mix with 100% ordinary portland cement (OPC) and second mix with 90% OPC and 10% coal bottom ash (CBA). The fine aggregate (sand) was passed through 4.75 mm sieve and coarse aggregate of nominal maximum size 10 mm was used. ACI Mix method of concrete mix was adopted and material quantity was calculated as provided in Table 5.

**Fig. 1.** Original Coal bottom ash.

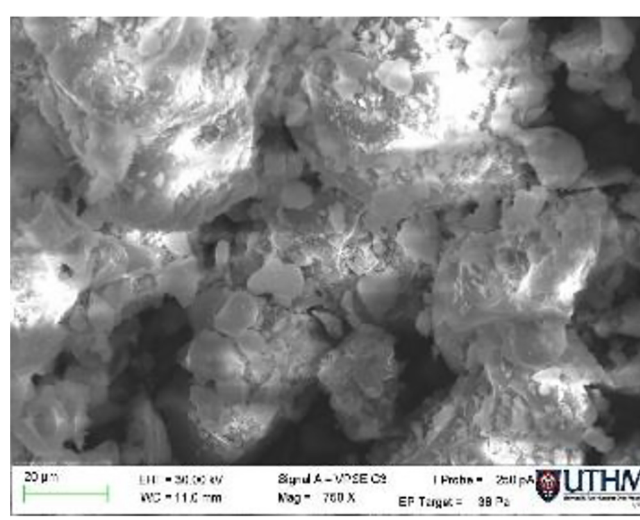


**Fig. 2.** SEM image of coal bottom ash.

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**Table 3**
Chemical composition of OPC and CBA.

| Oxides (%) | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $TiO_2$ | LOI |
|---|---|---|---|---|---|---|---|---|
| OPC | 20.61 | 3.95 | 3.46 | 63.95 | 1.93 | 3.62 | 0.20 | 2.18 |
| CBA | 52.50 | 17.65 | 8.30 | 4.72 | 0.58 | 0.84 | 2.17 | 4.01 |

**Table 4**
Physical properties of OPC and CBA.

| Properties | OPC | CBA |
|---|---|---|
| Particle Size Range (μm) | 3.81–21.15 | 4.03–47.78 |
| Specific surface area ($cm^2/g$) | 4870.81 | 3835.75 |
| Specific gravity ($g/cm^3$) | 3.10 | 2.41 |
| Cement paste | 100% OPC | 90% OPC + 10% CBA |
| Water requirement for standard consistency (%) | 30 | 32 |
| Initial setting time (Minutes) | 90 | 110 |
| Final setting time (Minutes) | 270 | 280 |

### 2.3. Casting and curing

Concrete cubes of size 100 mm were prepared with and without coal bottom ash (CBA) for the determination of compressive strength. Total 54 specimens were prepared, 27 of control mix and 27 of concrete containing 10% CBA as partial cement replacement. Concrete cubes were de-moulding after 24 h of casting and then all specimens were immersed in a water tank for the period of 28 days to get the designed/targeted strength. Afterward, 9 specimens of M1 and 9 specimens of M2 were shifted in each solution of 5% $Na_2SO_4$ and in 5% NaCl, rest of specimens were kept in water for the additional curing period of 28, 56 and 90 days. Specimens were immersed under three different exposure conditions; under water, 5% $Na_2SO_4$ and 5% NaCl solutions as shown in Fig. 3 and the detail of specimens is provided in Table 6.

## 3. Results and discussion

### 3.1. Workability

The workability of concrete was evaluated with slump cone method in according with ASTM C143 [45]. The distance between top of the metallic cone and top of concrete cone was measured as workability of concrete. The detailed results of workability of concrete mix M1 (Control mix) and M2 (Concrete containing 10% ground CBA) are provided in Table 7. The results revealed that 10% slump reduction as compared to control mix, with 10% coal bottom ash in concrete. The reductions in workability are due to the presence of CBA in concrete which absorbed extra water in the mixture, it was also confirmed by Khan & Ganesh [36].

**Table 6**
Detail of specimens.

| Specimen detail | Curing Period (days) | Immersed under | | |
|---|---|---|---|---|
| | | Water | 5% $Na_2SO_4$ | 5% NaCl |
| Control Mix (M1) | 28 | 3 | 3 | 3 |
| | 56 | 3 | 3 | 3 |
| | 90 | 3 | 3 | 3 |
| Concrete containing 10% CBA (M2) | 28 | 3 | 3 | 3 |
| | 56 | 3 | 3 | 3 |
| | 90 | 3 | 3 | 3 |
| Sub total | | 18 | 18 | 18 |
| Total number of specimens | | 54 | | |

### 3.2. Change in weight

The weight of concrete specimens was taken before and after exposure conditions under sodium sulphate and sodium chloride. The results of change in weight of control mix (M1), concrete containing 10% ground CBA (M2) at the curing of 28, 56, and 90 days are provided in Fig. 4. It was observed that both type of

**Table 7**
Workability of concrete.

| Concrete Mix | Slump value (mm) | Remarks |
|---|---|---|
| Control Mix (M1) | 56 | – |
| Mix with 10% CBA (M2) | 50 | 10% reduction |

**Table 5**
Concrete mix design ($kg/m^3$).

| Description | Notation | % Repl. | Cement | CBA | Fine Aggregate | Coarse Aggregate | Water |
|---|---|---|---|---|---|---|---|
| Control Mix Concrete | M1 | 0 | 440 | 0 | 805 | 828 | 220 |
| Concrete Mix with CBA | M2 | 10% | 396 | 44 | 805 | 828 | 220 |


**Fig. 3.** Curing tanks for different exposure conditions.

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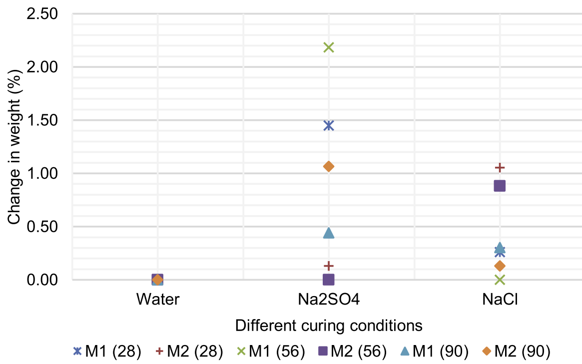


**Fig. 4.** Change in weight of concrete under sulphate and chloride exposure.

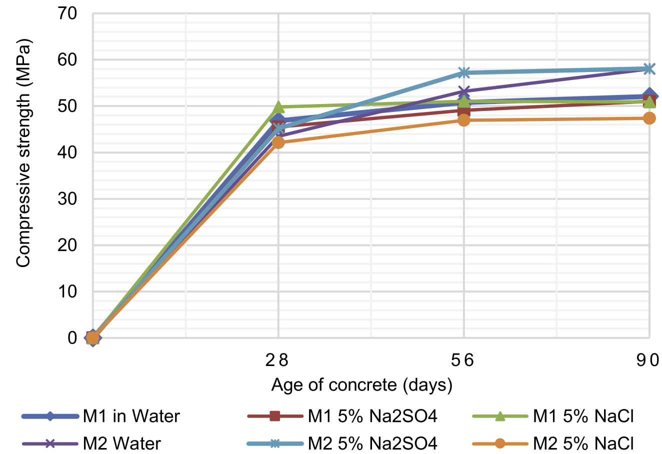


**Fig. 5.** Compressive strength of concrete with and without CBA under sulphate and chloride exposure at different curing ages.

concrete does not change its weight in normal water curing. However, when it was exposed to 5% $Na_2SO_4$ and 5% NaCl solutions, there was notable change in weight was noticed in all mixes. The highest weight gain was observed in M1 under $Na_2SO_4$ at 56 days at the same situation lower weight gain was observed by M2. It shows that concrete containing ground CBA reduces the penetrability of salts and lower values were recorded as compared to the control mix. It was also agreed by Xu, et al., [46] that high strength concrete with 30% fly ash immerged in 10% $Na_2SO_4$ solution provides growth in weight of specimens due to formation of more hydration products and consequently higher quantities of sulphate ions and the reaction products, ettringite and gypsum. This indicated that in the presence of CBA in concrete (M2) could reduce the hydration process and reduces the salts penetrability in the concrete, therefore less weight gain was observed in M2 concrete. It assured that the addition of supplementary cementing material in concrete could reduce the permeability [47,48] of aggressive salts solutions which cause the corrosion in reinforcement and at the end failure of structure. Hence, the overall performance of concrete containing CBA was observed to be adequate under 5% $Na_2SO_4$ and 5% NaCl conditions.

### *3.3. Compressive strength*

Compressive strength results of concrete with and without CBA are provided in Table 8 and graphically presented in Fig. 5.

Under the water curing, the results demonstrated that the performance of M2 (43.5 MPa) is lower than the M1 (46.8 MPa) at the early 28 days, exhibited that pozzolanic reactions does not yet takes place. But at later ages, the compressive strength of M2 is higher around 4.7% and 11.32% than the M1 at the of 56 and 90 days respectively. It was observed that the pozzolanic reaction due to presence of ground CBA was taken place after 56 days and increased continuously with age of concrete.

Beside that under 5% sodium sulphate ($Na_2SO_4$) exposure condition Fig. 5 shows that the performance of concrete containing ground CBA (M2) and concrete without CBA (M1) was found to be comparable at the age of 28 days and 90 days. It was observed that there is not any significant influence of sodium sulphate solution on the concrete with and without CBA for short-term exposure conditions. Similar findings have been reported by Demir et al., [25] they were investigated on OPC mortar with fly ash, bottom ash, and blast-furnace slag as a partial cement replacement under $Na_2SO_4$ solution for the exposure period up-to 360 days and They declared that the compressive strength of blended cement mortar exposed to $Na_2SO_4$ for 360 days was around 2% greater than that of OPC mortar. It was also mentioned by Akoz [49] that lower proportion of $Na_2SO_4$ (0.27–1.8%) has not creates any significant disturbance in the mortar properties even up-to 300 days. Moreover, the mechanism of $Na_2SO_4$ reaction was earlier known as the sulfate ions diffuse in pores of the concrete, and chemical reaction may happen between cement hydration and sulfate ions and $Na_2SO_4$ react with Ca $(OH)_2$ and mono-sulfate develop gypsum and ettringite (crystal needle) in the concrete pores [49,50]. Although the formation of ettringite is not good for long-term but its formation could be reduced due addition of CBA due to reduction in pores sizes of concrete.

Moreover, the strength development in M2 concrete was found to be slower under 5% sodium chloride (NaCl) exposure condition as compared to the M1 concrete. Similar strength development issue was also found in the concrete containing 5% RHA under 5% $Na_2SO_4$ solution [34]. However, the pore size distribution is very important in hardened concrete and due to presence of chloride ions it is being influenced [51]. Chloro-aluminate produced in chloride solutions and deterioration take place by de-calcifications that are more noticeable at later ages [52,53]. The de-calcification effects of NaCl, the porous C-S-H gel formation and the leaching of calcium hydroxide takes place in the concrete [34]. The leaching phenomena of calcium hydroxide (Ca $(OH)_2$) is worth important in the concrete, but due to addition of ground CBA which contained amorphous silica, reacts with the Ca $(OH)_2$ formed by the hydration of cement thus reducing the total Ca $(OH)_2$ existing in the concrete. Therefore, the presence of chlorides, affects the pore sizes and creates disturbance in the hydration process, ultimately affects the physically appearance of concrete. Considering the facts about chloride influence on the concrete, it was observed through experimental results that M1 (control mix) concrete under 5% NaCl solu-

**Table 8**
Compressive strength (MPa) test results.

| Exposure conditions | Water | | 5% $Na_2SO_4$ | | 5% NaCl | |
|---|---|---|---|---|---|---|
| Curing (days) | M1 | M2 | M1 | M2 | M1 | M2 |
| 28 | 46.8 (2.05) | 43.5 (2.18) | 45.5 (1.94) | 45.2 (0.76) | 49.8 (2.85) | 42.1 (5.01) |
| 56 | 50.8 (2.35) | 53.2 (2.25) | 49.1 (1.81) | 57.2 (3.03) | 51.0 (0.75) | 46.9 *(5.20)* |
| 90 | 52.1 (1.30) | 58.0 (1.93) | 51.0 (2.45) | 58.1 (0.84) | 50.9 (1.31) | 47.4 (2.25) |

Values in bracket show the standard deviation of three specimens.

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tion, slowly gain its strength up-to age of 56 days and M1 decline its strength at the exposure period of 90 days. However, the performance of M2 (concrete with CBA) was found to be lower than M1 but continual growth in the strength was notice in the M2.

Hence, it was formerly acknowledged that the pozzolanic reaction consumed calcium hydroxide, making the concrete denser while the product of sulphate attack, ettringite, hard to develop [51,54,56]. However, coal bottom ash (CBA) has less amount of calcium oxide due to that it could reduce the sulphate attack. Hence, it was experimentally found that concrete containing CBA gives the adequate compressive strength and found to be unaffected under $Na_2SO_4$ solution. But under 5% NaCl, its pozzolanic reaction become slow and takes more time to recover.

### 3.4. Variation in compressive strength

In this study, the variation in compressive strength was obtained through the strength comparison of M2 (concrete with ground CBA) with reference to M1 (concrete without ground CBA) under different exposure conditions at the age of 28, 56 and 90 days. It was observed that at the early age of 28 days compressive strength of concrete containing ground CBA was not increased but the significant rise in the compressive strength was notices at the age of 56 and 90 day except NaCl exposure conditions. The superior performance of concrete containing CBA was observed under water and $Na_2SO_4$ solution. It has attained almost 11.32% and 13.92% higher strength than the control mix in water and $Na_2SO_4$ exposure conditions respectively at the age of 90 days. Subsequently, the reduction in strength variation was noticed in concrete containing CBA under 5% NaCl solution. The results analysis of percentage variation in compressive strength concrete containing CBA under sodium sulphate and sodium chloride exposure at different curing ages are demonstrated in Fig. 6.

### 3.5. Degree of damage

The damage degree can be defined as the sign of deterioration of concrete and according to the definition of the damage degree, the following formula was used to calculate damage degree and it was previously obtained by Niu, [57]:

$$Di = 1 - \frac{\sigma i}{\sigma o} \quad (1)$$

Whereas, Di is the degree of damage after certain immersing period; $\sigma$i is the compressive strength of concrete after certain immersing time; and $\sigma$o is the initial compressive strength of concrete. In this study the $\sigma$o value represents the compressive strength value of M1 and M2 at the age of 28 days, before shifted into sulphate and chloride solutions. The concrete degree of damage with and without CBA exposed to sulphate and chloride conditions were evaluated by above Eq. (1) and results are graphically presented in Fig. 7. The results demonstrated that the higher degree of damage was noticed in control mix (M1) at all conditions. Beside that concrete containing ground CBA (M2) have less degree of damage as compared to the control mix(M1). It was also agreed by Ming et al., [33] that the increase in damage degree gives reduction in the bearing of the concrete construction and after some time the damage reaches a certain degree, the concrete structure will fail entirely. However, higher values were noticed in M1 concrete -0.14, -0.15 and -0.17 under NaCl, $Na_2SO_4$ and water respectively. Subsequently, lower values were observed in M2 concrete -0.21, -0.48 and -0.48 under NaCl, $Na_2SO_4$ and water respectively. Thus, here it is specified as lower the degree of damage, higher the strength and durability of concrete.

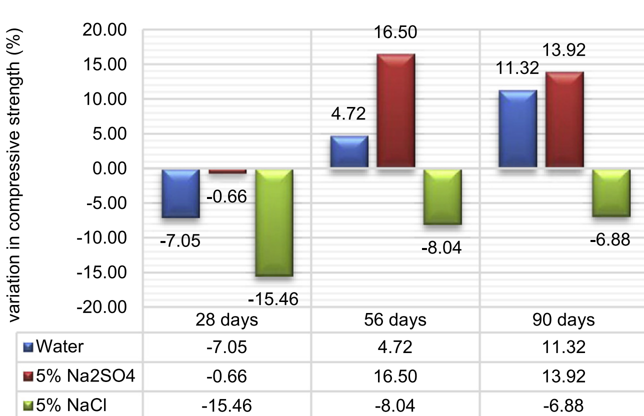


**Fig. 6.** Variation in compressive strength of concrete containing CBA under sulphate and chloride exposure at different curing ages.

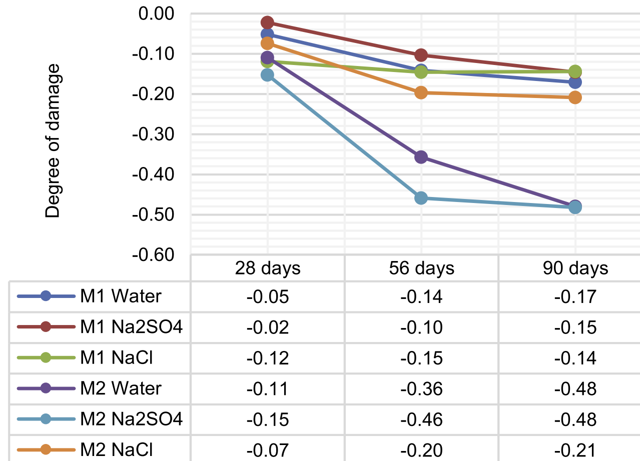


**Fig. 7.** Degree of damage of concrete containing CBA under sulphate and chloride exposure at different curing ages.

### 3.6. Scanning electron microscopy

The scanning electron microscopy analysis of concrete containing coal bottom ash (CBA) under water, 5% sodium sulphate ($Na_2SO_4$) and 5% sodium chloride (NaCl) exposure conditions at the total age of 56 days were performed at Environmental analysis laboratory Universiti Tun Hussein Onn Malaysia (UTHM) and

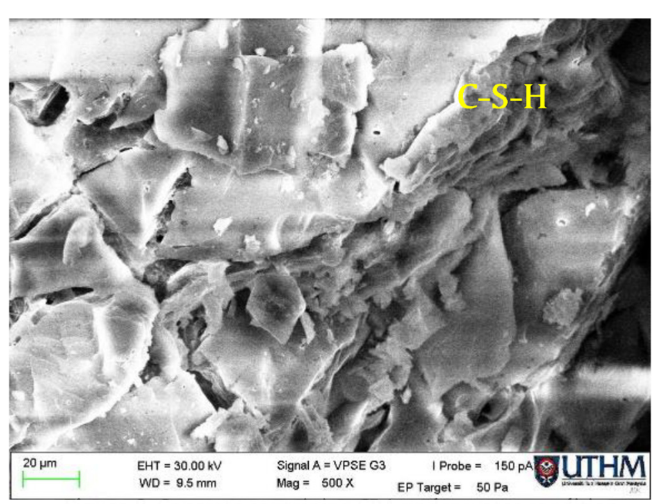


**Fig. 8.** Concrete containing CBA under water condition.

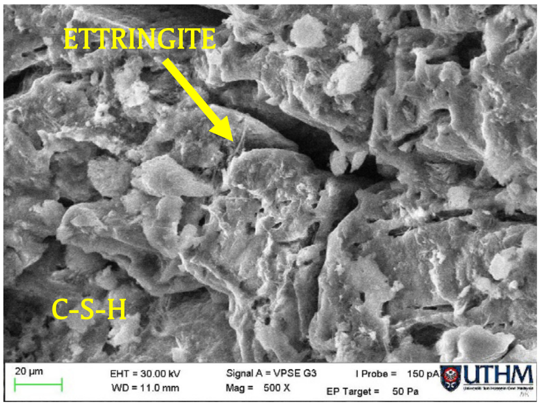


**Fig. 9.** Concrete containing CBA under 5% $Na_2SO_4$ solution.

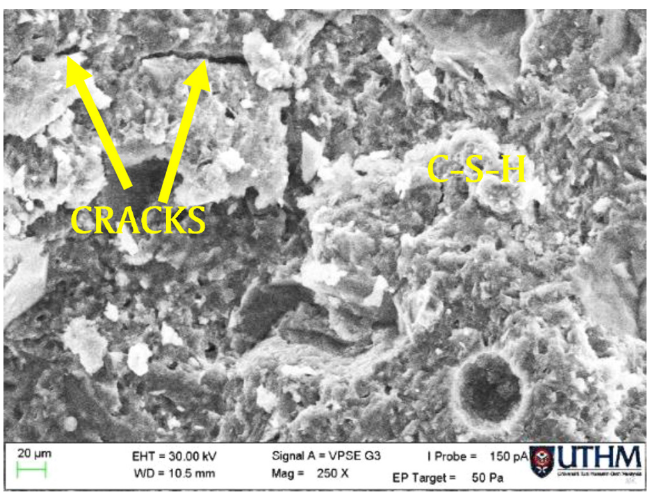


**Fig. 10.** Concrete containing CBA under 5% NaCl solution.

images are illustrated in Figs. 8–10, it can clearly be observed that pozzolanic reaction begins at the age of 56 days and a reaction among calcium hydroxide and CBA was noticed to form well shape of C-S-H. The formation of C-S-H gel was also found in the concrete containing ground CBA. While it was exposed under $Na_2SO_4$ solution, slight portion of ettringite (white, needle-like crystals) was formed within the concrete, which could partial filling the voids in the concrete and leads to the strength development [34,55]. Similarly, C-S-H formation was also noticed in CBA concrete under NaCl solution, but here a sign of crack development was noticed, which is the significant case of reduction in compressive strength.

## 4. Conclusions

Following conclusions could be drawn from the experiment study;

i. This study indicated the potentiality of coal bottom ash (CBA) as partial replacement of ordinary portland cement in concrete under normal as well as in aggressive environment.
ii. It was observed that concrete with and without CBA does not change its weight in normal water curing. However, when they were exposed to 5% $Na_2SO_4$ and 5% NaCl solutions, notable change in weight was observed in all mixes. The highest weight gain was observed in control mix(M1). However, the presence of CBA in concrete (M2) could reduce the hydration process and decreases the salts penetrability, therefore less weight gain was observed in M2.
iii. The strength performance of M2 (concrete with CBA) is lower than the M1 (concrete without CBA) cured in water at the early age of 28 days. It indicates that pozzolanic reactions does not yet initiated, but at later ages, the compressive strength of M2 is higher around 4.7% and 11.32% than the M1 at the of 56 and 90 days respectively.
iv. The performance of concrete containing CBA (M2) and concrete without CBA (M1) under 5% sodium sulphate ($Na_2SO_4$) exposure was found to be comparable up-to 90 days. There is not any substantial influence of $Na_2SO_4$ solution on the concrete with and without CBA for short-term exposure.
v. Under the 5% sodium chloride (NaCl) solution, M1 (concrete without CBA) concrete slowly gain its strength up-to age of 56 days and decline its strength at the exposure period of 90 days. However, the performance of M2 (concrete with CBA) was found to be lower than M1 but continual growth in the strength was notice in the M2.
vi. The application of CBA as a partial cement replacement does not have any adverse effects on the strength performances of the concrete. However, it delivers adequate strength performances under normal water as well as in sulphate and chloride exposure conditions.
vii. The possibility of replacing ordinary cement with industrial waste such as CBA offers technical, and environmental benefits which are of foremost importance in the current situation of sustainable development.

Hence, the ground CBA is recommended as a pozzolanic material and it is hereby suggested that future studies required to extend the research boundaries on its long-term strength and durability performances under combined effects of sulphate and chloride and seawater exposure.

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