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Strength Behaviour of Coal Bottom Ash Self-Compacting Concrete Exposed to Cyclic Wetting-Drying in Seawater

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Abstract: This study presents the strength behaviour of the self-compacting concrete which incorporated the coal bottom ash that was exposed to cyclic wetting and drying processes under the condition of seawater environment. The mixtures were produced by combining 0.40 water/powder ratio and coal bottom ash in varying percentages of 0, 10, 15, 20, 25 and 30%. The samples arising from each mixture were exposed to seawater environment with an average of 15 h of wetting process and 9 h of drying process per day. Consequently, the compressive strength behaviour of the concrete at the durations of 28, 60, 90 and 180 days under curing process were observed to understand the physical mechanisms that affected the concrete during the cyclic wetting and drying phases while exposed to harsh environments. The results of the cyclic wetting and drying processes in the laboratory indicated that there were significant strength reductions across all mixtures. It was found that that the strength of 10% coal bottom ash replacement sample is slightly higher than the control samples.

Key words: Compressive strength, coal bottom ash, wetting-drying, self-compacting concrete, seawater envrinment, physical mechanisms

INTRODUCTION

The durability of concrete contributed significantly to the construction industry; however, harsh environments were known to influence the durability of the concrete (Nie *et al*., 2014). It is important to understand that the term durability itself is defined as the capability of the concrete to maintain its performance and every aspects of its strength during a long period of exposure to normal and harsh environments (Otieno *et al*., 2016). In practice, concrete and cement-based materials must be able to operate in a combination of harsh and aqueous based environments. The harsh environments can be referred as a situation in which the concrete might suffer from degradation where the ion addition and/or ion exchange reactions will occur, hence leading to a breakdown of the matrix microstructure and consequent weakening of the structure. The degradation of the concrete was due to the interplay of several causal factors, namely harsh environment, marginal aggregations, inappropriate specifications and unskilled manpower (Bader, 2003). However, the durability of the concrete referred to its ability of resisting quality degradation after a prolonged exposure to environments that induced deleterious effects to the concrete. In other words, the concrete failure may be prone to internal or external factors. The internal factors are related to the materials selection and unsuitable combination of materials. For the case of the external factors, the problems arise due to the physical or chemical effects contributed by the nature such as weathering, extreme variations in temperature, wetting and drying cycles,

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abrasion and exposure to harsh environment. Concrete durability under harsh environment had drawn the attentions of engineers and scientists for over a century where the durability of concrete is as important as the compressive strength. Some of the harsh environments that a concrete structure usually experienced were alkali aggregated reaction, sulfate attack, chloride attack, acid attack, effect of seawater, effect of de-icing salts, efflorescence and direct contact to fire. According to Zacarias concrete structure that was exposed to severe conditions can be affected by three factors, namely environmental condition, chemical attack and others factor. The investigation on the concrete performance under harsh environment still requires extensive input where some of the parameters including concrete type, cement type, cement and chemical composition and admixture had been widely explored. However, several parameters including aggressive chemical concentration, temperature exposure, wetting and drying cycles, still require further and extended investigations (Jaya *et al*., 2014). Most importantly, concrete structure experienced severe deterioration during the wetting and drying cycle (Sahmaran *et al*., 2007), hence this particular investigation is extremely crucial. It is significant to study the influence of aggressive environment as a different type of concrete in saline environment exhibit different results. An innovative concrete called as self-compacting concrete are being developed and adjusted to extend concrete service life in the harsh environment including by utilized by-product in concrete production.

Self-compacting concrete incorporating coal bottom ash: Self-compacting concrete is a modern innovative method in concrete technology which can be categorized as a new type of high performance concrete with excellent deformability and segregation resistance (Hamzah *et al*., 2015). This particular concrete utilized the same cementitious material as in the production of normal concrete, except for the addition of either superplasticizer, viscosity modification agent or both. It had been reported that there were numbers of potentially wasted by products been used to produce the self-compacting concrete including fly ash, silica fume, granulated blast furnace slag, untreated rice husk and many more. These wasted by-products were used as part of the concrete construction, either as a filler or replacement to finely aggregate into cement. Generally, the by-product arise from thermal power plants including fly ash had been widely used in concrete industries as a pozzolanic material which replaced a part of cement due to its main benefits of higher workability and durability (Kasemchaisiri and Tangtermsirikul, 2008; Abidin *et al*., 2014). Apart from that coal bottom ash is one of the by-product materials that generated thorough coal-fired power plant. However, coal bottom ashes are less prevalent during the concrete production whereby very few studies had focused on the use of coal bottom ash within the production of self-compacting concrete, especially in the context of Malaysia (Abubakar and Baharudin, 2012).

Upon realizing the unique nature of the local environmental conditions and the locally available construction materials this research was initiated at Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia to successfully assess the concrete performance under localized harsh environmental conditions. As part of this research framework a laboratory study was initiated to investigate the durability of the self compacting concrete with the incorporation of coal bottom ash that was subjected to a weathering simulation via wetting and drying cycles. The main objective of this study was to explore the impact of coal bottom ash as a replacement material for sand and the relative strength performance of the self-compacting concrete while being exposed to seawater.

MATERIALS AND METHODS

In this study, the materials that were used underwent the similar process of the conventional concrete production. Silica-rich coal fly ash and Portland fly ash cements complied with MS EN 197-1:2007 standard which were widely used during the concrete making process within the main binder (Nochaiya *et al*., 2010). The fine aggregation included both coal bottom ash and river sand where the coal bottom ash was collected from one of the coal-fired power plant in Selangor, Malaysia that had a fine classified distribution size within the range of 0.075-20 mm. The coarse aggregations were graded according to the sizing of 16 mm and retained at 10 mm, meanwhile for the fine aggregations the sizing were in the range of 5 mm. Polymer-based superplasticizer with a specific gravity of 1.09 and pH value of 5.29 was used to magnify the workability of fresh concrete. Subsequently, the analysis of the coal bottom ash was examined by X-Ray Fluorescence (XRF). The chemical composition and physical properties of the coal bottom ash and cement are presented in Table 1.

The proportion of concrete mixtures was adopted from the proposed report by Jawahar (Nochaiya *et al*., 2010). The key proportions of the compositions are presented in Table 2. The water/binder ratio of 0.40 was considered for all six batches, namely SCC-BA0, SCC-BA10, SCC-BA15, SCC-BA20, SCC-BA25 and SCC-BA30. Based on the experimental work, coal bottom

Table 1: Chemical composition and physical properties of cement and coal bottom ash

	Chemical composition (%)											Physical properties		
Contents	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	TiO_2	MgO	Na_2O	CO_2	MnO	Loss on ignition	Specific gravity	Water (%) absorption	Moisture (%) content
Coal bottom ash	68.9	18.70	6.50	1.61	1.52	1.33	0.53	0.24	0.1	-	2.68	1.72	37.2	40
Cement	22.0	8.35	3.92	58.90	1.01	0.72	0.52	0.26	0.1	0.15	1.72	3.00	-	-

Table 2: Mix proportions in kg/m^3

Mix	Cement	Coarse aggregates	Fine aggregates	Coal bottom ash	Water	SP (%)
SCC-0BA	518	715.5	874.50	0.00	207.20	0.16
SCC-10BA	518	715.5	787.05	87.45	207.20	0.20
SCC-15BA	518	715.5	743.33	131.18	207.20	0.26
SCC-20BA	518	715.5	699.60	174.90	207.20	0.32
SCC-25BA	518	715.5	655.88	218.63	207.20	0.16
SCC-30BA	518	715.5	612.15	262.35	207.20	0.20

Table 3: Analysis of seawater

Chemicals	Symbols	Unit	Content
Sodium	Na^+	ppm	2075-2415
Potassium	K^+	ppm	389
Calcium	Ca^{2+}	ppm	293
Magnesium	Mg^{2+}	ppm	1073
Chloride	Cl^-	ppm	16219-18310
Sulphate	SO^{-2}_4	ppm	1967-2381

ash was partly substituted with sand gradually at the ratings of 10, 15, 20, 25 and 30%. The coarse aggregations and fine aggregations were well-maintained at 28% of concrete volume and 45% of mortar volume, respectively. During the experiment, the air content was assumed to be at 2% for all mixtures.

Casting and laboratory procedure: The cube specimens with a dimension of 100×100×100 mm were prepared accordingly to BS EN 12390-1:2012 and BS EN 12350-1:2009 standards. The fresh properties of the mixtures, namely slump flow, slump spread Time (T500), L-box ratio and segregation resistance were performed before the molding process. These tests were important to classify the rating and suitability of the mixtures to maintain a fresh state of self-compacting concrete. All specimens were unmolded after 24 h and placed in a water tank for curing process for up to 28 days. Thereafter, the cyclic simulation through wetting and drying processes were initiated.

Laboratory cyclic simulation and compression test: The cyclic simulation technique that was adopted in this study had been successfully applied by other researchers as reported by Ramadhansyah *et al.* (2012). The specimens were positioned in a square shaped 10 litre plastic container that was filled with seawater. Table 3 presents the analysis of the seawater that was used during the cyclic wetting and drying processes. In the drying cycles, specimens will be placed in an enclosed chamber with temperatures ranging from 25-31°C which was considered as a single cycle. In the next cycles, the samples will be placed again in the solutions for 15 h, followed by 9 h in enclosed chamber where the specimens will be located for the final drying stage. These processes were repeated until the periods of the cycles were completed as according to Ramadhansyah *et al.* (2012), MMD (2009), and McKnight and Hess (2000) whereby the time interval of wetting and drying cycles to emulate the Malaysian climate conditions require 15 h of wetting period, followed by 9 h of drying per day. The solutions were refreshed every week or as per requirement basis according to the changes of pH value. The densities of the concrete were recorded and the compressive strength was tested at the specimen's age of 28, 60, 90 and 180 days. In the case of compression test, the procedures of the test were conducted according to the technique described by the British Standard.

RESULTS AND DISCUSSION

Weight loss: The weight loss in the specimens is due to the seawater combination with wetting and drying cycles as presented in Fig. 1. Generally, the weight loss of control and coal bottom ashes self-compacting concrete initially increases at the early period of exposure. For an instance the weight loss due to seawater attack with cyclic wetting and drying processes after 28 days is 1.63% for controlled concrete specimens and subsequently followed by losses of 1.51, 1.68, 1.70, 1.72 and 1.72% for SCC-10BA, SCC-15BA, SCC-20BA and SCC-30BA, respectively. However, after 180 days of cycle, the weight losses of SCC-0BA, SCC-10BA, SCC-15BA, SCC-20BA, SCC-25BA and SCC-30BA samples are 4.11, 4.03, 4.28, 4.69, 4.58 and 4.92%, respectively. As reflected in Fig. 1, the weight of the concrete specimens increased proportionally to the time exposure. This could be attributed to the pores infiltration by the expansive reactive products such as ettringite thus densifying the hardened concrete and increasing the weight loss.

Compressive strength: Figure 2 depicts the compressive strength of self-compacting concrete which is a reflection of coal bottom ash added in the form fine aggregation and subjected to exposure of seawater environment. The specimens are cured by placing it underwater for 28 days and the cyclic simulation of wetting and drying processes

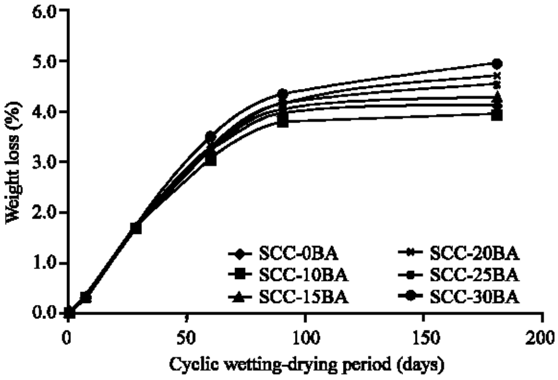

Fig. 1: Weight loss of coal bottom ash self-compacting concrete due to seawater attack

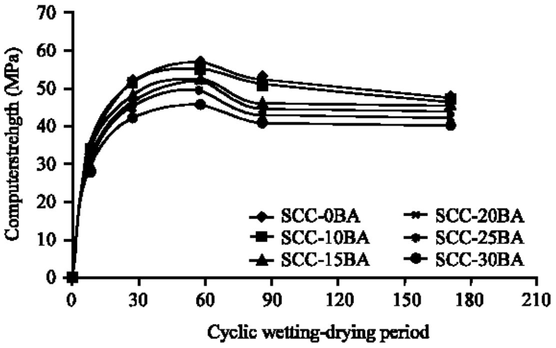

Fig. 2: Compressive strength of coal bottom ash self-compacting concrete due to seawater attack

are started from period of 29 days. From Fig. 2, it can be seen that the strength initially increased up to 60 days, followed by a declining trend until the specimens ultimately disintegrated after 180 days. Such trend could be explained via two different mechanisms that involved in influencing the increment of strength. Firstly, the formation of Calcium Hydroxide ($Ca(OH)_2$) by adding the coal bottom ash, pozzolanic and cementitious materials which transformed into Calcium Silicate Hydrate (CSH) gel. As a result, the strength of the concrete increased. Secondly, the reactions of sulphate and chloride ions with hydrated cement content formed the ettringite where the formation contributed to the increasing concrete strength. Conversely, the decrease in compressive strength is observed in this study which is predominantly arise from two phenomenon, namely disintegration as a result of the reaction of $MgSO_4$ with hydrated cement and the continuous process of crystallization cycles of $MgSO_4.nH_2O$ by wetting and drying processes of the hardened pastes thus produced pores internal stresses leading to the formation of cracks. Ganjian and Pouya (2009) explained that concrete or mortars that are exposed to seawater during the cyclic condition can be affected by the salts crystallization, hence distressing the defensive layer that facilitated the ions ingress. The reaction of specimens that are subjected to seawater is similar to the sulphate and chloride solutions, however the effects are not similar due to the inclusion of chloride ions (Hossain, 2008). The effect of seawater has been attributed to the reaction of $MgSO_4$ with $Ca(OH)_2$ which formed gypsum and $Mg(OH)_2$ (Hossain *et al*., 2009). On the other hand, Amoudi (2002) and Hossain *et al.* (2009) and Zega *et al*., 2016) stated that the presence of chlorides in seawater reacted with $Ca(OH)_2$ and as well as C_3A which produced the Friedel's salt. This statement was supported by Santhanam *et al.* (2002) who claimed that the formation of Friedel's salts was possible if one of the factors led to compressive strength reduction. As illustrated in Fig. 2, self-compacting concrete with 10% of replacement of coal bottom ash to sand exhibited a significant increase of compressive strength and demonstrated more resistant to seawater attack compared to other mixtures in a period of up to 28 days. However, at the cyclic period of 60-180 days, the control specimens exhibited significant improvement in the strength value while SCC-10BA demonstrated slightly lower value than the control. For an instance, at the age of 28 days, the compressive strength of SCC-0BA, SCC-10BA, SCC-15BA, SCC-20BA, SCC-20BA, SCC-25BA and SCC-30BA are 55.23, 56.12, 51.79, 50.08, 49.20 and 45.89 MPa, respectively. At the age of 180 days, the compressive strengths of SCC-0BA concrete that is subjected to seawater resulted in 51.23 MPa whereas for SCC-10BA, SCC-15BA, SCC-20BA, SCC-20BA, SCC-25BA and SCC-30BA, the values are approximately 50.42, 49.30, 47.89, 45.91 and 43.72 MPa, respectively. From the overall measurements, it can be concluded that the incorporation of 10% of coal bottom ash to replace sand in the concrete exhibited good strength with a material behaviour that is comparable to that of control mixtures. The quality of the proposed mixture exhibited improvement even after the exposure to seawater environment via cyclic wetting and drying processes. Kasemchaisiri and Tangtermsirikul (2008) had reported on the properties of self-compacting concrete that contained coal bottom ash which was a replacement material with fine aggregation and observed a 10% improvement and subsequently claimed the achievement as a good performance measure in terms of strength and durability. All the specimens including control, demonstrated a strength reduction. The result indicated that the 10% replacement of sand with coal bottom ash can be potentially applied in the construction of marine structures which require high durability and strength.

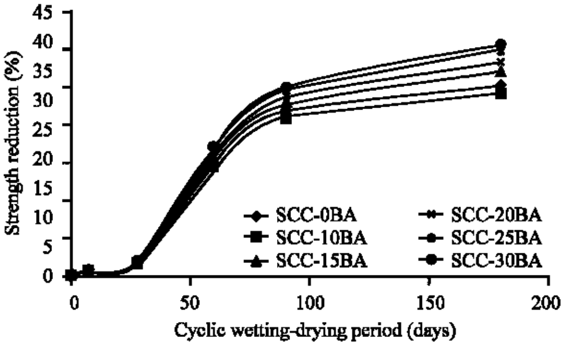

Fig. 3: Strength reduction of coal bottom ash self-compacting concrete due to seawater attack

Strength reduction: Figure 3 demonstrated the strength reduction of the specimen subjected to the seawater whereby it increased proportionally with the age of exposure. The strength reductions are calculated in the form of percentage as presented in Eq. 1. It shows a subtraction of the average strength of the specimens that are subjected to seawater exposure and the average strength of the specimens which are cured in tap water. It is clear that the increase of strength reduction started after 28 days of consistent exposure which consequently lead to the formation of ettringite. For an instance, at 28 days of exposure to seawater with wetting and drying processes, the strength reduction of SCC-0BA, SCC-10BA, SCC-15BA, SCC-20BA, SCC-25BA and SCC-30BA are 1.15, 1.13, 1.83, 2.04, 2.05 and 2.36%, respectively. However, after the 180 days cycle, the reduction in the compressive strength of SCC-0BA, SCC-10BA, SCC-15BA, SCC-20BA and SCC-30BA are 32.34, 31.54, 34.64, 36.28, 38.52 and 39.28%, respectively. The decreasing trend in the compressive strength is revealed to be an association with the exposure of cyclic seawater wetting and drying processes which lead to the increase of salts crystallization and gypsum and ettringite. Therefore, the concrete gradually became porous due to the leaching action of the product which contributed loss to the concrete strength (Islam and Islam, 2010). Based on the Fig. 3, it can be observed that the increase in the amount of coal bottom ash replacement lead to a higher reduction in strength. The finding of the proposed study is paralleled with many researchers who have found that the presence of pozzolanic materials in a hardened cement paste led to a greater loss in strength (Ramadhansyah *et al.*, 2012; Islam and Islam, 2010; Abidin *et al.*, 2015; Aggarwal and Siddique, 2014). Despite that coal bottom ash possessed similar size and behaviour to natural sand, the chemical composition of coal bottom ash provided unique pozzolanic properties similar to cementitious materials which resulted in a favourable time-dependent increase in strength:

$$\text{Reduction (\%)} = \frac{f'_{dw} - f'_{sw}}{f'_{dw}} \times 100 \qquad (1)$$

CONCLUSION

The effects of partial replacement of coal bottom ash in the self-compacting concrete and concurrent exposure to seawater via wetting and drying cycles were experimentally investigated. The results of the proposed investigation demonstrated that all specimens including the control were affected when placed under a saline environment. However, it was found that the increase of coal bottom ash content actually resulted in the reduction of compressive strength which can also caused the increase of weight loss of the hardened concrete. By properly controlling the mixture of coal bottom ash, for an example by incorporating only 10% of coal bottom ash as a replacement of sand in self-compacting concrete, good strength and comparable results to that of control mixtures were observed even after the exposure to seawater environment via cyclic wetting and drying processes.

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