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Contributed Paper

Strength, Chloride Penetration and Corrosion Resistance of Ternary Blends of Portland Cement Self-compacting Concrete Containing Bagasse Ash and Rice Husk-bark Ash

Sumrerng Rukzon* [a] and Prinya Chindaprasirt [b]
[a] Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Rattanakosin, Nakhon Pathom, 73170 Thailand.
[b] Sustainable Infrastructure Research and Development Center,Department of Civil Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen, 40002 Thailand.
* Author for correspondence; e-mail: sumrerng.ruk@rmutr.ac.th

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ABSTRACT

This paper presents a study on the strength, chloride penetration and resistance to corrosion of SCC made with ternary blend of Portland cement containing ground bagasse ash (BA) and ground rice husk-bark ash (RB). Portland cement type I (CT) was partially replaced by BA and RB at dosage levels of 0%, 10%, 15%, 20%, 30% and 40% by weight of cementitious materials. Test results reveal that the use of BA and RB produced excellent resistance to chloride penetration. The compressive strength of SCC containing RB was higher than that containing only CT and only BA. The concrete containing ternary blends viz., 15% of BA+15% of RB or 20% of BA+20% of RB were better than those containing only 30% of BA or 40% of BA. The compressive strength is a significant factor as it directly affects the chloride penetration of the self-compacting concrete.

Keywords: Chloride, corrosion, self-compacting concrete, bagasse ash, rice husk-bark ash

1. INTRODUCTION

Today self-compacting concrete (SCC) has evolved to become a preferred building material owing to its structural complexity in place where conventional concrete is used. In addition, SCC is extensively utilized in many construction buildings owing to its excellent fresh state characteristics with high-workability and favorable mechanical properties in hardened state [1-4].

Pozzolanic materials such as fly ash, rice husk ash, palm oil fuel ash and bagasse ash are increasingly applied in the production of concrete instead of solely using cement [2-7]. In contrast, pozzolanic materials demonstrate more reactivity compared to normal cement. The product obtained from the reaction is calcium silicate hydrate (CSH), which can penetrate the cavities of concrete resulting in a reduction of the average pore size. From this reaction, the texture of the concrete has more density resulting in stronger concrete.

Rice husk-bark ash is waste material generated by small plants in Thailand when two portions of rice husk and one portion of eucalyptus bark are fuel burnt at 800-900°C [7,8]. The residue of the fuel burning is the useless rice husk-bark ash; however, it has been found to be a substitute for cement in producing concrete. There is very few research on rice husk-bark ash characteristics and its mechanical properties, related to self-compacting concrete work [4].

Bagasse ash is another cited waste material; it is the by-product obtained in sugar mills in some parts of Thailand. Sugar cane is the raw material used for producing sugar [7]. If bagasse ash can be applied to manufacture new pozzolanic cement for the construction industry, it is anticipated that the production cost will be decreased and reduce ash waste. Moreover, it will be a good way of earning for the community enterprise to produce this new material in the future.

The application of bagasse ash and rice husk-bark ash for making concrete was mentioned in some previous research articles [8,9]. However, these investigations focused on only one pozzolanic material mixed with cement. Unfortunately, at present there are fewer studies about the combination of two pozzolanic materials for producing self-compacting concrete (SCC) instead of single cement. It is necessary for many construction projects to consider the cost savings of concrete production, the convenience, and the swiftness as well. The purpose of this research is to evaluate the utilization of rice husk-bark ash and bagasse ash as pozzolans for partially replacing Portland cement to produce self-compacting concrete (SCC) in addition to reducing negative environmental effects and landfill volume which is required for eliminating the waste of ash [7,10,11]. This research presents the use of two kinds of pozzolanic materials in producing self-compacting concrete (SCC). Cement can partially be replaced by either one or the combination of both bagasse ash and rice husk-bark ash.

2. MATERIALS AND EXPERIMENT DETAILS

2.1 Materials

Portland cement type I (CT), rice husk-bark ash, bagasse ash and Superplasticizer were the materials used for this study. Local crushed limestone was used as coarse aggregate. The coarse aggregate was locally available crushed limestone with a maximum size of 12.5 mm, fineness modulus of 7.0 and specific gravity of 2.74. The maximum aggregate size of 12.5 mm was chosen because it produces the high-workability concrete without segregation problems. In addition, graded river sand was used as fine aggregate. Rice husk-bark ash and bagasse ash were ground by a ball mill until 3% weight was retained on a sieve No. 325# (opening 45 μm). It is observed that the increased fineness of pozzolanic materials resulted in an increase of the surface area and pozzolanic reaction [12].

2.1.1 Physical properties of materials

Physical properties of Type I Portland cement (CT), ground rice husk-bark ash (RB) and bagasse ash (BA) are shown in Table 1. The RB is characterized by a specific gravity of 2.24 and a specific surface of 11,500 cm^2/g. Specific gravity and specific surface of BA were 2.23 and 11,000 cm^2/g, respectively. The particle size distribution as presented in Figure 1. In addition, the SEM images of the BA and RB are shown in Figure 2a) and 2b). After grinding, BA and RB mainly consisting of fine irregular-shaped particles (see Figure 2.)

Table 1. Specific gravity and fineness of materials.

Physical properties	CT	BA	RB
Median particle size (μm), d_{50}	25	18	20
Retained on a sieve No. 325 (%)	N/A	3	3
Specific Gravity	3.14	2.23	2.24
Blaine Fineness (cm^2/g)	3,600	11,000	11,500

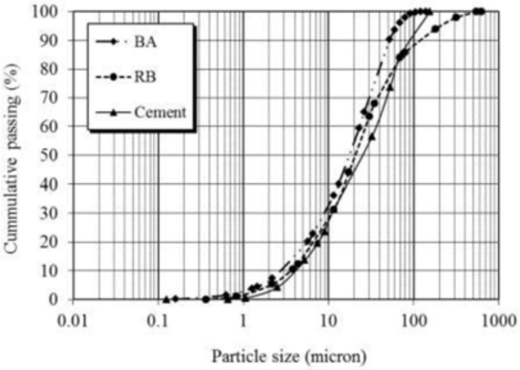
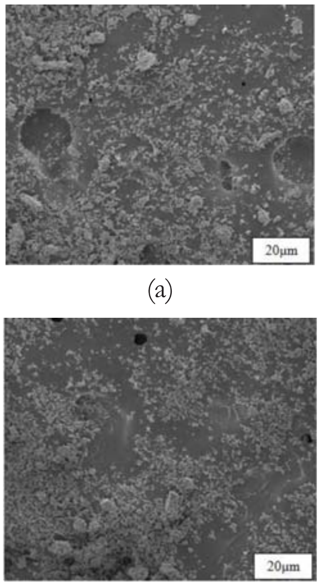


Figure 1. The particle size distribution of CT (Cement), RB and BA.



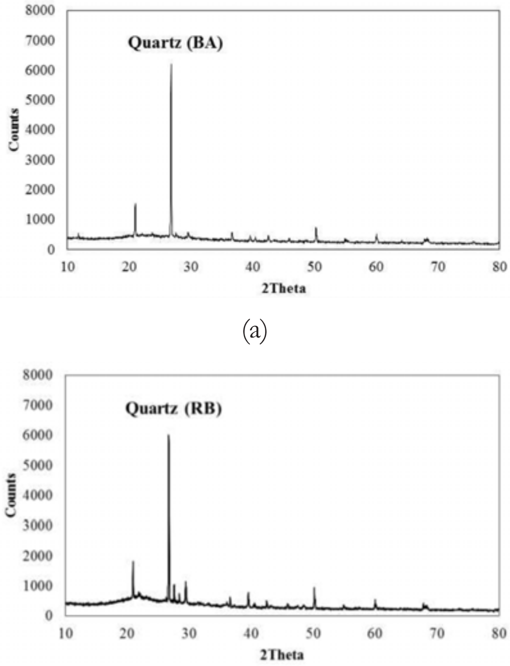
(a)

(b)

Figure 2. SEM images of a) bagasse ash (BA) and b) rice husk-bark ash (RB).

2.1.2 Chemical compositions of materials

The powder sample was used to determine the amount of chemical compositions in the XRF analysis. The results of the chemical compositions test are presented in the Table 2. It is found that CaO (54.9%) is the major component of CT. By XRF analyzing the chemical factors of the BA, the most important element of BA is SiO_2 (65%). Loss on Ignition (LOI) is 18%. The product of SiO_2+Al_2O_3+Fe_2O_3 is 73.2%, which is higher than 70%. Therefore, the ground bagasse ash is the common pozzolanic material classified as Class N [13]. For rice husk-bark ash, RB composed of 76% SiO_2 with 8.2% LOI [7]. The sum of SiO_2, Al_2O_3 and Fe_2O_3 is 79.0%. Also RB could be classified as Class N pozzolanic material [13]. In addition, the XRD pattern (X-ray diffraction) of BA and RB powders as shown in Figure 3a) and 3b) confirms that it consists mainly of amorphous silica.



(a)

(b)

Figure 3. XRD patterns of a) bagasse ash (BA) and b) rice husk-bark ash (RB).

Table 2. Chemical compositions of pozzolanic materials.

Oxides (%)	CT	RB	BA
CaO	54.9	5.5	9.0
SiO_2	25.0	76.0	65.0
Al_2O_3	5.5	1.5	5
Fe_2O_3	5.5	1.5	3.2
MgO	3.0	-	-
K_2O	0.5	3.9	2.0
SO_3	4.5	0.9	0.9
LOI	0.9	8.2	18.0
SiO_2+ Al_2O_3+ Fe_2O_3	-	79.0	73.2

2.2 Mix Proportions of SCC and Curing Methods

Portland cement type I (CT) was partially replaced with RB and BA at the dosages of 0%, 10%, 15%, 20%, 30% and 40%. CT was partially replaced with pozzolans in order to produce pozzolanic self-compacting concrete (SCC) having a compressive strength at 28 days higher than 30 MPa (design at 28 days). Single pozzolan and a blend of different weight portions of BA and BA were also used. The content of cementitious materials (or binder) was maintained at 650 kg/m^3. All concrete mixtures had constant water to binder ratio (W/B) of 0.46. As the slump flow test is an easy method to identify self-compacting concrete, it was thus used for determining the workability of mixtures. A Superplasticizer (SP) was used for maintaining high-workability with a slump flow of 650-800 mm. These values conformed to those required for self-compacting concrete [2-4].

The cast specimens were covered with polyurethane sheet and damped cloth and placed in 23 ± 2°C chamber for one day. After that, the specimens were demoulded and cured in water at 23 ± 2°C until the test age. The self-compacting concrete (SCC) mix proportions are given in Table 3-5.

Table 3. Self-compacting concrete mixture proportions with RB.

Mix	*W/B	Mix proportions (kg/m^3)					SP (kg)	Flow (mm)
		Cement	RB	Fine aggregate	Coarse Aggregate	Water		
CT	0.46	650	0	780	975	299	2	750
10RB	0.46	585	65	780	975	299	3	750
15RB	0.46	552.5	97.5	780	975	299	4	780
20RB	0.46	520	130	780	975	299	5	760
30RB	0.46	455	195	780	975	299	6	750
40RB	0.46	390	260	780	975	299	7	745

Note: *W/B = Water to binder ratio (B = Binder or cementitious materials), CT = Cement, and SP = Superplasticizer (Viscocrete by SIKA).

Table 4. Self-compacting concrete mixture proportions with BA.

Mix	*W/B	Mix proportions (kg/m^3)					SP (kg)	Flow (mm)
		Cement	BA	Fine aggregate	Coarse Aggregate	Water		
CT	0.46	650	0	780	975	299	2	750
10BA	0.46	585	65	780	975	299	5	760
15BA	0.46	552.5	97.5	780	975	299	6	790
20BA	0.46	520	130	780	975	299	8	750
30BA	0.46	455	195	780	975	299	10	770
40BA	0.46	390	260	780	975	299	12	775

Note: *W/B = Water to binder ratio (B = Binder or cementitious materials), CT = Cement, and SP = Superplasticizer (Viscocrete by SIKA).

Table 5. Self-compacting concrete mixture proportions with RB+BA.

Mix	*W/B	Mix proportions (kg/m^3)						SP (kg)	Flow (mm)
		Cement	BA	RB	Fine aggregate	Coarse Aggregate	Water		
CT	0.46	650	0	0	780	975	299	2	750
5RB+5BA	0.46	585	32.5	32.5	780	975	299	4	770
7.5RB+7.5BA	0.46	552.5	48.75	48.75	780	975	299	5	770
10RB+10BA	0.46	520	65	65	780	975	299	6	760
15RB+15BA	0.46	455	97.5	97.5	780	975	299	4	760
20RB+20BA	0.46	390	130	130	780	975	299	8	755

Note: *W/B = Water to binder ratio (B = Binder or cementitious materials), CT = Cement, and SP = Superplasticizer (Viscocrete by SIKA).

2.3 Compressive Strength Test

The compressive strength test was carried out as per ASTM C39 [14]. The 100 mm diameter and 200 mm height cylindrical concretes were used for compressive strength testing. The samples were tested at the age of 28 days. As a result of the 28-day curing, more products of hydration reaction and pozzolanic reaction were produced. The reported results are the average of three samples.

2.4 Resistance to Chloride Penetration Test

Chloride penetration is one of the main factors that can lead to concrete deterioration and failure. The durability of concrete can be compromised by the ingress of water with dissolved chlorides which cause corrosion of the reinforcing steel. Steel embedded in concrete is protected against corrosion by both a chemical and physical mechanism. The chloride diffusion coefficients value for concrete was determined by using Eq. (1). In Eq. (1), Dc was evaluated based on Fick's second law of diffusion [15].

$$\frac{\partial C}{\partial t} = D_c \frac{\partial^2 C}{\partial x^2} \tag{1}$$

The amount of chloride penetrated in this test was indicatively measured by the electrical charge passed or coulomb. The 100 mm dia. × 200 mm height concrete cylinders were prepared in accordance with ASTM C39 [14]. After the concrete cylinders had been cured in water for 27 days-arranged for the test at the ages of 28 days-the concretes were cut into 50 mm thick slices and the 50 mm ends were discarded. The 50 mm slices were then coated with epoxy around the cylindrical surface. They were tested for rapid chloride penetration test (RCPT) the next day in accordance with the method described in ASTM C1202 [16]. The RCPT test set-up is shown in Figure 4. The reported results are the average of three samples.

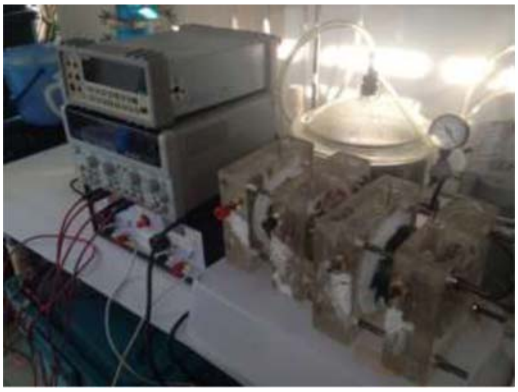


Figure 4. The chloride penetration test set up.

2.5 Immersion Test

The immersion test of concrete was performed using 3% NaCl solution. The test set-up is shown in Figure 5. The samples were prepared in the same manner as the RCPT samples. The 100 mm × 200 mm concrete cylinders were prepared in accordance with ASTM C39 [14]. The concretes were cut into 50 mm thick slices and the 50 mm ends were discarded. The specimens of 100 mm in diameter and 50 mm in height were used. Apart from coating the cylindrical surface, the top surface was also epoxy-coated. The specimens were immersed in NaCl solution for 30 days after the curing age of 28 days. The specimens were then split and the chloride penetration depths were determined using a 0.1 M $AgNO_3$ solution.

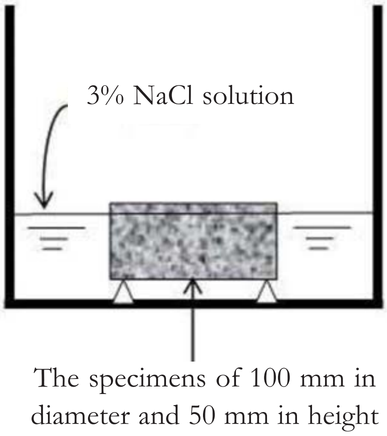


Figure 5. The immersion test for 30 days.

2.6 Accelerated Corrosion Test

This test was successfully used in the previous research work on the corrosion of steel in mortar and concrete containing pozzolanic materials [7,11,17,18]. The test result needs a timing record-in hours-when the high strength concrete starts to crack or to be destroyed due to the electric pressure acceleration [7,11,19,20]. This is called “Time of first crack”. The 100 mm × 100 mm concrete cubes with an embedded steel bar of 12 mm diameter and 200 mm in length were used for this study. The steel bar was secured such that it protruded from the top surface of the cube, thus providing sufficient concrete covers of 44 mm at the bottom and the sides of the cube as shown in Figure 6. The concretes were subjected to the accelerated corrosion test with impressed voltage using a 5% NaCl solution and a constant voltage of 12 volt direct current (12 volt DC)-with the embedded steel bar acting as the anode. The condition of self-compacting concrete cube was monitored visually at interval of 4 hours and the time of initiation of first crack was recorded-expressed in hours. The accelerated corrosion test set up is shown in Figure 7.

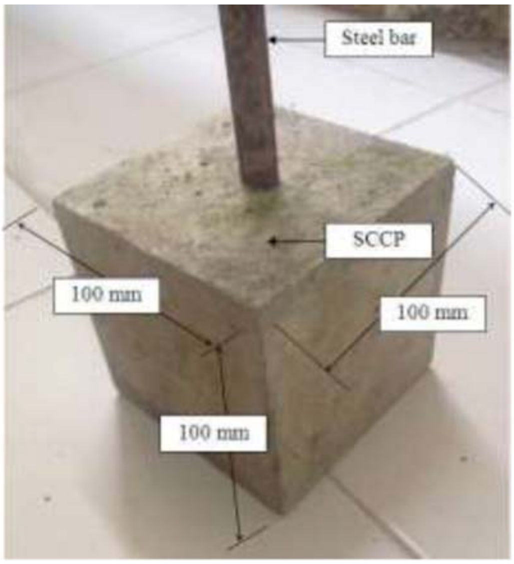


Figure 6. The concrete cube for corrosion test.

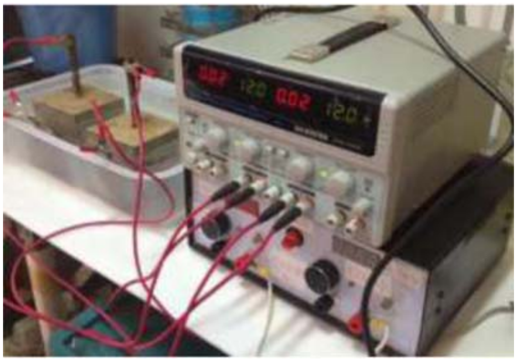


Figure 7. The accelerated corrosion test.

3. RESULTS AND DISCUSSIONS

3.1 SP Requirement and Compressive Strength of SCC

The results of the required SP of SCC are given in Table 3-5. The incorporation RB and BA increases the SP content of the mixes [14,21]. This is due to the higher specific surfaces of the particles of RB and BA. Furthermore, LOI of both RB and BA are high (8.2% and 18%). So, the amount of SP requirement is augmented [6,7]. The results indicated that the incorporation of BA increased the amount of SP required-compared to the mixes with CT and RB.

For a blend of equal weight portions of RB and BA, the required amounts of SP for the ternary blended of SCC are determined. The amount of SP required for RB+BA materials is less than that of single BA. Owing to the fineness and porosity of BA, concrete required more SP than the CT and RB concrete. For this work, it was found that the slump flow was between 745 to790 mm, which is considered as the slump flow required for self-compacting concrete [2-4].

The result of compressive strengths and relationship between compressive strength and level of replacement are presented in Figure 8 and 9 respectively. RB concrete showed better performance in term of strength compared to the CT due to pozzolanic reaction of pozzolans [22,23]. The compressive strength of RB concrete is higher than that of the CT and BA concrete for all the mixes. For RB, these small particles can also penetrate spaces between the cavities of the concrete [6,7]. Therefore, the concrete will become denser and stronger. The compressive strengths at 28 days of RB self-compacting concretes were in the range of 118%-137% of that of CT concrete and those of BA self-compacting concretes were in the range of 67%-76% of the CT concretes.

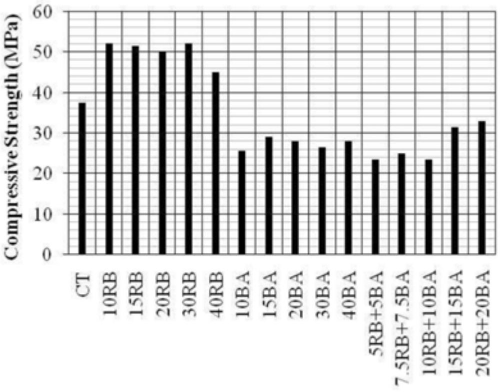


Figure 8. Compressive strength of SCC at 28 days.

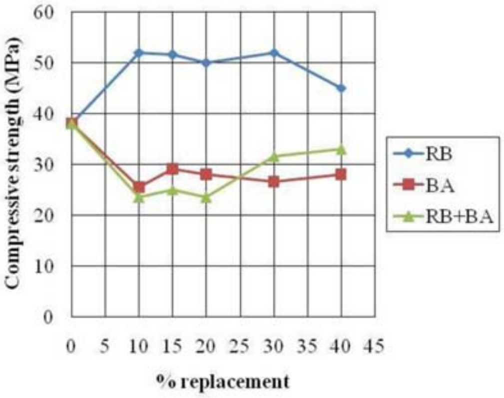


Figure 9. Relationship between compressive strength and % replacement at 28 days.

For a blend of equal weight portions of RB and BA, the test result showed a tendency to improve, compared to that of only BA used for replacing the Portland cement at 30% and 40% level (15RB+15BA and 20RB+20BA). It is informed that the SCC that is a substitute for Portland cement, by means of ternary blended, tends to be stronger than the BA concrete for replacement at 30-40% level. The high level of RB+BA replacement can improve the strength of the concrete because of the pozzolanic reaction and synergic effect as compared to the low level of replacement of RB+BA. The normalized compressive strengths of 5RB+5BA, 7.5RB+7.5BA and 10RB+10BA is in the range of 62%-66% of the CT concrete. The normalized compressive strengths of 15RB+15BA and 20RB+20BA is range from 83%-87% of the CT concrete. This test points out that ternary blended system can improve the strength of the concrete because of the synergic effect [7,10,24].

This investigation reveals that the compressive strength varies from 32 to 52 MPa, which is somewhat higher than the design level of 30 MPa at the age of 28 days. Regarding the range of compressive strengths of these SCC's, it is suggested that the RB is effective for producing self-compacting concrete (SCC) with 10%-40% of RB replacement. The relationship between compressive strength and level of replacement is presented in Figure 9. This result indicates that RB+BA are effective for producing self-compacting concrete (SCC) with 30%-40% of RB+BA replacement. This is due to the synergic effect of two pozzolanic materials.

3.2 Chloride Penetration of SCC

The result of the rapid chloride penetration test of the self-compacting concrete is shown in Figure 10. This work indicated that the replacements of cement with RB or BA reduced the number of coulombs indicating the increase in the resistance to chloride penetration [25]. The fine particles of pozzolan (RB and BA) could fill the void and will also introduce nucleation sites for the precipitation and accelerate the hydration reaction in the cement paste [6,7]. As a result of the 28-day curing, more products of hydration reaction and pozzolanic reaction were produced. In addition, with respect to the chloride penetration resistance, the SCC mixed with RB and BA is more effective than the CT concrete because the major component of both RB and BA is SiO_2 [8,9,17]. This result is similar some conclusions found in previous researches [7,11]. The results indicate that the electrical charge passed through BA self-compacting concrete were lower than that of RB concrete due to the fact that RB contained a higher amount of SiO_2 (SiO_2 of RB = 76%). The product from the pozzolanic reaction between calcium hydroxide and silica is calcium silicate hydrate, which causes the concrete to be stronger. Besides, a large amount of CSH product and the ability of chloride ion absorption are helpful to reduce the penetration rate [7]. Moreover, the SiO_2 left from the reaction can withstand chloride [6,7,17,20].

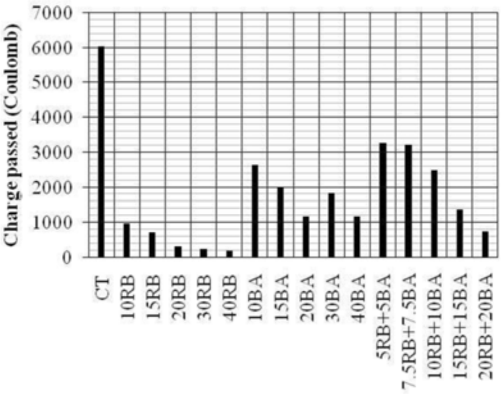


Figure 10. Chloride penetration of SCC at 28 days.

For the blends of equal weight portions of 15% RB+15% BA and 20% RB+20% BA, the results showed that the amount of the chloride penetration of the two kinds of materials (RB+BA) is less than that of the single 30% BA and 40% BA concrete, by using equal percentage of cement replacement (see Figure 11). According to the chloride resistance of the RB and BA materials, they can penetrate well into the big cavities due to their fineness. This causes the occurrence of nucleation sites for accelerating the hydration reaction in the cement paste [7,17]. As a result, the concrete is more durable with respect to corrosion and salinity and consequently its lifetime is extended. Regarding the resistance to chloride of the two kinds of materials (RB+BA) applied as a substitute for the cement, the tendency of applying the combination of three sorts of materials for the chloride resistance is more satisfactory than that of the usage of only one kind of integrated material owing to the synergistic effect [7,17,24,26]. To improve the resistance to chloride ingress of the pozzolanic materials used as a substitute for the cement, this study is useful to convince the construction industry for making the self-compacting concrete from the waste materials such as rice husk-bark ash and bagasse ash. For this work, the results as shown in Figure 12 also indicate that the reduction in electrical charge passed was accompanied by an increase in compressive strength. So, the compressive strength may be used as a significant indicator as it indirectly affects the chloride penetration of the self-compacting concrete.

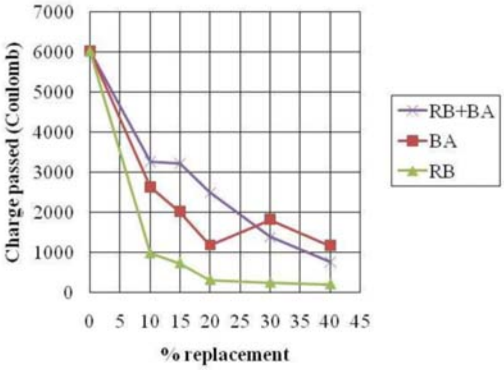


Figure 11. Relationship between % replacement and electrical charge passed at an age of 28 days.

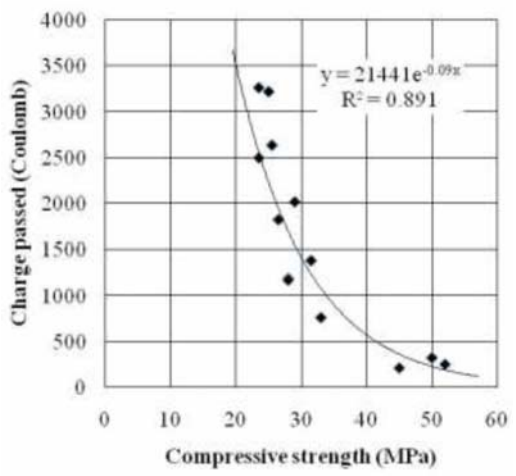


Figure 12. Relationship between compressive strength and charge passed at an age of 28 days.

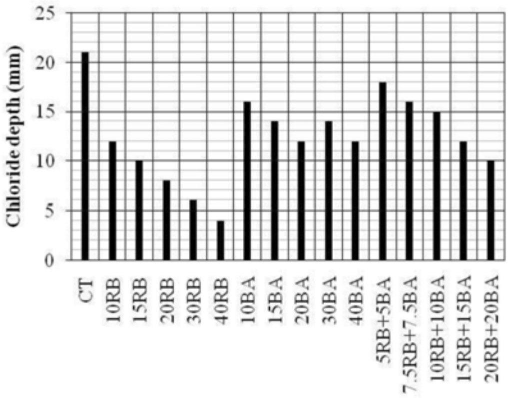


Figure 13. Chloride penetration depth of SCC.

3.3 Chloride Depth of SCC

The results of chloride penetration depth of SCC immersed in 3% NaCl solution for 30 days are shown in Figure 13. The results follow the same pattern as those of the results of the rapid chloride penetration test (RCPT). The incorporation of RB and BA improves the resistance to chloride penetration of SCC. The additions of RB and BA, both single and a blend of RB+BA reduce the chloride penetration depth of SCC (at 30%-40% replacement level). The excellent improvement in the resistance to chloride penetration using single and blend of pozzolan are evident [17,26]. This test points out that ternary blended system can improve the chloride penetration depth of the concrete because of the synergic effect [7,17,24,26]. The high level of replacement of RB and BA increases the resistance to chloride penetration of SCC as compared to the low level of replacement of RB and BA.

3.4 Resistance to Corrosion of SCC

The test result is presented in Figure 14. It is found that the time of first crack of the CT concrete is low whereas for RB and BA concrete it takes more time of first crack [7,11,19,27]. This means that the SCC concrete mix containing RB and BA can resist steel corrosion well because of its longer time of first crack. By comparison with the result of the chloride penetration test, the result of the accelerated corrosion test is compatible. A difference between them is only a measured unit. The times to first crack increased with the increase in the RB or BA content. The time of first crack of self compacting concrete control (CT) was 98 hours whereas the time of first crack of self compacting concretes containing RB and BA were longer, ranging from 122 to 245 hours.

For a blend of equal weight portions of RB and BA, considering the pozzolanic materials by RB+BA, the result shows the advantage of the corrosion resistance. Furthermore, the RB+BA high strength concrete takes more time of first crack. Besides this, the pozzolanic materials accelerate the hydration reaction [17,20,28] and reduce the volume of the cavities in the paste. This confirms the results of the time of first crack that incorporation of RB and BA improves the resistance to corrosion of self-compacting concretes. This suggests that $Ca(OH)_2$ consumption in SCC are high [6,7,29,30]. The pozzolanic materials increased the amount of reaction products and reduced the volume of the cavities in the paste. An example of time of first crack result is shown in Figure 15.

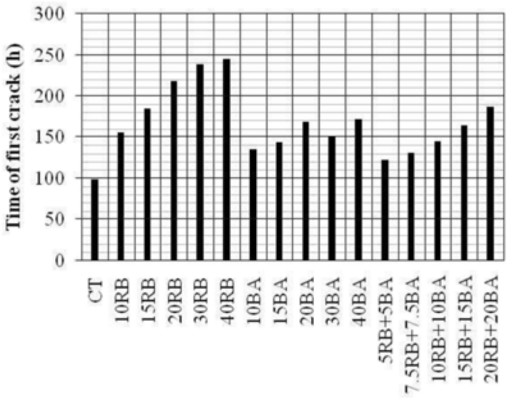


Figure 14. Time of first crack (hours) for all mixes investigated.

Figure 15. The sample of concrete crack.

4. CONCLUSIONS

From the tests, it can be concluded that the slump flow was between 745 to790 mm, which is considered as the slump flow required for self-compacting concrete. BA and RB containing fine irregular-shaped particles increases the amount of SP required. The RB is effective for producing self-compacting concrete (SCC) with 10%-40% of RB replacement. The use of the blend of pozzolans of fine RB and BA also effectively improves the properties of self-compacting concretes (SCC) in terms of corrosion and resistance to chloride penetration. The use of the ternary blends of pozzolans in the equal portion of RB and BA (RB+BA) also effectively improves the SCC in terms of compressive strength, resistance to chloride penetration and resistance to corrosion. This is due to the pozzolanic reaction between calcium hydroxide and silica is calcium silicate hydrate, which causes the concrete to be stronger. In addition, the compressive strength is a significant factor as it directly affects the chloride penetration of the self-compacting concrete. This is due to the reduction in electrical charge passed was accompanied by an increase in compressive strength.

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