Computers and Concrete, *Vol. 13, No. 1 (2014) 17-30*
DOI: http://dx.doi.org/10.12989/cac.2014.13.1.017

Chloride penetration resistance of concrete containing ground fly ash, bottom ash and rice husk ash

Somchai Inthata[1a] and Raungrut Cheerarot[*2]

[1]*Faculty of Science and Technology, Rajabhat Mahasarakham University, Mahasarakham 44000, Thailand*
[2]*Faculty of Engineering, Mahasarakham University, Mahasarakham 44150, Thailand*

(*Received October 15, 2011, Revised May 3, 2013, Accepted July 11, 2013*)

Abstract. This research presents the effect of various ground pozzolanic materials in blended cement concrete on the strength and chloride penetration resistance. An experimental investigation dealing with concrete incorporating ground fly ash (GFA), ground bottom ash (GBA) and ground rice husk ash (GRHA). The concretes were mixed by replacing each pozzolan to Ordinary Portland cement at levels of 0%, 10%, 20% and 40% by weight of binder. Three different water to cement ratios (0.35, 0.48 and 0.62) were used and type F superplasticizer was added to keep the required slump. Compressive strength and chloride permeability were determined at the ages of 28, 60, and 90 days. Furthermore, using this experimental database, linear and nonlinear multiple regression techniques were developed to construct a mathematical model of chloride permeability in concretes. Experimental results indicated that the incorporation of GFA, GBA and GRHA as a partial cement replacement significantly improved compressive strength and chloride penetration resistance. The chloride penetration of blended concrete continuously decreases with an increase in pozzolan content up to 40% of cement replacement and yields the highest reduction in the chloride permeability. Compressive strength of concretes incorporating with these pozzolans was obviously higher than those of the control concretes at all ages. In addition, the nonlinear technique gives a higher degree of accuracy than the linear regression based on statistical parameters and provides fairly reasonable absolute fraction of variance (R^2) of 0.974 and 0.960 for the charge passed and chloride penetration depth, respectively.

Keywords: chloride penetration; colourimetric method; coulomb charge passed, multiple regression techniques

1. Introduction

Concrete is selected for use as a construction material in aggressive or potentially aggressive environments. In recent years, the demand places on concrete in marine environments have increased greatly, as concrete structures are used in floating platforms, jetties, lighthouse and offshore structures. In all of these instances, engineers have become increasingly concerned over

∗Corresponding author, Assistant Professor, E-mail: raungrut@hotmail.com
[a]Ph.D., E-mail: somchai_asap@hotmail.com
[b]Assistant Professor, E-mail: raungrut@hotmail.com

http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198 (Print), 1598-818X (Online)

deterioration of concrete due to the action of sea water, that is, chloride ingress which leads to corrosion of the steel reinforcement and a subsequent decrement in the strength, service lifetime and aesthetics of the structure. It is not only marine RC structures which are exposed to chloride, but also road RC structures suffer from deicing salts, and several industries apply chloride in their production such as abattoirs and osterias. A common method for preventing deterioration of structures from chloride attack is to prevent chlorides ingress into concrete by using relatively impermeable concrete. One of the simplest ways is a use of pozzolanic materials as supplementary cementing materials and its practicing for several decades either for cost reduction or improved on concrete durability (Mejlbro and Poulsen 2006, Stanish *et al*. 1997). According to the total anthropogenic CO_2 emissions, about 8.5% of these CO_2 emissions that is responsible for global warming come from the provision of cement. Recently, the utilization of by-products wastes from industry and agriculture have initiated increasing interests in using these materials as pozzolanic materials which reduces the environmental problems of power plants and decreases electric costs besides reducing the amount of solid waste, greenhouse gas emissions and conserves existing natural resources (Habert *et al*. 2010, Yazici *et al*. 2005).

Fly ash and bottom ash are by-product solid waste from combustion of pulverized coal. In Thailand, Mae Moh power plant has the potential to produce both wastes approximately 10,000 tons annually which has bottom ash about 20 percent of total waste. Most of fly ash has successfully been used in the construction industry and cement production because the fine-gained of spherical and glassy particles can be achieved through their advantageous properties. Bottom ash is a large-high porous material and irregular particles. The utilization of bottom ash is limited due to the shape characteristics of particles as compared to other pozzolanic materials.

Rice husk is an agricultural waste of the milling process that husks were removed from the rice grain. In the northeastern part of Thailand, the amount of rice husk is approximately 1.97 million tons a year but only 800,000 tons a year were used as fuel for power generation in the Roi-et Green biomass power plant. This husk contains about 75 % organic volatile matter and the balance 25 % of the weight of this husk is converted into ash during the firing process, is known as rice husk ash. Rice husk ash is a highly reactive pozzolanic material due to the control of incineration temperature up to 700˚C and attributed to its high content of amorphous silica or non-crystalline form (Kiattikomol *et al*. 2001, Cheerarot and Jaturapitakkul 2003, Ganesan *et al*. 2008). In this study, three different types of pozzolanic materials are considered to be partial cement replacement: fly ash, bottom ash, and rice husk ash.

Many researchers have been reported on the performance of fly ash, bottom ash, and rice husk ash blended Portland cement concretes with an adequate grinding and appropriate replacement contribute to the enhancement of quality of concrete in terms of its strength and durability (Cheriaf *et al*. 1999, Nair *et al*. 2008, Gastaldini *et al*. 2007). In addition, the incorporation of ground pozzolanic materials significantly improved the microstructure of the interfacial transition zone between aggregate and the matrix. The increasing of specific surface area of pozzolan was important to increase the early strength of concrete due to the packing effect. Besides, it provides several advantages such as the reduction in bleeding, improved workability, reduced heat of hydration and increased the resistance to aggressive chemical attack (Chindaprasirt *et al*. 2007, Chindaprasirt *et al*. 2005, Tangpagasit *et al*. 2005). Accordingly, the use of pozzolans plays an important role in contributing to resist chloride penetration. Hence, the faster determination of concrete properties by applying suitable predictable models has received considerable interest in recent years (Wang *et al*. 2012, Marks *et al*. 2012).

The purpose of this study is to examine the effect of various ground pozzolanic materials in blended cement concrete on the strength and chloride penetration resistance. In addition, by using this experimental database, linear and nonlinear multiple regression techniques were developed to predict the chloride permeability of concretes as function of water to binder ratio (W/B), percent replacement (PR), testing ages (A), pozzolans type (PT), aggregate to cement ratio (Ag/C) and compressive strength (CS). The main results and trends obtained here would be beneficial to improve the concrete durability.

2. Experimental program

2.1 Materials

2.1.1 Cement

Ordinary Portland cement (OPC) conforming to Thai Industrial Standards code TIS 15 Part 1-2004 was used in this study.

2.1.2 Pozzolanic materials

Rice husk ash is a by-product from Roi-et green biomass power plant in the northeastern region of Thailand. Lignite coal fly ash and bottom ash was obtained from Mae Moh thermal power plant in the northern region of Thailand. Each of them was ground by ball mill until the particle size retained on sieve No. 325 was less than 5% by weight, namely ground fly ash (GFA), ground bottom ash (GBA) and ground rice husk ash (GRHA).

2.1.3 Aggregates

Coarse aggregate was crushed limestone with maximum size of 20 mm. The preliminary properties are as following: fineness modulus of 7.15 and specific gravity of 2.70. Local river sand at saturated surface dry condition with fineness modulus of 2.73 and specific gravity of 2.64 was used as fine aggregate. The grading of sand is conformed to ASTM C33.

2.2 Mix proportions

The weight of used materials in this experimental program is shown in Table 1. The mixed proportions of control concretes (without pozzolans, CC) were designed to use water to binder ratio (W/B) at the rate of 0.35, 0.48, and 0.62. These mixes are considered to represent low, normal and high strength concrete series, respectively. Then concretes were mixed by replacing each pozzolanic material to Portland cement at the level of 10, 20, 30, and 40% by weight of binder and the superplasticizer was adjusted to keep the required slump between 100-120 mm. For each batch of concrete, fifteen 100 × 200 mm cylinders were cast in steel molds and stored in an ordinary temperature room. The concrete specimens were stripped from the molds after 24 hours and cured in water at 23 ± 2 ˚C until the time of testing.

2.3 Compressive strength test

The slump of the fresh concrete was measured by using the standard slump test apparatus and the cylinder specimen of 100 mm in diameter and 200 mm in height were used to measure the compressive strengths of concrete at the ages of 28, 60, and 90 days. For each batch, the tests were carried out on three specimens and the average of compressive strength was reported.

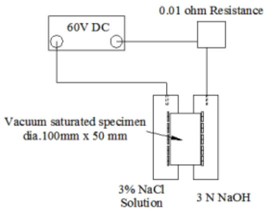


Fig. 1 Schematic diagram of RCPT test

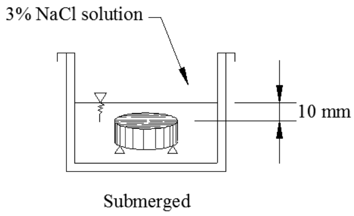


Fig. 2 Immersion of concrete specimen

2.4 Chloride penetration test

2.4.1 Preparation of test specimens

Two days before testing age, concrete specimens were sawn into 50 mm thick slice from central portion of the cylinder and stored in the laboratory environment for 24 h. The slices specimens were coated with epoxy on the cylindrical surface for rapid chloride penetrability test and coated with epoxy on all surfaces except one sawn surface for the immersion test. The coated specimens were left in the room temperature for another 24 h.

2.4.2 Rapid chloride penetrability test (RCPT)

The resistance to chloride ion penetration in term of total charge passed in coulombs was conducted in accordance with ASTM C1202. Place the slice specimens into the vacuum saturation apparatus and maintain vacuum for 3 h. After that release de-aerated water and allow vacuum pump to run for one additional hour and keep soak specimens under water for another 18 ± 2 h. Afterward, place the slice specimen between two acrylic cell blocks and seal with a silicone adhesive sealant. Fill the side of the cell block with 3.0% of sodium chloride solution (cathode) while the other side filled with 0.3 N of sodium hydroxide solution (anode) and connect the power supply under a potential difference of 60 V DC as shown in Fig. 1. The current was reported every 30 minutes intervals during 6 h test.

2.4.3 Colourimetric method

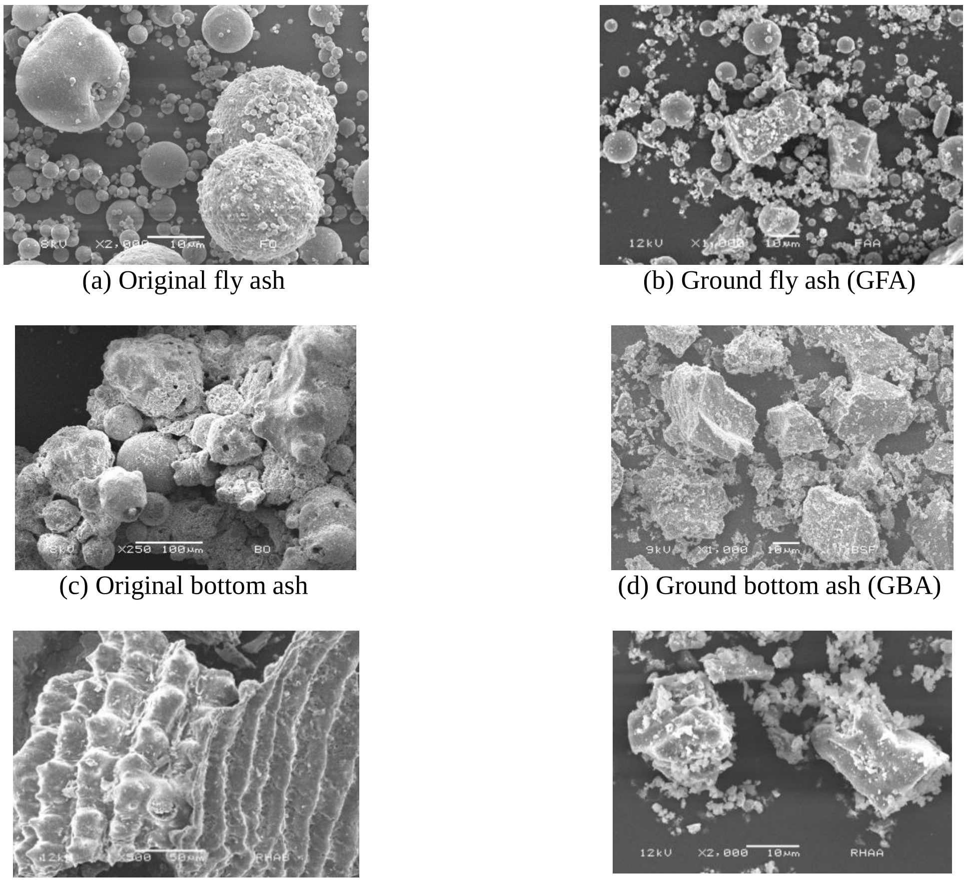
This test is the simulation method of concrete structures submerged in sea water and determined the ingress of chloride. After 26 days of water curing, the specimens were prepared as described above and fully immersed in a solution containing 3% of sodium chloride until the testing age as shown in Fig. 2. The specimen after being taken out of solution was split into two halves lengthwise and sprayed with 0.1 N of silver nitrate aqueous solution ($AgNO_3$) to determine the chloride penetration fronts. The black and greyish-white regions were clearly distinguished boundaries because of the $AgNO_3$ aqueous solution on a split slice specimen. The black region is assumed to correspond to the “no chloride zone” and the greyish-white region represents the area that contains chloride (chloride zone) due to precipitation of silver chloride (AgCl). The average depth of chloride penetration fronts was measuring five equidistant spots along the circumference of each face of the split specimen.

The charge passed and the depth of chloride penetration are the independent properties of concrete controlled by different factors; the charge passed depends on the microstructure and the pore fluid conductivity (especially OH^- ions) of the concrete, while the depth of chloride penetration depends primarily on microstructure of concrete (Wee *et al*. 2000).

3. Results and discussions

3.1 Physical and chemical analysis of OPC, GFA, GBA and GRHA

Physical properties of materials are summarized in Table 2. The specific gravities of OPC, GFA, GBA and GRHA are 3.14, 2.59, 2.70 and 2.27, respectively. In consideration of particles retained on a sieve No. 325, Blaine fineness and median particle size the results obviously show that GRHA was the finest particle size, followed by GFA and GBA, respectively. The Blaine fineness of OPC is 3270 cm^2/g. It revealed that the total surface areas of these pozzolans are approximately double those of OPC. As seen in Table 2, elemental analysis of materials carried out by technique of XRF indicated that the sum of SiO_2, Al_2O_3, and Fe_2O_3 in GFA and GBA are 85.41% and 82.14%, respectively. They could be classified as class F fly ash in accordance with ASTM C618 due to the sum of SiO_2, Al_2O_3, and Fe_2O_3 is higher than 70%, the loss on ignition (LOI) is less than 6% and the SO_3 content is less than 5%. The chemical composition of GRHA is mainly composed of 90.20% SiO_2 that conforms to the ASTM C618 requirements as a natural pozzolans. The loss on ignition value for RHA is 3.41 which is an indication of complete oxidation of the carbon in the ash.



(a) Original fly ash

(b) Ground fly ash (GFA)

(c) Original bottom ash

(d) Ground bottom ash (GBA)

(e) Original rice husk ash

(f) Ground rice husk ash (GRHA)

Fig. 3 SEMs of various pozzolanic materials

Table 1 Mix composition of concrete

Type of concrete	Mix proportion (kg/m^3)					GFA		GBA		GRHA	
	Water	Cement	Pozz.	Sand	Stone	Slump	%SP	Slump	%SP	Slump	%SP
CC-0.62	195	315	0	740	1024	110	-	110	-	110	-
10-0.62	195	284	32	738	1021	115	-	105	-	115	-
20-0.62	195	252	63	736	1018	110	-	115	-	110	-
30-0.62	195	221	95	734	1015	120	-	110	-	110	-
40-0.62	195	189	126	732	1012	120	-	110	-	115	-
CC-0.48	195	406	0	667	1024	105	-	105	-	105	-
10-0.48	195	365	41	664	1020	110	-	110	-	105	-
20-0.48	195	325	81	662	1016	120	-	105	-	110	-
30-0.48	195	284	122	659	1012	115	-	110	-	115	-
40-0.48	195	244	162	657	1008	110	0.21	115	0.55	110	0.32
CC-0.35	170	485	0	658	1024	110	0.74	110	0.74	110	0.74
10-0.35	170	437	49	655	1019	115	0.52	115	1.27	110	0.71
20-0.35	170	388	97	652	1014	110	0.58	120	1.79	105	0.63
30-0.35	170	340	146	649	1010	110	0.51	120	1.57	115	0.80
40-0.35	170	291	194	646	1005	115	0.32	115	1.93	120	1.14

Note: The first 2-digit number denotes as “percent replacement of pozzolans” and the decimal number after means water to binder ratios (W/B), %SP = percent superplasticizer content by weight of the total binder.

Table 2 Chemical composition and Physical properties

Sample	OPC	GFA	GBA	GRHA
Chemical composition (%)				
SiO_2	20.62	49.83	48.12	90.20
Al_2O_3	5.22	25.25	23.47	0.67
Fe_2O_3	3.10	10.33	10.55	0.95
CaO	64.99	7.76	11.65	0.94
MgO	0.91	2.73	3.45	0.49
K_2O	0.07	2.92	3.45	3.75
Na_2O	0.50	0.08	0.07	0.12
SO_3	2.70	1.77	1.76	0.21
LOI	1.13	1.85	3.41	4.02
$SiO_2 + Al_2O_3 + Fe_2O_3$	-	85.41	82.14	91.82
Specific gravity	3.14	2.59	2.70	2.27
Retaining on a sieve No.325 (%)	10.8	3.4	3.6	2.8
Blaine fineness (cm^2/g)	3,270	6,355	5,750	6,850
Median particle size (µm)	13.0	7.0	9.5	6.3

Note: OPC = Ordinary Portland cement, GFA = Ground fly ash, GBA = Ground bottom ash, GRHA = Ground rice husk ash

The scanning electron micrograph (SEM) photo as illustrated in Fig. 3(a)-(f) shows that the original fly ash is mostly spherical in particle shapes and varies in size, whereas some surface comprises with rough texture. After improving its quality with a grinding machine, it accompanies with small smooth spherical particles and larger solid angular shape. The SEMs photo of GBA reveals that the particle shape of original bottom ash is large, irregular and high porous. After being ground, the particle size becomes smaller and it is solid, angular and nonporous. On the other hand, original rice husk ash is very porous due to its honeycomb microstructure. After being ground, GRHA consists of very irregular-shaped particles with porous cellular surface. In addition, the grinding times for fly ash, bottom ash and rice husk ash were 6.0, 8.0 and 3.0 hours, respectively due to the difference in size and hardness of materials.

3.2 Evaluation of slump and superplasticizer content

Workability of fresh concrete is conventionally quantified in terms of slump. The values of the slump test are also indicated in Table 1, where superplasticizer percentages are used in relation to weight of binder. It can be seen that the incorporation of GFA, GBA and GRHA as a partial cement replacement marginally improve the workability as indicated in concretes at W/B of 0.62 and 0.48. GFA was marginally more effective than the others at each dosage level. This is due to the spherical particle shape of fly ash participates in improving workability, also known as ball bearing

Table 3 Compressive strength and percentage compressive strength of concretes

Type of concrete	Compressive strength, MPa – *(Percentage compressive strength, %)*								
	28 days			60 days			90 days		
	GFA	GBA	GRHA	GFA	GBA	GRHA	GFA	GBA	GRHA
CC-0.62	32.4 *(100)*	32.4 *(100)*	32.4 *(100)*	36.5 *(100)*	36.5 *(100)*	36.5 *(100)*	38.0 *(100)*	38.0 *(100)*	38.0 *(100)*
10-0.62	35.2 *(109)*	34.1 *(105)*	34.7 *(107)*	38.8 *(106)*	38.2 *(105)*	37.5 *(103)*	41.5 *(109)*	40.8 *(107)*	41.2 *(108)*
20-0.62	36.7 *(113)*	33.9 *(105)*	35.8 *(110)*	41.2 *(113)*	38.9 *(107)*	39.2 *(107)*	44.2 *(116)*	41.1 *(108)*	43.2 *(114)*
30-0.62	34.9 *(108)*	31.0 *(96)*	33.2 *(102)*	39.2 *(107)*	35.3 *(97)*	37.4 *(102)*	45.4 *(119)*	38.2 *(101)*	41.4 *(109)*
40-0.62	33.8 *(104)*	29.9 *(92)*	32.7 *(101)*	37.7 *(103)*	35.7 *(98)*	36.9 *(101)*	41.0 *(108)*	38.1 *(100)*	39.9 *(105)*
CC-0.48	41.0 *(100)*	41.0 *(100)*	41.0 *(100)*	45.2 *(100)*	45.2 *(100)*	45.2 *(100)*	48.4 *(100)*	48.4 *(100)*	48.4 *(100)*
10-0.48	44.9 *(110)*	43.7 *(107)*	43.7 *(107)*	50.1 *(111)*	49.2 *(109)*	47.2 *(104)*	54.3 *(112)*	53.2 *(110)*	55.3 *(114)*
20-0.48	46.6 *(114)*	44.0 *(107)*	44.6 *(109)*	52.3 *(116)*	49.5 *(110)*	48.9 *(108)*	55.9 *(115)*	53.9 *(111)*	55.5 *(115)*
30-0.48	47.2 *(115)*	43.2 *(105)*	45.4 *(111)*	56.3 *(125)*	49.2 *(109)*	52.3 *(116)*	58.5 *(121)*	54.2 *(112)*	57.1 *(118)*
40-0.48	44.2 *(108)*	40.2 *(98)*	42.5 *(104)*	50.8 *(112)*	46.1 *(102)*	48.7 *(108)*	54.2 *(112)*	50.7 *(105)*	52.3 *(108)*
CC-0.35	61.7 *(100)*	61.7 *(100)*	61.7 *(100)*	64.7 *(100)*	64.7 *(100)*	64.7 *(100)*	67.5 *(100)*	67.5 *(100)*	67.5 *(100)*
10-0.35	63.8 *(103)*	62.4 *(101)*	62.8 *(102)*	67.0 *(103)*	65.6 *(101)*	66.1 *(102)*	69.8 *(103)*	68.6 *(102)*	68.8 *(102)*
20-0.35	65.7 *(107)*	63.5 *(103)*	64.3 *(104)*	69.7 *(108)*	66.9 *(103)*	67.6 *(104)*	72.5 *(107)*	69.7 *(103)*	70.5 (104)
30-0.35	68.1 *(110)*	64.5 *(105)*	65.9 *(107)*	72.6 *(112)*	68.1 *(105)*	69.5 *(107)*	75.2 *(111)*	71.1 *(105)*	72.3 *(107)*
40-0.35	65.0 *(105)*	62.2 *(101)*	63.0 *(102)*	69.4 *(107)*	65.7 *(101)*	67.1 *(104)*	72.6 *(108)*	69.8 *(103)*	70.7 *(105)*

effect (Sata *et al*. 2007, Chindaprasirt *et al*. 2001). For the high strength concrete series, it was found that the SP contents increased along with the percent replacement of pozzolans. This is due to the high specific surface area of pozzolans which would increase the water demand and this is consistent with previous studies (Habeeb and Fayyadh 2009)**.** Therefore, to maintain required slump, superplasticizer was added to the 40-0.48 concrete mixtures and superplasticizer content rose up to 1.93% for the concrete with 40-0.35 of GBA. It can be noted that GFA blended concretes required lower superplasticizer as compared to the other concretes.

3.3 Evaluation of compressive strength

The results of compressive strength and percent of compressive strength as compared to those of the control concrete are given in Table 3. It is therefore not surprisingly that prolonged curing leads to an increment in compressive strength due to its advantage for promoting the hydration of cement as compared to the corresponding concrete. For the concrete with W/B of 0.62, the compressive strength increases with ground pozzolans content up to 20% and starts to decrease at 30% of cement replacement. Therefore, 20% replacement level seems to be the optimal limit. At 40% replacement level, the compressive strength still decreases to a value which is higher than that of the control concretes except for GBA blended concretes at 28 and 60 days with 30% replacement level, the value was lower compared to that of control concrete. However, the compressive strength of GBA blended concretes was higher than 92% as compared to the control concrete.

For the concrete with W/B of 0.48 and 0.35, it can be seen that the compressive strength gradually increases with an increase in pozzolans content up to 40% and the highest values of compressive strengths were mostly achieved in concretes with 30% of cement replacement. Moreover, the results show that the compressive strength of concretes incorporating with pozzolans were obviously higher than those of the control concretes at all ages. It has been suggested that incorporation of very fine pozzolans improves the strength of concrete due to the filler and dispersing effects contribute to the relatively good strength development of the concrete (Chindaprasirt *et al*. 2007). In addition, it seems that GFA blended concretes produces the highest compressive strength followed by GRHA and GBA. This suggests that the spherical particles of GFA act as small bearings to increase dispersing effect of cement grains causes segmentation of large pores and increases nucleation sites for precipitation of hydration products in cement paste, resulting in a denser pore structure of the matrix (Chindaprasirt *et al*. 2005, Chindaprasirt *et al*. 2008).

3.4 Evaluation of chloride permeability

3.4.1 RCPT test

The coulombs charge passed is calculated from integrate area underneath the graph of current (in amperes) versus time (in seconds) during the 6-h test period. The results of resistance to penetration of chloride ions into concrete are presented in Table 4. As can be expected, the prolonged curing ages and the reduction in water to binder ratio improve chloride penetration resistance as compared to corresponding concretes due to its strength could be attributed to a denser concrete showing lower permeability (Naik and Singh 1994). These results can be regarded as equivalent to the qualitative chloride ion penetrability as defined in the ASTM C1202, very low permeability concretes have RCPT values below 1000 coulombs, while moderate permeability concretes have an RCPT value between 2000 and 4000 coulombs. Coulomb values above 4000 indicate high-permeability concrete. For the concrete with W/B of 0.62 and 0.48 at all ages, it was found that the incorporation of 10-20% pozzolans reduced qualitative chloride ion from “high” to “moderate-to-low” and 30-40% replacement level dropped from “moderate-to-low” to “low”. Meanwhile, the blended concrete with W/B of 0.35 was slightly more on chloride penetration resistance as compared to the corresponding blended concrete.

In addition, the results clearly show that the charge passed for the control concrete is higher than those of the pozzolan blended concretes in the same group. The charge passed of blended concrete continuously decreases with an increase in pozzolans content up to 40% of cement replacement and yields the highest reduction in the total charge passed at all ages. Hence, the use of pozzolans significantly improved the resistance to chloride penetration of concrete.

3.4.2 Colourimetric method

The most common quick and easy present practice to measure the chloride penetration depth is the spraying 0.1 N silver nitrate aqueous solution on a cross-section of split concrete (Otsuki *et al*. 1993). The test results for chloride penetration depth of concrete are given in Table 5. From Tables 4 and 5, it could be inferred that, colourimetric method and RCPT test give the results in a similar trend (Zhang *et al*. 2013). The chloride penetration depth depended on water to binder ratios and percent replacement of pozzolans. Thus, concretes with higher replacement level and lower water to binder ratio exhibit the improved chloride penetration resistance. Moreover, the chloride penetration depth of blended concretes continuously decreases with an increase in pozzolan content up to 40% of cement replacement. It revealed that the 40% of cement replacement yielded a significant reduction in the chloride penetration depth at all ages. It should be noted that, GRHA blended concretes with W/B of 0.35 detect very small of the chloride penetration fronts at 28 days.

In summary, the incorporation of GFA, GBA and GRHA produces more quantity of nucleation

Table 4 RCPT test of concretes

Type of concrete	Total charge passed (coulombs)								
	28 days			60 days			90 days		
	GFA	GBA	GRHA	GFA	GBA	GRHA	GFA	GBA	GRHA
CC-0.62	8,489	8,489	8,489	7,641	7,641	7,641	7,965	7,965	7,965
10-0.62	4,324	4,936	3,969	3,511	3,750	3,358	3,059	3,555	3,347
20-0.62	2,637	2,814	2,402	2,364	2,536	2,173	1,900	2,335	2,238
30-0.62	1,843	2,017	1,735	1,561	1,812	1,452	1,205	1,368	1,328
40-0.62	1,398	1,482	1,278	1,223	1,236	1,192	1,003	1,062	1,109
CC-0.48	7,056	7,056	7,056	5,929	5,929	5,929	5,529	5,529	5,529
10-0.48	3,651	3,911	3,173	2,521	2,683	2,254	1,468	1,851	1,617
20-0.48	2,458	2,581	2,198	1,247	1,314	1,108	1,052	1,144	1,087
30-0.48	1,170	1,262	1,095	922	961	915	599	759	627
40-0.48	973	1,059	958	851	876	804	611	710	642
CC-0.35	5,652	5,652	5,652	3,785	3,785	3,785	2,607	2,607	2,607
10-0.35	2,100	2,364	1,887	1,621	1,831	1,234	1,008	1,175	982
20-0.35	1,497	1,639	1,171	921	1,167	857	885	969	796
30-0.35	664	804	572	528	675	463	477	541	367
40-0.35	516	673	478	470	594	361	297	483	388

Chloride ion penetrability based on total charge passed according to ASTM C1202: more than 4000, High; 2000 – 4000, Moderate; 1000 – 2000, Low; 100 – 1000, Very low; less than 100, Negligible.

Table 5 Colourimetric method of concretes

Type of concrete	Chloride penetration depth (mm)								
	28 days			60 days			90 days		
	GFA	GBA	GRHA	GFA	GBA	GRHA	GFA	GBA	GRHA
CC-0.62	8.0	8.0	8.0	12.0	12.0	12.0	15.5	15.5	15.5
10-0.62	7.0	7.0	6.0	9.0	9.5	8.5	11.0	11.0	10.0
20-0.62	6.5	7.0	5.0	7.5	8.0	6.5	8.0	8.5	7.5
30-0.62	4.5	5.0	4.5	6.0	6.5	5.5	7.0	7.0	6.0
40-0.62	4.0	4.5	4.0	4.5	5.5	4.5	4.5	5.5	5.0
CC-0.48	6.5	6.5	6.5	9.0	9.0	9.0	12.0	12.0	12.0
10-0.48	5.5	5.0	4.5	7.0	7.0	6.5	7.5	8.0	7.0
20-0.48	4.5	4.5	4.0	5.5	5.0	4.5	6.5	6.0	5.0
30-0.48	3.5	4.0	3.5	4.5	4.5	4.0	5.0	5.5	4.5
40-0.48	3.0	3.5	2.5	3.5	4.5	3.0	4.0	4.5	3.5
CC-0.35	4.0	4.0	4.0	5.5	5.5	5.5	7.0	7.0	7.0
10-0.35	3.0	3.5	2.5	4.0	5.0	3.5	5.5	5.5	5.0
20-0.35	2.5	3.0	2.0	3.5	4.0	3.0	4.5	5.0	4.5
30-0.35	1.0	1.0	0.5	2.0	2.0	1.5	3.0	3.5	2.0
40-0.35	1.0	1.0	-	1.5	2.0	1.0	2.0	3.0	1.5

Table 6 The input and output quantities used in model

Input variables	Data used in the models	
	Minimum	Maximum
Water to binder ratio	0.30	0.80
Percent replacement (%)	0	40
Testing age (day)	28	90
Pozzolans type (GBA=1, GFA=2, GRHA=3)	1	3
Aggregate to cement ratio	3.47	9.23
Compressive strength (MPa)	29.9	75.2

Table 7 Statistical performance of proposed regression models

Statistical Parameters	Coulomb charge passed		Chloride penetration depth	
	Linear	Nonlinear	Linear	Nonlinear
RMSE	541.58	338.95	0.598	0.587
MAPE (%)	38.25	27.90	51.593	29.76
R^2	0.950	0.974	0.958	0.960

sites to begin the hydration reactions, and the final result would be a higher amount of hydrated products and, consequently, higher calcium hydroxide consumption and pozzolanic activity (Isaia *et al*. 2003). These mechanisms are the principle reasons for the excellent resistance to chloride penetration of concretes. The GRHA blended concretes had the highest chloride penetration resistance in comparison to those of GFA and GBA blended concretes. This suggests that the presence of reactive silica in GRHA is mainly in amorphous form and the finest particle is necessary to reach excellence the impermeability. Also, this is probably due to the highest un-burnt carbon content (loss on ignition value 4.02%) might have contributed to the significant reduction in the electrical charge passed (Ganesan *et al*. 2008).

3.5 Predicting the chloride penetration using multiple regression techniques

3.5.1 System models and data sets

In this approach, the prediction of linear and nonlinear regression models was performed under SPSS version 15 to determine the best fit of the data. Classical statistical method was employed for linear regression and the various possible equations of non-linear regression were tried to find the appropriate equation based on the absolute fraction of variance (R^2) results that estimates the proportion of the total variation in the series by using the following Eq. (1).

$$R^2 = 1 - \left(\frac{\sum_j (P_j - T_j)^2}{\sum_j (T_j)^2} \right) \quad (1)$$

In addition, root mean square error (RMSE) and mean absolute percentage error (MAPE) are used to measure the variation of a dependent series from its model-predicted patterns by using the following Eqs. (2) and (3), respectively.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \sum_j (P_j - T_j)^2} \quad (2)$$

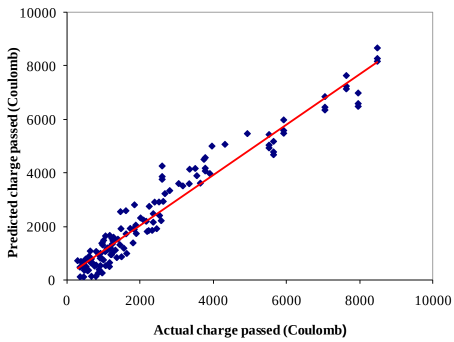


Fig. 4 Performance of the charge passed by nonlinear regression model

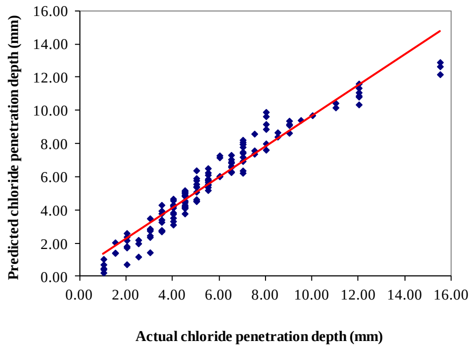


Fig. 5 Performance of the chloride penetration depth by nonlinear regression model

$$\text{MAPE} = \frac{100}{n}\sum_j\left(\left|\frac{T_j - P_j}{T_j}\right|\right) \tag{3}$$

where P is the value prediction of *j*th pattern, T is the actual value of *j*th pattern, and n is the number of patterns.

In this experiment, it is clear from the test data that the water to binder ratio (W/B), percent replacement (PR), testing ages (A), pozzolans type (PT), aggregate to cement ratio (Ag/C) and compressive strength (CS) had significant influence on the resistance to chloride permeability of the concretes. Therefore, these six important input parameters were taken into account in the proposed regression models. Two output parameters of the system are the charge passed (coulomb) and chloride penetration depth (mm) of concretes. The limit values of input and output variables used in regression models are listed in Table 6.

3.5.2 Performance of the proposed models

The overall performances of both linear and nonlinear regression were evaluated via statistical parameters as seen in Table 7. Based on absolute fraction of variance (R^2), the nonlinear technique gives a higher degree of accuracy than the linear regression. In addition, the nonlinear model provided fairly reasonable mean absolute percentage errors of 27.90 and 29.76% for the charge passed and chloride penetration depth data sets, respectively. Therefore, the detail of the best nonlinear regression equation for charge passed and chloride penetration depth are given as

$$\begin{aligned}\text{Charge passed (coulomb)} &= 18922.30 + (20979.48*W/B) - (264.95*PR) - (57.99*A)\\ &- (541.58*PT) - (2102.80*Ag/C) - (455.56*CS) + (6.40*PR^2)\\ &+ (107.98*PT^2) + (4.13*CS^2) + (0.32*W/B*A*Ag/C*CS)\end{aligned} \tag{4}$$

$$\begin{aligned}\text{Chloride penetration depth (mm)} &= -14.40 + (34.90*W/B) - (0.19*PR) + (0.087*A)\\ &+ (0.068*PT) - (0.761*Ag/C) + (0.228*CS) + (0.003*PR^2)\\ &- (0.108*PT^2) - (0.002*CS^2)\end{aligned} \tag{5}$$

Figs. 4 and 5 demonstrated that the nonlinear regression was reasonably high capable of generalizing between the input parameters variables and the output response as a chloride permeability.

4. Conclusions

An experimental study was conducted to investigate the effect of percentage replacement of various ground pozzolanic materials in blended concrete on the strength and chloride penetration resistance. A mathematical model by linear and nonlinear multiple regression techniques was also constructed. The following conclusions can be drawn:

•The incorporation of GFA, GBA and GRHA as a partial cement replacement marginally improve the workability as indicated in concretes at W/B of 0.62 and 0.48. GFA was the most effective that achieved a reduction of SP contents due to some spherical particle shape of fly ash, also known as ball bearing effect.

•The addition of GFA, GBA and GHA exhibit the improvement of compressive strength and chloride penetration resistance. For the concretes with W/B of 0.62, concretes containing 20% of ground pozzolans seems to be the optimal limit at all ages. As high as 30% by weight of binder can be replaced with ground pozzolans without any adverse effect on strength and permeability properties for concretes with W/B of 0.48 and 0.35, based on the highest compressive strength and the lowest chloride permeability of concretes.

•It should be noted that the GBA blended concretes at 28 and 60 days with 30% replacement level, the values of compressive strength was lower compared to that of the control concrete. However, the percentage compressive strength of GBA blended concretes was higher than 92%.

•The GRHA blended concretes had the highest chloride penetration resistance in comparison to those of GFA and GBA blended concretes. Herein, the 40% of cement replacement yields a significant reduction in the chloride permeability.

•The best prediction of chloride permeability was achieved by using nonlinear multiple regression technique and a high absolute fraction of variance with a low mean absolute percentage error was obtained for the charge passed and chloride penetration depth data sets.

Acknowledgements

The authors would like to thank the faculty of engineering, Mahasarakham University for providing facilities and equipments during the investigation. The authors also thank Mr.Sunit Inthata for his valuable support and suggestions.

References

Cheerarot, R. and Jaturapitakkul, C. (2003), “Development of bottom ash as pozzolanic material”, *J. Mater Civil Eng*., **15**(1), 48-54.

Cheriaf, M., Rocha, J.C. and Pera, J. (1999), “Pozzolanic properties of pulverized coal combustion bottom ash”, *Cement Concrete Res*., **29**(9), 1387-1391.

Chindaprasirt, P., Chotithanorm, C., Cao, H.T. and Sirivivatnanon, V. (2007), “Influence of fly ash fineness on the chloride penetration of concrete”, *Constr. Build. Mater*., **21**(2), 356-361.

Chindaprasirt, P., Jaturapitakkul, C. and Sinsiri, T. (2005), “Effect of fly ash fineness on compressive strength and pore size of blended cement paste”, *Cement Concrete Compos*., **27**(4), 425-428.

Chindaprasirt, P., Ruangsiriyakul, S., Cao, H.T. and Bucea, L. (2001), “Influence of Mae Moh fly ash fineness on characteristics, strength and drying shrinkage development of blended cement mortars”, *In: The Eighth East Asia-Pacific Conference on Structural Engineering and Construction,* Singapore, December.

Chindaprasirt, P., Rukzon, S. and Sirivivatnanon, V. (2008) “Resistance to chloride penetration of blended portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash”, *Constr. Build. Mater*., **22**(5), 932-938.

Ganesan, K., Rajagopal, K. and Thangavel, K. (2008), “Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete”, *Constr. Build. Mater*., **22**(8), 1675-1683.

Gastaldini, A.L.G., Isaia, G.C., Gomes, N.S. and Sperb, J.E.K. (2007), “Chloride penetration and carbonation in concrete with rice husk ash and chemical activators”, *Cement Concrete Compos*., **29**(3), 176-180.

Habeeb, G.A. and Fayyadh, M.M. (2009), “Rice husk ash concrete: the effect of RHA average particle size on mechanical properties and drying shrinkage", *Aust. J. Basic Appl. Sci.*, **3**(3), 1616-1622.

Habert, G., Billard, C., Rossi, P., Chen, C. and Roussel, N. (2010), "Cement production technology improvement compared to factor 4 objectives", *Cement Concrete Res*., **40**(5), 820-826.

Isaia, GC., Gastaldini, ALG. and Moraes, R. (2003), "Physical and pozzolanic action of mineral additions on the mechanical strength of high-performance concrete", *Cement Concrete Compos*., **25**(1), 69-76.

Kiattikomol, K., Jaturapitakkul, C., Songpiriyakij, S. and Chutubtim, S. (2001), "A study of ground coarse fly ashes with different finenesses from various sources as pozzolanic materials", *Cement Concrete Compos*., **23**(4-5), 335-343.

Marks, M., Jozwiak, N.D. and Glinicki, M.A. (2012), "Automatic categorization of chloride migration into concrete modified with CFBC ash", *Comput Concr.*, **9**(5), 375-387.

Mejlbro, L. and Poulsen, E. (2006), *Diffusion of Chloride in Concrete*, Taylor and Francis Inc, New York.

Naik, T.R. and Singh, S.S. (1994), "Permeability of concrete containing large amounts of fly ash", *Cement Concrete Res*., **24**(5), 913-922.

Nair, D.G., Fraaij, A., Klaassen, A.K. and Kentgens, P.M. (2008), "A structural investigation relating to the pozzolanic activity of rice husk ashes", *Cement Concrete Res*., **38**(6), 861-869.

Otsuki, N., Nagataki, S. and Nakashita, K. (1993), "Evaluation of $AgNO_3$ solution spray method for measurement of chloride penetration into hardened cementitious matrix materials", *Constr. Build. Mater*., 7(4), 195-201.

Stanish, K.D., Hooton, R.D. and Thomas, M.D.A. (1997), *Testing the chloride penetration resistance of concrete: A literature review*, Department of Civil Engineering, University of Toronto, Ontario, Canada.

Sata, V., Jaturapitakkul, C. and Kiattikomol, K. (2007), "Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete", *Constr. Build. Mater*., **27**(7), 1589-1598.

Tangpagasit, J., Cheerarot, R., Jaturapitakkul, C. and Kiattikomol, K. (2005), "Packing effect and pozzolanic reaction of fly ash in mortar", *Cement Concrete Res*., **35**(6), 1145-1151.

Wang, X.Y., Park, K.B. and Lee, H.S. (2012), "Modeling of chloride diffusion in a hydrating concrete incorporating silica fume", *Comput. Concr.*, **10**(5), 523-539.

Wee, T.H., Suryavanshi, A.K. and Tin, S.S. (2000) "Evaluation of rapid chloride permeability test (RCPT) results for concrete containing mineral admixtures", *ACI Mater. J.*, **97**(M29), 221-232.

Yazici, H., Aydun, S., Yigiter, H. and Baradan, B. (2005), "Effect of steam curing on class C high-volume fly ash concrete mixtures", *Cement Concrete Res*., **35**(6), 1122-1127.

Zhang, S., Dong, X. and Jiang, J. (2013), "Effect of measurement method and cracking on chloride transport in concrete", *Comput. Concr.*, **11**(4), 315-316.

CC