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Mathematical model of strength and porosity of ternary blend Portland rice husk ash and fly ash cement mortar

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Abstract. This paper presents a mathematical model for strength and porosity of mortars made with ternary blends of ordinary Portland cement (OPC), ground rice husk ash (RHA) and classified fly ash (FA). The mortar mixtures were made with Portland cement Type I containing 0-40% FA and RHA. FA and RHA with 1-3% by weight retained on a sieve No. 325 were used. Compressive strength and porosity of the blended cement mortar at the age of 7, 28 and 90 days were determined. The use of ternary blended cements of RHA and FA produced mixes with good strength and low porosity of mortar. A mathematical analysis and two–parameter polynomial model were presented for the strength and porosity estimation with FA and RHA contents as parameters. The computer graphics of strength and porosity of the ternary blend were also constructed to aid the understanding and the proportioning of the blended system.

Keywords: fly ash; rice husk ash; compressive strength; porosity; mortar.

1. Introduction

A large number of researches have been directed towards the utilization waste materials. For the construction industry, the development and use of blended cements is growing rapidly. Pozzolans from industrial and agricultural by-products such as fly ash and rice husk ash are receiving more attention now since their uses generally improve the properties of the blended cement mortar or concrete, and reduce the environmental effects.

Rice husk is one of the major agricultural by-products and is available in many parts of the world. When rice husk is burnt at temperature lower than 700°C, the rice husk ash with cellular microstructure is produced. Rice husk ash contains high silica content in the form of non-crystalline or amorphous silica. The silica content in rice husk ash is high at approximately 90%. This rice husk ash is a pozzolanic material and can be used as supplementary cementitious materials (Metha 1979, Chindaprasirt and Rukzon 2007).

Fly ash is the most common pozzolan and is being used worldwide in concrete works. It is generally realized that the use of fine fly ash improves the properties of mortar and concrete (Erdogdu and Tucker 1998, Lee, *et al.* 1999). Although, the porosity of the paste is increased as a result of an incorporation of fly ash, the average pore size is reduced. This results in a less

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permeable paste (Poon, *et al.* 1997, Chindaprasirt, *et al.* 2005). The interfacial zone of the interface between aggregate and the matrix is also improved as a result of the use of fly ash (Wong, *et al.* 1999, Kuroda, *et al.* 2000).

The use of the blend of pozzolan has been shown to be advantages owing to the synergic effects (Isaia, *et al.* 2003). In this work, fly ash and rice husk ash are used as base materials for studying the ternary blended system. The mathematical model is performed on the results and is presented in the form of computer graphic to aid the understanding and the proportioning of the blended system. The knowledge would be beneficial to the understanding of the mechanism as well as for future applications of these materials.

2. Experimental details

2.1. Materials

Lignite fly ash from Mae Moh power plant in the northern part of Thailand was used. Rice husk ash was obtained from open burning in a small heap of 20 kg rice husk with maximum temperature of burning of 650°C. The burning was self–sustained with the total burning time of 24 hours. Ordinary Portland cement (OPC), river sand with specific gravity of 2.63 and fineness modulus of 2.82, and type-F superplasticizer (SP) were the materials used in this study.

Classified fly ash (FA) and ground rice husk ash (RHA) were used. Fine fly ash (FA) with 1-3% retained on a sieve No. 325 (opening 45 μm) was obtained from air classification of as-received coarse fly ash. The ground rice husk ash (RHA) was obtained using ball mill grinding of rice husk ash until the percentage retained on a sieve No. 325 (opening 45 μm) was 1-3% as well.

The fineness, specific gravity and mean particle size of Portland cement and pozzolanic materials are given in Table 1. The particle size distributions are given in Fig. 1 and the chemical constituents in Table 2. Fly ash was a Class F fly ash with 74% of SiO_2 + Al_2O_3 + Fe_2O_3, 2.2% of SO_3 and 2.5% of loss on ignition (LOI) meeting the requirement of ASTM C618 (2001). However, as this fly ash was from lignite, the CaO content was rather high at 14.4%. The scanning electron micrograph (SEM) of fly ash as shown in Fig. 2 revealed that as-received fly ash consisted of a large range of particle sizes. The particles were spherical in shape but the surfaces of the large particles were usually rough. After classification, FA mainly consisted of small spherical particles with smooth surface. RHA, on the other hand, consisted mainly of SiO_2 and the other components were not significant. The SiO_2 content of 93% satisfied ASTM C618 (2001) requirement as a natural pozzolan and 3.7% of LOI indicated a complete burning. The SEM photo revealed that the rice husk ash still maintained its cellular structure. After grinding, RHA consisted of very irregular-shaped particles with porous cellular surface (Chindaprasirt and Rukzon 2007).

Table 1 Physical properties OPC, FA and RHA

Sample	Median particle size (μm)	Retained on a sieve No. 325 (%)	Specific gravity (g/cm^3)	Blaine fineness (cm^2/g)
OPC	15.0	-	3.14	3,600
FA	4.9	1-3	2.45	5,700
RHA	10.0	1-3	2.23	11,200

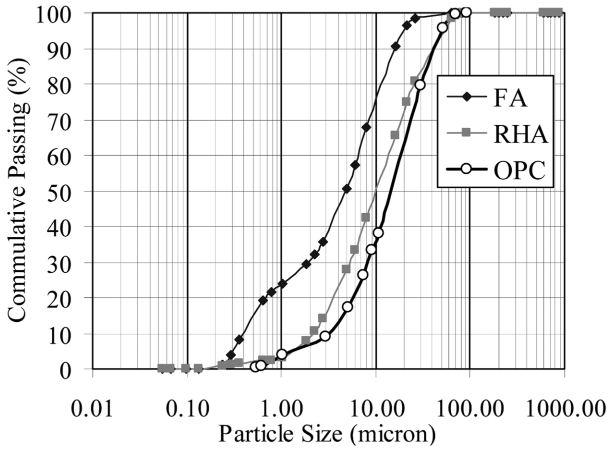


Fig. 1 Particle size distribution of FA, RHA and OPC

Table 2 Chemical composition of OPC, RHA and FA

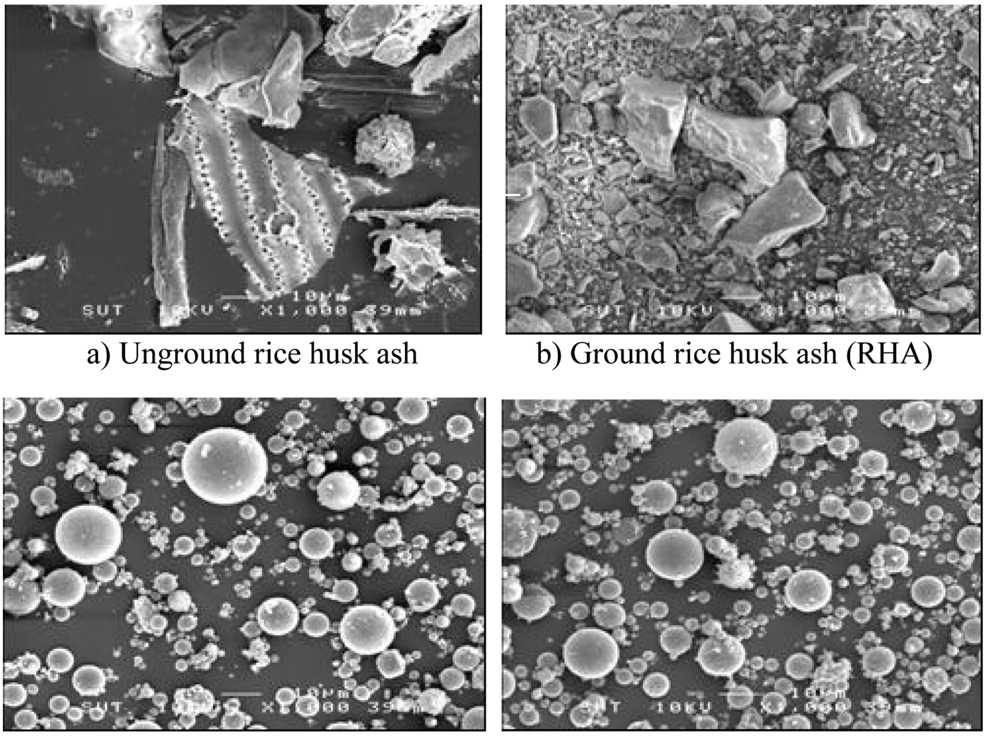
Oxides	OPC	RHA	FA
SiO_2	20.5	93.0	41.0
Al_2O_3	4.5	0.5	21.5
Fe_2O_3	3.4	0.1	11.5
CaO	65.4	1.1	14.4
MgO	1.3	0.1	3.3
Na_2O	0.2	0.1	1.1
K_2O	0.4	1.3	2.6
SO_3	2.7	0.9	2.2
LOI	0.9	3.7	2.5
$SiO_2 + Al_2O_3 + Fe_2O_3$	-	93.6	74.0

2.2. Mix proportions and curing

Ordinary Portland cement was partially replaced with pozzolans at the dosage of 0-40% by weight of cementitious materials. In addition to single pozzolan, a blend of different weight portions of RHA and FA were also used. Sand-to-binder ratio of 2.75 by weight and water to binder ratio (W/B) of 0.5 were used. SP was incorporated in order to obtain mortar mixes with similar flow of 110 ± 5%. The cast specimens were covered with polyurethane sheet and damped cloth in the 23 ± 2-°C chamber. They were demoulded at the age of 1 day and moist cured at 23 ± 2-°C until the test ages. The mortar mix proportions and abbreviations are given in Table 3. The mortar mix proportions and abbreviations are taken from previous publication (Chindaprasirt and Rukzon 2007).

2.3. Compressive strength

The 50×50×50 mm cube was used for the compressive strength test of mortar. They were tested at the age of 7, 28 and 90 days. The test was done in accordance with the ASTM C109 (2001). The reported results were the average of three samples.



a) Unground rice husk ash   b) Ground rice husk ash (RHA)

c) As–received fly ash   d) Fine fly ash (FA)

Fig. 2 SEM of rice husk ash and fly ash

Table 3 Mortar mix proportions

Mix No.	Symbol	OPC	FA	RHA	SP (%)
1	OPC	100	-	-	1.9
2	10FA	90	10	-	0.6
3	10RHA	90	-	10	2.0
4	20FA	80	20	-	0.4
5	20RHA	80	-	20	2.2
6	10FA10RHA	80	10	10	1.1
7	20FA10RHA	70	20	10	1.1
8	15FA15RHA	70	15	15	1.2
9	10FA20RHA	70	10	20	1.3
10	40FA	60	40	-	0.1
11	40RHA	60	-	40	3.7
12	20FA20RHA	60	20	20	1.6

Note: Sand-to-binder ratio 2.75, W/B = 0.5, Flow 110 ± 5%

2.4. Porosity tests

The 100×200 mm cylinders were prepared in accordance with ASTM C39 (2001). They were tested at the age of 7, 28 and 90 days. After being cured in water, they were cut into 50 mm in thick slices with the 50 mm ends discarded. They were dried at $100 \pm 5^{o}C$ until constant weight were achieved and were then placed in desiccators under vacumm for 3 hours. The set-up was finally filled with de-aired, distilled water to measure the porosity of the mortar. The porosity was calculated using Eq. (1).

$$porosity(\%) = \frac{(Wa - Wd)}{(Wa - Ww)} \times 100 \quad (1)$$

where, *porosity* (%) = vacuum saturated porosity (%),
Wa = the weight of specimen in the air at saturated condition (g),
Wd = the dry weight of the specimen after 24 hours in oven at $100 \pm 5^{o}C$ (g), and
Ww = the weight of the specimen in water (g).

This method was used to measure the porosity of the cement-based materials successfully (Papadakis, *et al.* 1992, Cabrera and Lynsdale 1988, Rossignolo and Agnesini 2004, Gonen and Yazicioglu 2007). The reported results were the average of two samples. The experimental details are taken from previous publication (Chindaprasirt and Rukzon 2007).

3. Results and discussions

3.1. Compressive strength and porosity (the experimental data)

The results of compressive strength and porosity are taken from previous publication (Chindaprasirt and Rukzon 2007). Tables 4 and 6 give the results of the compressive strength and porosity of the blended cements mortar containing FA and RHA.

3.2. Mathematical modeling

3.2.1. Compressive strength

The second order polynomial mathematical analysis method using FA and RHA contents were used to calculate the strength and porosity of the mortar. The model of compressive strength could be expressed as follows:

$$C_{st}(a) = \beta_0 + \sum_{i=1,2}^{n} \beta_{ii} x_i^2 = \sum_{i=1}^{n} \sum_{j=2}^{n} \beta_{ij} x_i x_j \quad (2)$$

or could be expressed as:

$$C_{st}(a) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \quad (3)$$

where $C_{st}(a)$ = compressive strength at a days (a = 7, 28 and 90 days),
x_1 = FA content by % replacement,
x_2 = RHA content by % replacement.

$\beta_0, \beta_1, \beta_2, \beta_{11}, \beta_{22}$ and β_{12} were the regression coefficients obtained after the best fit to models using the least squares method (Oakdale engineering trial version program).

Table 4 Compressive strength of blended cements mortars

Mix No.	Symbol	Tested compressive strength (MPa)			Predicted compressive strength (MPa)		
		7 d	28 d	90 d	7 d	28 d	90 d
1	OPC	43.5	57.0	60.0	43.7	56.9	60.0
2	10FA	45.0	59.2	62.7	44.6	58.9	62.7
3	10RHA	44.2	58.2	62.0	44.3	58.3	61.9
4	20FA	44.5	59.5	63.5	43.2	59.5	63.9
5	20RHA	44.5	58.5	62.5	42.9	58.5	62.8
6	10FA10RHA	42.0	58.0	64.0	44.7	59.0	63.3
7	20FA10RHA	42.4	58.4	63.4	42.7	58.3	63.2
8	15FA15RHA	43.1	58.5	63.0	43.1	58.1	63.1
9	10FA20RHA	42.5	58.7	62.8	42.7	57.9	63.0
10	40FA	33.0	56.5	62.0	33.3	56.5	61.9
11	40RHA	33.5	55.0	62.0	33.9	55.1	61.9
12	20FA20RHA	41.0	55.5	61.5	40.1	55.9	61.6

The results were analyzed with two-parameter polynomial model at each age. The equations for strengths at 7, 28 and 90 day based on the results of 12 mixes are obtained as shown in Eqs. (4)-(6) with the correlation coefficients, R^2 of 0.93, 0.91 and 0.91, respectively.

$$C_{st}(7) = 43.6547 + 0.2167x_1 + 0.1692x_2 - 0.0119x_1^2 - 0.0103x_2^2 - 0.0060x_1x_2 \tag{4}$$

$$C_{st}(28) = 56.9024 + 0.2758x_1 + 0.2015x_2 - 0.0072x_1^2 - 0.0062x_2^2 - 0.0131x_1x_2 \tag{5}$$

$$C_{st}(90) = 60.0458 + 0.3361x_1 + 0.2341x_2 - 0.0072x_1^2 - 0.0047x_2^2 - 0.0126x_1x_2 \tag{6}$$

From the strength equations, the compressive strength of ternary blended mortars could be calculated using two factor variables or proportion of FA and RHA for two experimental variables. Where $C_{st}(7)$, $C_{st}(28)$ and $C_{st}(90)$ were compressive strength (MPa) at 7, 28 and 90 days, respectively; x_1 was the mount of FA as partial cement replacement (%); x_2 was the amount of RHA as partial cement replacement (%). The calculated strengths are shown in Table 4 and agreed well with the experimental data (Fig. 3).

In Table 4, the strengths of mortar containing 10% and 20% of pozzolans and blend of pozzolans were higher than that of the control at all ages. The incorporation of RHA also produced the filler effect due to its fine particle size. The dispersing effect had not been reported for the RHA, however, as RHA surface was very high and thus the reactivity of RHA was also high. The incorporation of FA produced filler and dispersing effects and increased the nucleation and precipitation sites (Poon, *et al.* 1997, Chindaprasirt, *et al.* 2005). At this level of cement replacement of up to 20%, the filler and dispersing effects could offset the reduction in strength due to the reduction in the OPC. The increase in the hydration could also offset the strength reduction due to reduced OPC.

In Table 5, the increase in the amount of replacement to 40% reduced the early strength of both

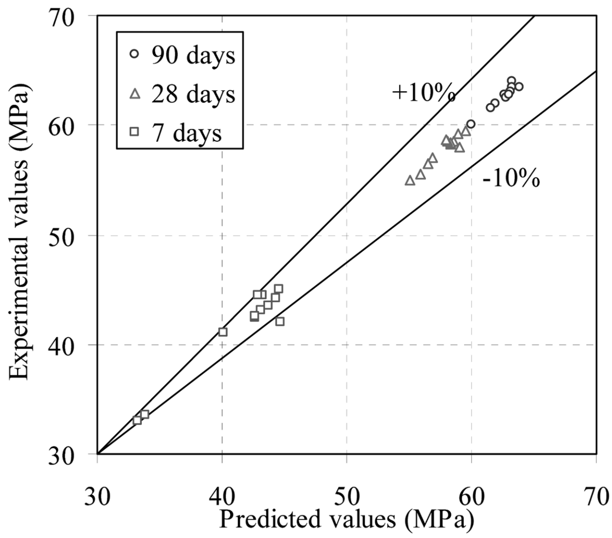


Fig. 3 Relationship between experimental values and predicted values of strength

FA and RHA mortars (ranged between 76-94% of that of OPC). However, the strengths at the ages of 28 and 90 days of both FA and RHA mortars ranged between 96-103% of that of OPC. This indicated that both FA and RHA were pozzolanic materials and the early pozzolanic reaction rate was thus slow. The pozzolanic reaction of both cases; however, could be seen at the age of 28 days onwards. The resulted in the higher strength of both FA and RHA mortar in comparison to those of the control. The results also suggested that both FA and RHA in this experiment were quite reactive and the pozzolanic reaction started quite early.

For the blend of pozzolans, the strengths of mortar were comparable to those of OPC mortars at the same age. The strengths at the age of 7 days blended pozzolan mortars ranged between 95-102% of that of OPC (Table 5). At the age of 28 and 90 days, the normalized strength ranged

Table 5 Normalized strength of blended cements mortars

Mix No.	Symbol	Tested *normalized* strength (%)			Predicted *normalized* strength (%)		
		7 d	28 d	90 d	7 d	28 d	90 d
1	OPC	100	100	100	100	100	100
2	10FA	103	104	105	102	104	105
3	10RHA	102	102	103	101	102	103
4	20FA	102	104	106	99	105	107
5	20RHA	102	103	104	98	103	105
6	10FA10RHA	97	102	107	102	104	106
7	20FA10RHA	97	102	106	98	102	105
8	15FA15RHA	99	103	105	99	102	105
9	10FA20RHA	98	103	105	98	102	105
10	40FA	76	99	103	76	99	103
11	40RHA	77	96	103	78	97	103
12	20FA20RHA	94	97	103	92	98	103

between 97-104% and 103-107% respectively (Table 5). The results indicated that for the high replacement level of 40%, the use of blend of RHA and FA improved the early strength development of mortar in comparison to normal single pozzolan mortar. The incorporation of blend of fine pozzolans improved the strength of concrete due to synergic effect (Isaia, *et al.* 2003).

Figs. 4-6 present the isoresponse curves of compressive strength showing the interaction of FA and RHA for the domain studied in the ternary system. At the age of 7 days, the computer graphic revealed the equal contribution to strength development between FA and RHA. However, at the age of 28 and 90 days, FA contribution to the strength development of the ternary system was larger than that of the RHA as the region of high strength lied close to the zero RHA content axes. It should be reminded here that the FA used in this study was fine fly ash and hence its properties and its effect on the strength development were better than the normal as-received fly ash.

3.2.2. Porosity

The mathematical model used for the strength could also be applied to the case of porosity *(P)*. The equations for porosities at the ages of 7, 28 and 90 days were obtained from the experimental results of 12 mixes as shown in Eqs. (7)-(9). The relatively high correlation coefficients, R^2 of 0.99, 0.98 and 0.91 for the porosities at 3, 7 and 28 days were obtained.

$$P(7) = 17.6757 - 0.1334x_1 - 0.1051x_2 + 0.0054x_1^2 + 0.00052x_2^2 + 0.0056x_1x_2 \quad (7)$$

$$P(28) = 13.7501 - 0.1125x_1 - 0.0901x_2 + 0.0033x_1^2 + 0.0030x_2^2 + 0.0066x_1x_2 \quad (8)$$

$$P(90) = 12.8018 – 0.0608x_1 - 0.0178x_1 - 0.0014x_1^2 + 0.0005x_2^2 + 0.0038x_1x_2 \quad (9)$$

From the porosity equations, the porosities of mortars of the ternary blend system could be calculated using FA and RHA proportions as two factor variables. Where *P*(7), *P*(28) and *P*(90) are porosity (%) at 7, 28 and 90 days, respectively; x_1 was a mount % of FA as partial cement replacement; x_2 was a

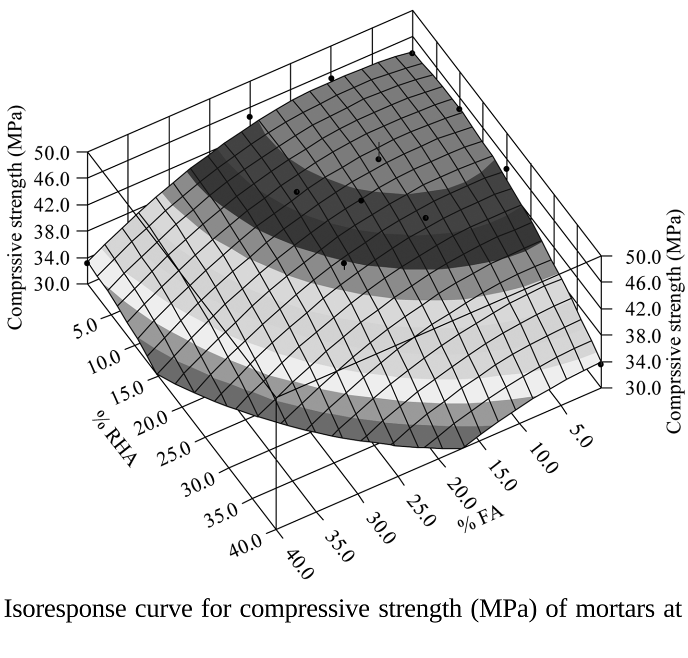


Fig. 4 Isoresponse curve for compressive strength (MPa) of mortars at 7 days

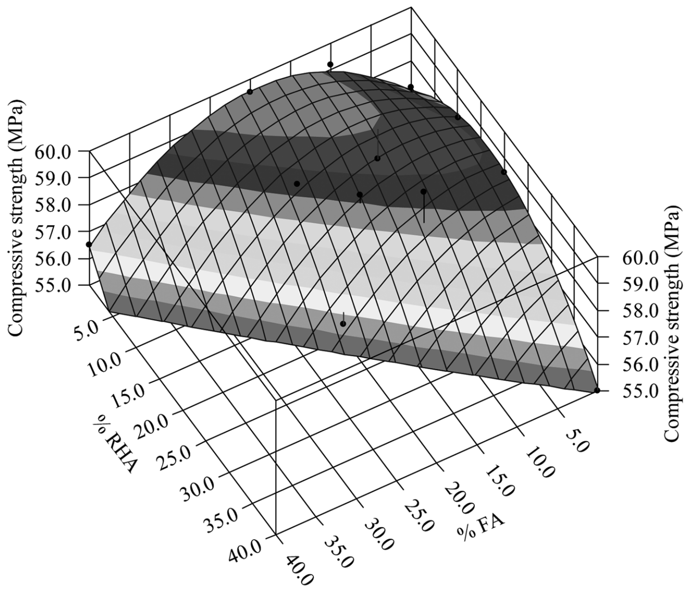


Fig. 5 Isoresponse curve for compressive strength (MPa) of mortars at 28 days

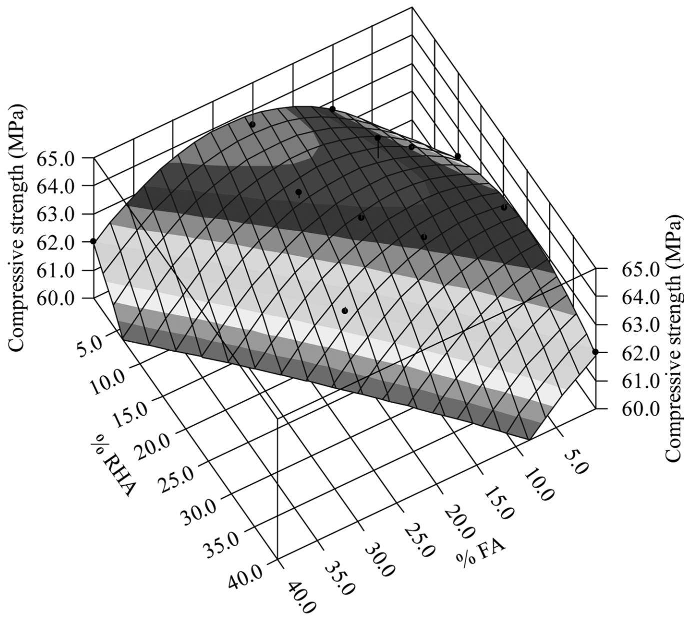


Fig. 6 Isoresponse curve for compressive strength (MPa) of mortars at 90 days

mount % of rice husk ash as partial cement replacement. The calculated porosities are shown in Table 6 and the values were in good agreement with the experimental data (Fig. 7).

The results of the porosity of mortar at 7, 28 and 90 days are shown in Table 6. At the age of 7 days, the porosities of mortar containing 10% and 20% of pozzolans and blend of pozzolans were lower than that of the control at all ages. At this low level of replacement, the filler effect of the

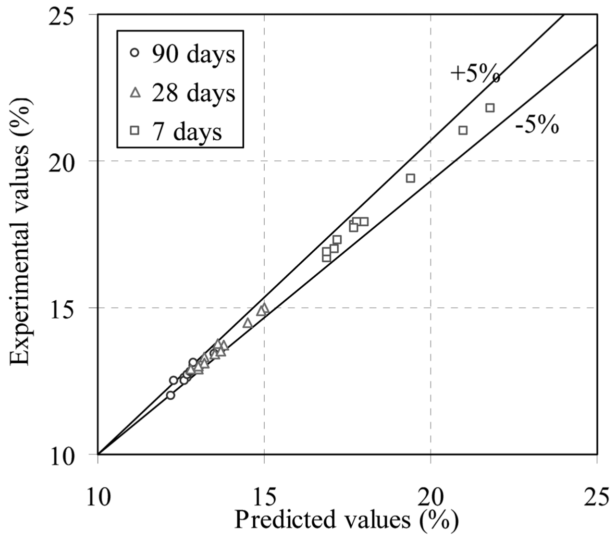


Fig. 7 Relationship between experimental values and predicted values of porosity

pozzolans modified pore and reduced the porosity of mortars. Similar results were reported for the paste containing fly ash (Chindaprasirt, *et al.* 2005). It was reported that the incorporation of RHA also refined the pore system (Metha 1979). The mortar containing FA gave slightly less porosity than that of RHA. In other words, FA was slightly more effective in modifying pore and reduced the porosity of mortar. The porosity of 20FA mortar was 17.3% in comparison with 17.8% of both OPC and 20RHA mortars.

At high replacement level of 40%, the porosities of the mortars containing pozzolans increased in comparison with that of the control. At the age of 7 days, the porosities of 40FA, 40RHA and 20FA20RHA mixes were 21.0%, 21.8% and 19.4% which were significantly larger than 17.8% of the OPC mortar (Table 6). The increases in porosity with a relative large amount of pozzolans

Table 6 Porosity of blended cements mortars

Mix No.	Symbol	Tested porosity (%)			Predicted porosity (%)		
		7 d	28 d	90 d	7 d	28 d	90 d
1	OPC	17.8	13.7	12.8	17.7	13.8	12.8
2	10FA	16.7	12.9	12.5	16.9	13.0	12.3
3	10RHA	17.0	13.3	12.6	17.1	13.2	12.7
4	20FA	17.3	12.9	12.0	17.2	12.8	12.2
5	20RHA	17.8	13.1	12.6	17.7	13.2	12.6
6	10FA10RHA	16.9	13.0	12.5	16.9	13.0	12.6
7	20FA10RHA	17.9	13.4	12.8	17.8	13.5	12.8
8	15FA15RHA	17.7	13.8	13.0	17.7	13.6	12.9
9	10FA20RHA	17.9	13.5	13.1	18.0	13.7	12.9
10	40FA	21.0	14.5	12.7	21.0	14.5	12.7
11	40RHA	21.8	15.0	12.8	21.8	15.0	12.8
12	20FA20RHA	19.4	14.9	13.4	19.4	14.9	13.5

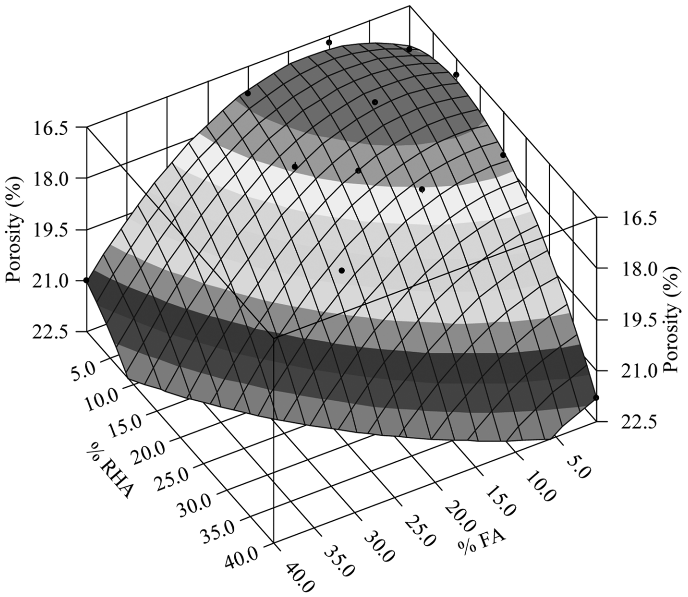


Fig. 8 Isoresponse curve for porosity (%) of mortars at 7 days

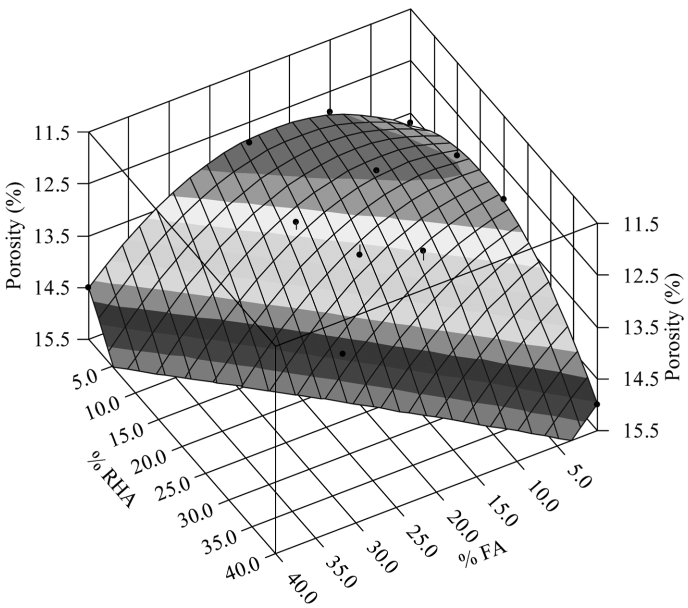


Fig. 9 Isoresponse curve for porosity (%) of mortars at 28 days

resulted from the reduced hydration products associated with the lower amount of OPC and the low pozzolanic reaction at the early age.

The porosities of the mortars reduced with an increase in age as expected. This was due the increase in the hydration of cementitious materials. At a later age of 90 days, the porosities of the mortars containing pozzolans reduced to similar values to that of OPC mortar owing to the

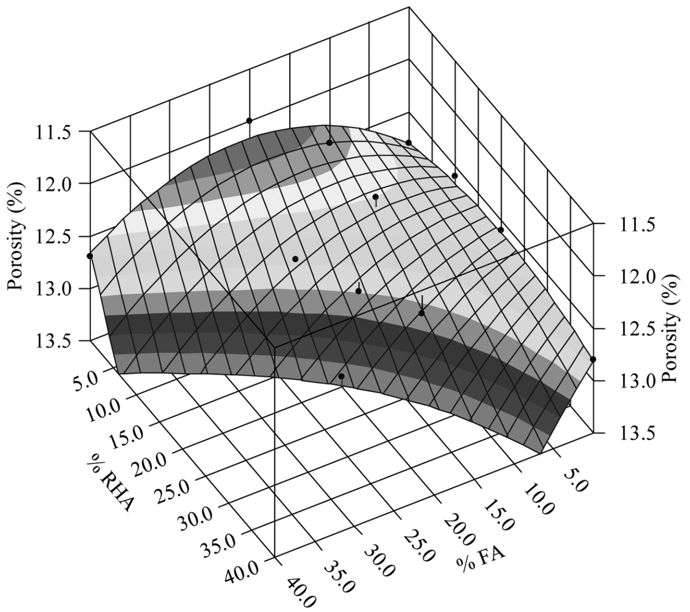


Fig. 10 Isoresponse curve for porosity (%) of mortars at 90 days

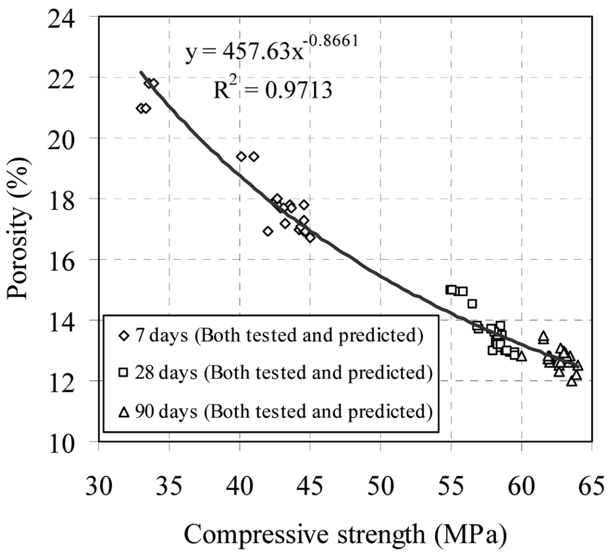


Fig. 11 Relationship between porosity and compressive strength

pozzolanic reaction of the pozzolans. The porosities of 40FA, 40RHA and 20FA20RHA mixes at 90 days were 12.7%, 12.8% and 13.4% as compared to 12.8% of OPC mortar at the same age.

The isoresponse curves for 7, 28 and 90 days porosity, as a function of FA and RHA proportions were presented in Figs. 8-10. As for the strength curve, the porosity curve at 7 days showed a similar trend of approximately equal contribution of FA and RHA to porosity of mortar. At a later age of 90 days, the contribution of FA to the porosity reduction was larger than that of the RHA as the region of low porosity lied close to the zero RHA content axes. The results corresponded well with the strength curves.

The computer graphics of strength and porosity were easy to interpret and thus aided the understanding of behavior and the mix proportioning of the ternary blend system of OPC, FA and RHA. When all ages were considered, this range stretched from 12% to 21.8%. In Fig. 11, this range of porosity values corresponded to compressive strength over the range 33 to 64 MPa (Both tested and predicted).

4. Conclusions

Both FA and RHA were quite good pozzolans. FA reduced the SP requirement to produce similar flow due to its spherical shape and smooth surface. RHA, however, increased the amount of SP owing to its high fineness and porous cellular structure. The strengths of the mortar containing FA and RHA were relatively high. The strengths of mortar containing up to 20% of these pozzolans or blend of pozzolans were higher than those of the OPC mortar. The incorporation of FA produced filler and dispersing effects and increased the nucleation and precipitation sites whereas the incorporation of RHA produced filler effect and pozzolanic reaction.

The second order polynomial mathematical analysis method using the FA and RHA content were used to calculate the strength and porosity of the mortar. Computer graphic in the form of isoresponse curves were easily formed and used to aid the understanding and the mix proportioning of the ternary OPC, FA and RHA system. The curves indicated that at the age of 7 days, the contributions to strength development and reduction in porosities of mortar from FA and RHA were approximately equal. At the later age of 90 days, however, FA contribution to the strength development and reduction in porosities were significantly larger than that of the RHA.

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References

ASTM C109/C109M-99 (2001), *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in or [50 mm] Cube Specimens)*, Annual Book of ASTM Standards, Philadelphia, **04.01**, 83-88.

American Society for Testing and Materials, ASTM C150 (2001), *Standard Specification for Portland Cement*, In Annual Book of ASTM Standards, Philadelphia, **04.01**, 128-132.

American Society for Testing and Materials, ASTM C39/C39M-01 (2001), *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, Annual Book of ASTM Standards, Philadelphia, **04.02**, 18-22.

ASTM C618-00 (2001), *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete*, Annual Book of ASTM Standards, Philadelphia, **04.02**, 310-313.

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. and Rukzon, S. (2007), "Strength, porosity and corrosion resistance of ternary blend Portland cement, rice husk ash and fly ash mortar", *Constr. Build. Mater.*, doi: 10.1016/j.conbuildmat.2007.06.010

Cabrera, J. G. and Lynsdale, C. J. (1988), "A new gas parameter for measuring the permeability of mortar and concrete", *Mag. Concrete Res.*, **40**, 177-182.

Yang, D., Sun, W. and Tan, Y. (2005), "Performance evaluation of binary blends of Portland cement and fly ash with complex admixture for durable concrete structures", *Comput. Concrete.*, **2**(5).

Erdogdu, K. and Tucker, P. (1998), "Effects of fly ash particle size on strength of Portland cement fly ash mortars", *Cement Concrete Res.*, **28**, 1217-1222.

Gonen, T. and Yazicioglu, S. (2007), "The influence of compaction pore on sorptivity and carbonation of concrete", *Const. Build. Mater.*, **21**, 1040-1045.

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

Kuroda, M, Watanabe, T. and Terashi, N. (2000), "Increase of bond strength at interfacial transition zone by the use of fly ash", *Cement Concrete Res.*, **30**(2), 253-258.

Lee, S. H., Sakai, E., Diamond, M. and Bang, W. K. (1999), "Characterization of fly ash directly from electrostatic precipitator", *Cement Concrete Res.*, **29**, 1791-1797.

Metha, P. K. (1979). "The chemistry and technology of cement made from rice husk ash, In UNIDO/ESCAP/ RCTT", *Proceeding of Workshop on Rice Husk Ash Cement, Peshawar*, Parkistan, Regional Center for technology transfer, Bangalor, India; 113-22.

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Papadakis, V. G., Fardis, M. N. and Veyenas, C. G. (1992), "Hydration and carbonation of pozzolanic cements, *ACI Mater. J. Technical Paper*; 89:2.

Poon, C. S., Wong, Y. L. and Lam, L. (1997), "The influence of different curing conditions on the pore structure and related properties of fly ash cement pastes and mortars", *Constr. Build. Mater.*, **11**, 383-393.

Rossignolo, J. A. and Agnesini, M. V. (2004), "Durability of polymer-modified lightweight aggregate concrete", *Cement Concrete Compos.*, 375-380.

Wong, Y. L., Lam, L., Poon, C. S. and Zhou, F. P. (1999), "Properties of fly ash-modified cement mortar-aggregate interfaces", *Cement Concrete Res.*, **29**, 1905-1913.

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