

Compressive strength of mixture proportioning in ternary cementitious systems

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Abstract

This paper presents a study on the strength of mortars made with ternary blends of ordinary Portland cement (OPC), ground rice husk ash (RHA) and classified fly ash (FFA). The mortar mixtures were made with Portland cement Type I containing 0–40% FFA and RHA. FFA and RHA with 1–3% by weight retained on sieve No. 325 were used. Compressive strength of the blended cement mortar at the age of 7, 28 and 90 days were determined. The results reveal that the use of ternary blended cements of RHA and FFA produces good strength mortars.

A statistical analysis and two-parameter polynomial model are presented to predict the compressive strength. For compressive strength, the mathematical model correlates well with the experimental results. The computer graphics of strength of the ternary blended mortars are also constructed and can be used to aid the understanding and the proportioning of the blended system.

1. Introduction

A large number of researchers have been directed towards the utilization of 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 since their uses generally improve the properties of the blended cement concrete, cost saving and the reduction of negative 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 temperatures lower than 700 °C, rice husk ash with cellular microstructure is

produced. Rice husk ash contains high silica content in the form of non-crystalline or amorphous silica. Therefore, rice husk ash is a pozzolanic material and can be used as supplementary cementitious materials [1].

Fly ash is the most common pozzolan and is being used worldwide in concrete works. The incorporation of fly ash enhances the performance of concrete in terms of durability.

The use of the blend pozzolan has been shown to be advantages owing to the synergic effects [2,3]. In addition, Rukzon and Chindaprasirt [3], reported that the use of ternary blends of Portland cement, rice husk ash and fly ash with complex admixture increased strength of mortar.

In this work, fly ash and rice husk ash are used as base materials for studying the ternary blended system. The results of the study would be beneficial to the understanding of the mechanism as well as for future applications of these materials. In addition, the mathematical model is performed on the results and is presented in the form of 3-D graphic to aid the understanding and the proportioning of the blended system.

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 small heaps of 20 kg rice husk with maximum temperature of burning of 650 °C. ordinary Portland cement (OPC), river sand with specific gravity of 2.63 and fineness modulus of 2.82, and type-F superplasticizer (SP) were used.

Classified fly ash (FFA) and ground rice husk ash (RHA) were used. Fine fly ash

(FFA) with 1-3% retained on sieve No. 325 (opening 45 μm) was obtained from air classification of as-received fly ash. The ground rice husk ash (RHA) was obtained from ball mill grinding machine, the percentage retained on sieve No. 325 (opening 45 μm) was 1-3% as well. Grading analysis of FFA and RHA are shown in Fig. 1.

2.2 Mix proportions and curing

OPC is partially replaced with pozzolans at the dosage of 0–40% by weight of cementitious materials. In addition to single pozzolan, the blend of different weight portions of RHA and FFA 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 $110 \pm 5\%$.

The specimens were covered with polyurethane sheet and damped cloth in a 23 ± 2 °C chamber. They were demoulded at the age of 1 day and moist cured at a 23 ± 2 °C until the test ages. The mix proportions and abbreviations are given in Table 1.

Table 1 Mortar mix proportions (%)

Mix no.	Symbol	OPC	FFA	RHA	SP (%)
1	OPC	100	-	-	1.9
2	20FFA	80	20	-	0.4
3	10FFA10RHA	80	10	10	1.1
4	20RHA	80	-	20	2.2
5	40FFA	60	40	-	0.1
6	20FFA20RHA	60	20	20	1.6
7	40RHA	60	-	40	3.7
8	10FFA	90	10	-	0.6
9	10RHA	90	-	10	2.0
10	20FFA10RHA	70	20	10	1.1
11	15FFA15RHA	70	15	15	1.2
12	10FFA20RHA	70	10	20	1.3

Note: Sand-to-binder 2.75, W/B = 0.5 and flow $110 \pm 5\%$.

2.3 Compressive strength

The 50 × 50 × 50 mm mortar cube was used for the compressive strength test. They were tested at the age of 7, 28 and 90 days. The test was done in accordance with the ASTM C109 [4]. The result is the average of four samples.

3. Results and discussions

3.1 Characteristics of OPC, FFA and RHA

The fineness characteristics of Portland cement and pozzolanic materials are given in Table 2. The Blaine fineness of OPC is 3,600 cm^2/gm . The finenesses of the FFA and RHA are 5,700 and 11,200 cm^2/gm , respectively. The specific gravities of the OPC, FFA and RHA are 3.14, 2.45 and 2.23, respectively. The particle size distributions as shown in Fig. 1 suggest that FFA is finest, followed by RHA and OPC. The mean particle sizes of these are as follows: FFA 4.9 μm , RHA 10.0 μm and OPC 15 μm .

Table 2 Physical properties of FFA, RHA and OPC

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

The chemical constituents are given in Table 3. Fly ash in this experiment is a Class F fly ash with 74% of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$, 2.2% of SO_3 and 2.5% of LOI meeting the requirement of ASTM C618 [5]. However, as this fly ash is from lignite, the CaO content is rather high at 14.4%. RHA, on the other hand, consists mainly of SiO_2 and the other components are not significant. The SiO_2 content of 93.2% satisfies ASTM C618 [5] requirement as a natural pozzolan.

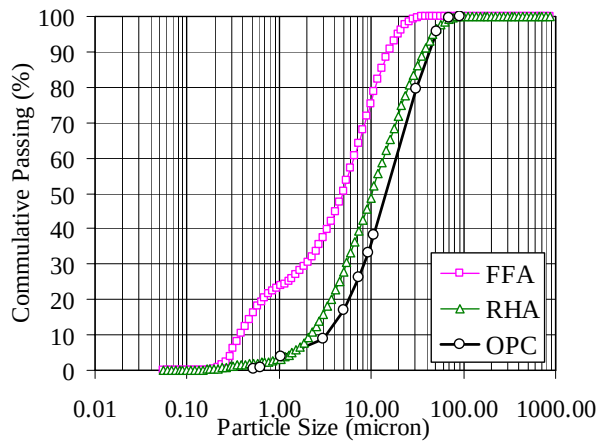


Fig. 1. Particle size distribution of FFA, RHA and OPC.

Table 3 Chemical composition of OPC, RHA and FFA

Oxides (%)	OPC	RHA	FFA
SiO ₂ (%)	20.9	93.2	41.1
Al ₂ O ₃ (%)	4.8	0.4	21.6
Fe ₂ O ₃ (%)	3.4	0.1	11.3
CaO (%)	65.4	1.1	14.4
MgO (%)	1.3	0.1	3.3
Na ₂ O (%)	0.2	0.1	1.1
K ₂ O (%)	0.4	1.3	2.6
SO ₃ (%)	2.7	0.9	2.2
LOI (%)	0.9	3.7	2.5
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ (%)	-	93.7	74.0

3.2 Compressive strength

Table 4 gives the results of the compressive strength of the blended cements mortar containing FFA and RHA. The strengths of the mortar containing FFA, RHA and the ternary blended cement were relatively high. The strengths of mortar containing 10% and 20% of pozzolans and blend of pozzolans are higher than that of the control at all ages. Only the strength at 7 days of mortar containing 10% FFA + 10% RHA is slightly lower than that of the OPC mortar at the same age.

The incorporation of FFA produces filler and dispersing effects and increases the nucleation and precipitation sites [6,7]. At the 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 incorporation of RHA also produces the filler effect due to its fine particle size. RHA surface is very high. Therefore, the reactivity of RHA is also high and the increase in the hydration could also offset the strength reduction due to reduced OPC.

The increase of both FFA and RHA in the replacement up to 40% reduces the early strength of mortars. However, the strength at the ages of 90 days of both FFA and RHA mortars are higher than that of the control. The early pozzolanic reaction rate is thus slow. The pozzolanic reaction of both cases; however, can be seen at the age of 90 days onwards resulting in the higher strength of both FFA and RHA mortars in comparison to those of the controls. The results also suggest that both FFA and RHA in this experiment were quite reactive and the pozzolanic reaction starts quite early.

For the blended of pozzolans, the strengths of mortar are comparable to those of OPC mortars at the same age. The strengths at the age of 7 days blended pozzolan mortars range between 95–99% of that of OPC. At the age of 28 and 90 days, the normalized strength ranges between 102–103% and 105–107% respectively. The results indicate that for the high replacement level of 40%, the use of blended RHA and FFA improves the early strength development of mortar in comparison to normal single pozzolan mortar. The incorporation of blended fine pozzolans improves the strength of concrete due to synergic effect [2,3].

Table 4 Compressive strength of blended cements mortars

Mix	Symbol	Compressive strength (MPa - normalized)		
		7 d	28 d	90 d
1	OPC	43.5-100	57.0-100	60.0-100
2	20FFA	44.5-102	59.5-105	63.5-105
3	10FFA10RHA	42.0-97	58.0-102	64.0-106
4	20RHA	44.5-102	58.5-103	62.5-104
5	40FFA	33.0-76	56.5-99	62.0-103
6	20FFA20RHA	41.0-95	55.5-102	61.5-106
7	40RHA	33.5-77	55.0-97	62.0-103
8	10FFA	45.0-103	59.2-104	62.7-105
9	10RHA	44.2-102	58.2-102	62.0-103
10	20FFA10RHA	42.4-97	58.4-102	63.4-106
11	15FFA15RHA	43.1-99	58.5-103	63.0-105
12	10FFA20RHA	42.5-98	58.7-103	62.8-105

3.3 Mathematical modeling

The model of compressive strength can be expressed as follows:

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

or can be expressed as:

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

where, $C_{st}(a)$ are compressive strength at a days ($a=7, 28$ and 90 days),

x_1 is FFA content by % replacement,

x_2 is RHA content by % replacement.

$\beta_0, \beta_1, \beta_2, \beta_{11}, \beta_{22}$ and β_{12} are the regression coefficients obtained after the best fit to models using the least squares method.

The results were analyzed with two-parameter polynomial model at each age. The strength of prediction equations at 7, 28 and 90 days are based on the 7 mixes viz., mixes 1–7 were obtained as shown in equations (3)–(5). The correlation coefficients, R^2 were 0.92, 0.97 and 0.92, respectively. The prediction from the mathematical model is then compared with the experimental results of 4 mixes viz., mixes 8–12 for checking the accuracy of the model as shown in Table 5.

$$C_{st}(7) = 43.500 + 0.2146x_1 + 0.2021x_2 - 0.0117x_1^2 - 0.0111x_2^2 - 0.0060x_1x_2 \quad (3)$$

$$C_{st}(28) = 57.0000 + 0.2312x_1 + 0.1688x_2 - 0.0126x_1x_2 \quad (4)$$

$$C_{st}(90) = 60.0000 + 0.3375x_1 + 0.2375x_2 - 0.0126x_1x_2 \quad (5)$$

From the equations, the compressive strength of ternary blended mortars can be predicted using two variables proportion of FFA and RHA. Where $C_{st}(7)$, $C_{st}(28)$ and

$C_{st}(90)$ are compressive strength (MPa) at 7, 28 and 90 days, respectively; x_1 is the mount of FFA as partial cement replacement (%); x_2 is the amount of RHA as partial cement replacement (%). The calculated strengths are shown in Table 5 and agree well with the experimental data.

Figs. 2–4 present the isoresponse curves of compressive strength showing the interaction of FFA and RHA for the domain studied in the ternary system. At the age of 7 days, the 3-D graphic reveals the equal contribution to strength development between FFA and RHA. However, at the age of 28 and 90 days, FFA contribution to the strength development of the ternary system is larger than that of the RHA as the region of high strength lies close to the zero RHA content axes. It should be reminded here that the FFA used in this study is fine fly ash and hence its properties and its effect on the strength development are better than the normal as-received fly ash.

Table 5 Prediction values compressive strength of blended cements mortars

Mix No.	Symbol	Predicted compressive strength (MPa)		
		7d	28 d	90 d
1	OPC	43.5	57.0	60.0
2	20FFA	43.1	59.2	63.9
3	10FFA10RHA	44.8	58.6	63.3
4	20RHA	43.1	58.2	62.9
5	40FFA	33.3	56.6	61.9
6	20FFA20RHA	40.3	55.4	61.7
7	40RHA	33.8	55.1	61.9
8	10FFA	44.5	58.7	62.6
9	10RHA	44.4	58.1	61.9
10	20FFA10RHA	42.8	57.8	63.2
11	15FFA15RHA	43.3	57.6	63.1
12	10FFA20RHA	42.9	57.4	62.9

At 7 days (Fig. 2), the stationary point corresponding to the maximum compressive strength is obtained by the replacement of 10% of FFA and a content of RHA around 10%. The maximum strength is 2% higher than the strength of control mortar. In addition, it is found that at high RHA level (more than 35%), there was large reduction in strength.

At 28 days, the maximum compressive strength is obtained when the ternary blended cement contains around 19% of FFA and around 1% of RHA. At this point, the strength was 3% higher than the corresponding OPC mortar (see Fig. 3). At the age of 90 days (see Fig. 4), the zone of maximum strength is located around 22% of FFA replacement and low level of RHA replacement at around 1%. In general, the point of maximum strength is around 10–22% of FFA and 1–3% RHA at all ages. The predicted values agree very closely with the experimental values as shown in Fig. 5.

The comparison of predicted values and experimental ones for checkpoint with number of mix 8–12 are shown in Table 5 together with the mixes 1–7. It can be seen that the compressive strength values at different ages of mortars of ternary blends can be calculated with an excellent accuracy by the model of strength prediction equations.

In summary, the computer graphics of strength is easy to interpret and thus aid the understanding of behavior and the mix proportioning of the ternary blended system of OPC, FFA and RHA. The comparison of predicted values and experimental ones for checkpoint with number of mix 8–12 are shown in Tables 4 and 5 together with the mixes 1–7. It can be seen that the compressive strength values at different ages of mortars of ternary blends can be calculated with an excellent accuracy by the model of strength prediction equations.

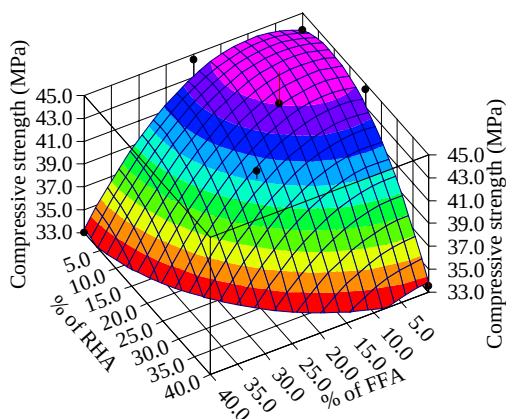


Fig. 2. Isoresponse curve for compressive strength (MPa) of mortars at 7 days.

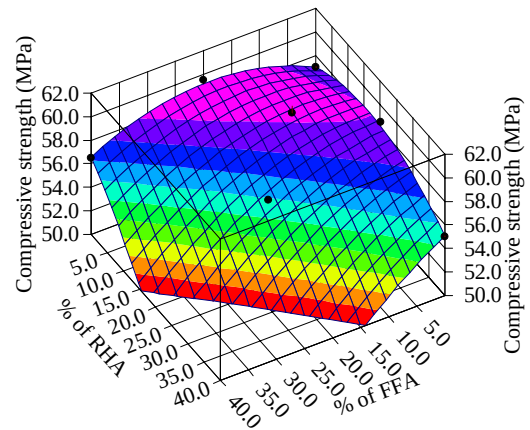


Fig. 3. Isoresponse curve for compressive strength (MPa) of mortars at 28 days.

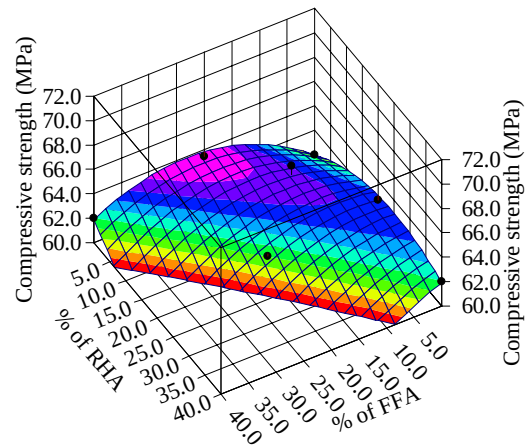


Fig.4. Isoresponse curve for compressive strength (MPa) of mortars at 90 days.

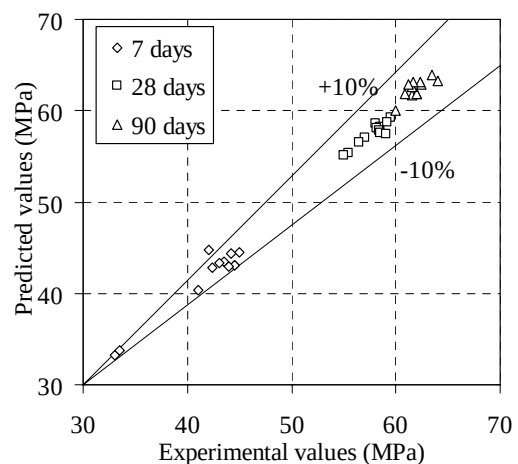


Fig. 5. Relationship between experimental values and predicted values of strength.

4. Conclusions

The strengths of the mortar containing FFA and RHA are relatively high. The strengths of mortar containing up to 20% of these pozzolans or blended of pozzolans are higher than those of the OPC mortar.

The second order polynomial statistical analysis method using the FFA and RHA content is proposed to calculate the strength of the mortar. Computer graphic in the form of isoresponse curves are easily formed and used to aid the understanding and the mix proportioning of the ternary OPC, FFA and RHA system. The curves indicate that at the age of 7 days, the contributions to strength development of mortar from FFA and RHA are approximately equal. At the later age of 28 and 90 days, however, FFA contribution to the strength development is significantly larger than that of the RHA.

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