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Research Article

Influence of rice husk ash substitution on some physical, mechanical and durability properties of the metakaolin-based geopolymer mortar

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ABSTRACT

In this study, it was investigated the influence of rice husk ash, which is a waste by-product of industrial production, on ultrasonic pulse velocity, compressive strength, flexural strength and high temperature endurance of the metakaolin-based geopolymer mortar. For this, the sand was substituted by rice husk ash (RHA) at the rate of 25%, 50% and 75% by wt. in the production of geopolymer mortar. A total of 4 series of metakaolin-based geopolymer mortars (reference series and three series with RHA substitution) were produced. In this study, the geopolymer, in other words, the binder of the mortar was produced by metakaolin and ground granulated blast furnace slag reacting with the mixture of sodium hydroxide (12M NaOH) and sodium silicate (Na_2SiO_3) solutions. The ratio of metakaolin and reactant mixture (12M NaOH + Na_2SiO_3) was determined for each series following the preliminary experiments. On the specimens produced as 50 mm cube and 40 x 40 x 160 mm prism, the intended experiments were carried out after specimens underwent curing in a dry oven at 60°C during 72 h and gained strength. The results have shown that RHA could be used as a filling material in metakaolin-based geopolymer mortars, and metakaolin-based geopolymer mortars with 50% RHA substitution can be an alternative to the pure metakaolin-based mortar.

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1. INTRODUCTION

Nowadays, the interest to geopolymers is increasing. This is because geopolymer technology allows an opportunity to obtain a construction material with higher engineering properties using waste materials, so that geopolymers can be an alternative to Portland cement. The recycling of waste materials provides for using natural resources economically. Another reason that makes geopolymers attractive is that much fewer CO_2 emissions occur during the production process [1–6]. Geopolymers were discovered through research on nonflammable and noncombustible plastic materials in the aftermath of various catastrophic fires involved common organic plastic in France between 1970–1972 and announced by Davidovits in 1978 [7]. Geopolymers are binders obtained as a result of the reaction

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Figure 1. Burned rice husk (≥63 μm).

Figure 2. The prism specimens after curing.

Table 1. Chemical composition of pozzolans of the binder

Chemical composition (%)	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	L.O.I.
Metakaolin	56.10	40.25	0.85	0.55	0.19	0.16	0.55	0.24	1.11
GGBS	40.60	12.83	1.37	0.75	36.08	6.87	0.68	0.79	0.03

Table 2. Compounds of geopolymer mortars (for 1000 g MK)

Geopolymer mortar	12M NaOH solution	Na_2SiO_3	12 M NaOH: Na_2SiO_3 rate	MK	MK:RM rate	GGBS	RS	RHA	RHA:RS rate
MK	433.3	866.7	1:2	1000	1:1.3	133.3	2250	–	–
MK-RHA25	466.7	933.3	1:2	1000	1:1.4	133.3	1687.5	562.5	25:75
MK-RHA50	583.3	1166.7	1:2	1000	1:1.75	133.3	1125	1125	50:50
MK-RHA75	700	1400	1:2	1000	1:2.1	133.3	562.5	1687.5	75:25

of wastes such as blast furnace slag, fly ash or red mud, or calcined natural sources like kaolin, zeolite or bentonite (metakaolin, metazeolite or metabentonite) with alkaline solutions. Hydroxide solutions (NaOH, KOH, LiOH) and silicates (Na_2SiO_3 and K_2SiO_3) used in the production of geopolymer are defined as reactants [7], or reagents, in other words, hardeners [8].

Although Kriven (2017) [9] has stated the optimum strength gain time of geopolymer mortar as 24 h, there are few studies on the strength-time relationship for geopolymer mortars and geopolymer concrete. Duxson et al. (2007) [10] have observed a minimal change in the compressive strength of metakaolin-based geopolymer specimens between 7 and 28 days of ageing. Albidah et al. (2021) [11] have obtained the results where the metakaolin-based geopolymer concrete specimens at 7 days of ageing have achieved 89.1–95.3% of the compressive strength obtained at 28 days. Also, some geopolymer concrete specimens at 14 days had a compressive strength nearly equivalent to the 28-day compressive strength. In this study, the compressive strength was evaluated at 7 and 28 days for geopolymer mortars based on metakaolin, which is obtained by calcining purified kaolin clay and represents an amorphous aluminosilicate. Because of these, metakaolin is compatible with alkaline solutions and gains strength quickly. In addition to this, ground granulated blast furnace slag was used for faster gaining strength, according to [7].

The reason for using rice husk ash (RHA) as a substitution material is because it has the highest silica content (by up to 94%–95%) among all plant residues [12, 13]. And so it can be used as pozzolan. Bezerra et al. (2011) [14] have observed that RHA presents pozzolanicity and the mortars with incorporated RHA had values superior to the reference mixtures in relation to the physical and mechanical performance probably due to pozzolanic reactions. In developed countries, RHA is used to generate electricity, and biochar

Figure 3. **(a)** Universal press, some views from **(b)** compression tests and **(c)** three-point flexural tests.

is used in the production of high-performance concrete or ultra-high-performance concrete [12, 15, 16].

Nowadays, there are studies on the influence of partial replacement of chief binder material (e.g. metakaolin, fly ash) with RHA in the geopolymer [17–21]. Results of studies, where metakaolin (MK) was replaced by 20–30 wt% RHA, show that MK+RHA generates a compact pore structure, which contributes to improvement of compressive strength [17, 18]. Wen et al. (2019) [20] have investigated the viability of a novel geopolymer derived from non-calcined sludge and modified rice husk ash blend. Yomthong et al. (2019) [21] have improved the compressive strength of fly ash-based geopolymer through usage of RHA at 3 wt%. On the one hand, there are studies where the ratios of RHA were higher. Mrema and Mboya (2016) [13] have investigated the influence of RHA/Lime ratio on the strength properties of sand mortars. There were 40/60, 50/50, 60/40, 70/30 and 80/20 RHA/Lime ratios in the binder. It has been found out in the study that the optimum proportions are 60% RHA and 40% lime. The compressive strength was increased when the rate of RHA was increased from 40 to 60 wt%, and it was decreased when RHA was increased from 60 to 80 wt%. In this study, considering all of these, it is researched the potential of using RHA at the rate of 25%, 50% and 75% by wt. in the sand of metakaolin-based geopolymer mortar.

2. MATERIALS AND MIX DESIGN

In the production of geopolymer mortars, there were used metakaolin with specific gravity of 2.52, ground granulated blast furnace slag with specific gravity of 2.91, 12 molar sodium hydroxide (12M NaOH) solution, sodium silicate (Na_2SiO_3), 2 mm river sand and 63 µm rice husk ash. The molarity of NaOH solution was selected according the existing study [22]. The specific gravity of river sand (RS) is 2.67 and it is 2.14 for rice husk ash (RHA). In Figure 1, there is shown the burned rice husk (≥63 µm). It was used after passing through the sieve. The chemical properties of the pozzolans of the binder and the compounds of geopolymer mortars are given in Table 1 and Table 2, respectively.

In Figure 2, there are shown the specimens underwent curing in a dry oven at 60°C during 72 h.

3. TEST METHODS

Experimental studies consist of two stages. In the first stage, a total of 24 cubes of 50 mm, and a total of 24 prisms of 40 x 40 x 160 mm were produced for compression and flexural testing of the specimens at 7 and 28 days of ageing. Testing for compressive strength was performed according to ASTM C109/C109M-20a [23] on the

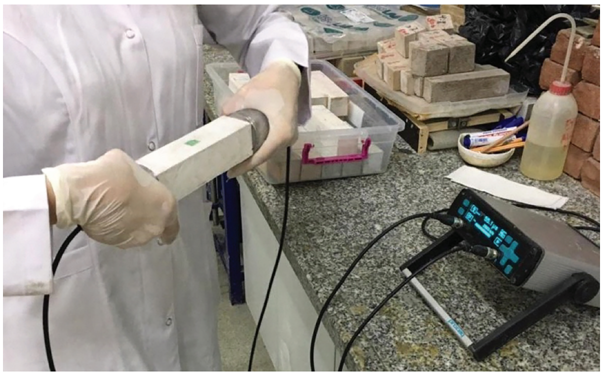

Figure 4. A view from ultrasonic pulse velocity tests.

Figure 5. Nabertherm B130 high temperature electric furnace.

Table 3. Compressive strength, ultrasonic pulse velocity (UPV) and flexural strength of geopolymer mortars at 7 and 28 days of ageing

Geopolymer mortar	Compressive strength (MPa)		Increase in compressive strength (%)		Flexural strength (MPa)		UPV (m/s)	
	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
MK	45.68	40.47	–	–	8.53	8.95	3403	3464
MK-RHA25	49.13	53.60	7.55	32.44	8.44	8.81	3381	3432
MK-RHA50	50.12	53.65	9.75	32.57	8.39	7.69	3118	3212
MK-RHA75	35.13	33.85	-23.1	-16.36	7.18	5.80	2725	2898

Table 4. The results for MK-RHA50 exposed to high temperatures

High temperature/ Geopolymer mortar	Weight loss (%)	UPV (m/s)		Flexural strength	Strength loss (%)
		Before test	After test		
200°C					
MK	0.48	3385	2630	3.62	57.56
MK-RHA50	–	3004	2855	3.86	53.99
400°C					
MK	3.57	3441	1396	1.89	77.84
MK-RHA50	5.02	2979	2215	1.49	82.24
600°C					
MK	5.84	3410	833	1.06	87.57
MK-RHA50	6.56	3008	2156	1.68	79.98
800°C					
MK	13.88	3400	0	0.73	91.44
MK-RHA50	7.35	2943	1688	0.97	88.44

cubes. Three-point flexural strengths of the prisms were obtained according to ASTM C349-18 [24].

In Figure 3, there are shown the universal press for compression and flexural testing, and some views from the testing.

In Figure 4, there is shown a view from the ultrasonic pulse velocity test performed according to ASTM C597-09 [25].

In the second stage, it was selected the highest value of the 7-day compressive strength from the series with RHA substitution, and the high temperature (200°C, 400°C, 600°C and 800°C) tests were performed on a total of 24 prisms (12 specimens each for both of MK and MK-RHA series). The high temperature testing was performed following the existing study [22]. Before the tests, oven dry prism specimens'

Figure 6. The prism specimens placed in the furnace.

weights and ultrasonic pulse velocities were determined. Then specimens were exposed to the effect of 200°C, 400°C, 600°C and 800°C in the Nabertherm B130 furnace shown in Figure 5. The applied temperature rise rate was 5°C/min. The specimens were kept at the target temperature for 60 min. After that, the heating was stopped and the furnace door was opened, and the specimens were cooled at the room temperature (23°C). In Figure 6, there are shown prism specimens placed in the furnace. Three days after the high temperature application, the specimens' weight, ultrasonic pulse velocity and flexural strength were obtained, and the losses were determined.

4. RESULTS AND DISCUSSIONS

The results from the first stage of experimental studies are given in Table 3 and Figure 7–9.

In Table 3, it is clearly seen that 25 and 50 wt% RHA substitution increases the metakaolin-based mortar compressive strength. The highest compressive strength was obtained by 50 wt% substitution. Also, the obtained results are shown that RHA increases the compressive strength and flexural strength, when it changes from 25 to 50 wt%, and RHA reduces both strengths, when it changes from 50 to 75 wt%. In existing studies, it is indicated that up to 60 wt% RHA added filling effects, and strong Si-O-Si bonds aid in enhancing strength [13, 17–19].

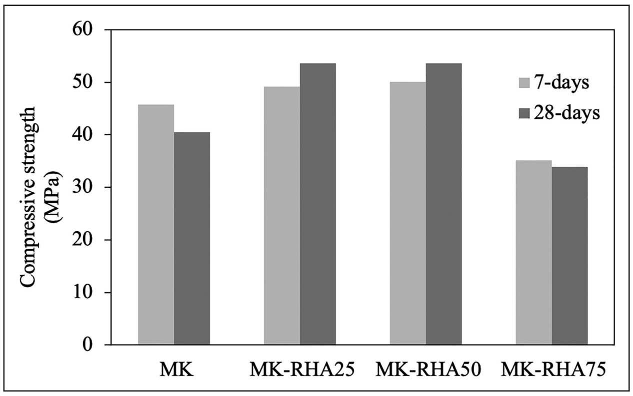

Figure 7. Compressive strength of geopolymer mortars at 7 and 28 days of ageing.

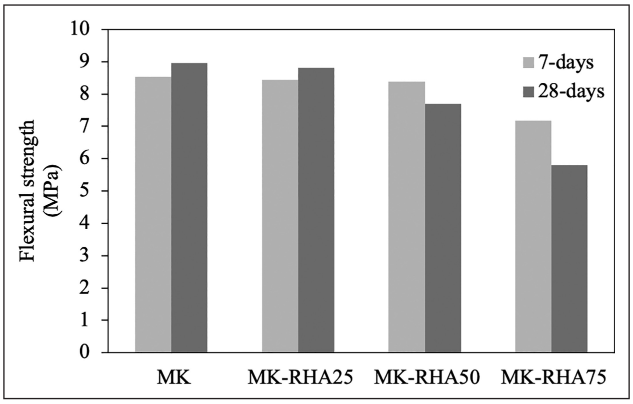

Figure 8. Flexural strength of geopolymer mortars at 7 and 28 days of ageing.

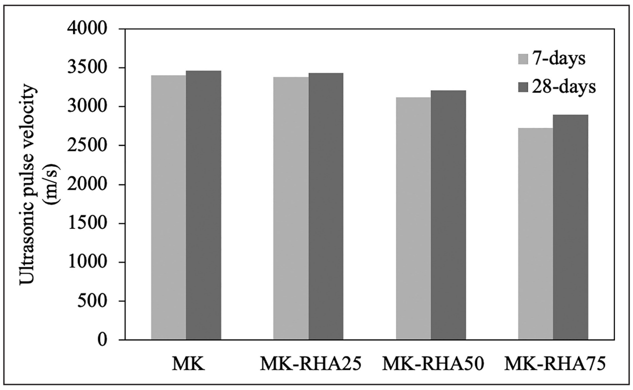

Figure 9. Ultrasonic pulse velocity of geopolymer mortars at 7 and 28 days of ageing.

In this study, also, no significant changes were noted at 28 days for both compressive strength and flexural strength. It is seen that the compressive strength of geopolymer mortars with 25 and 50 wt% RHA substitution at 7 days of ageing achieved 91.66% and 93.42% of the 28-day compressive strength, respectively. These results agree with the existing results [10, 11, 13].

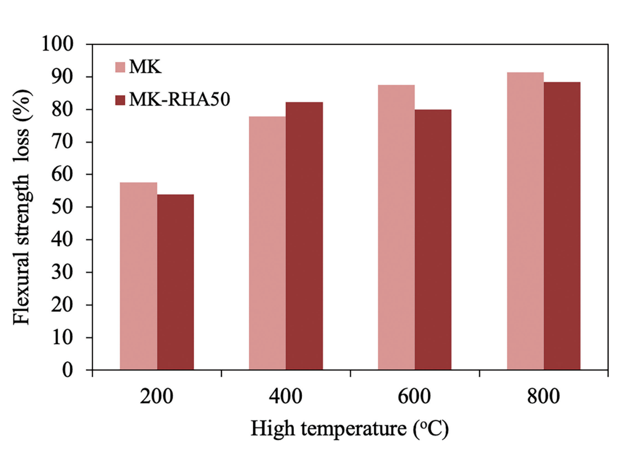

Figure 10. Flexural strength losses of MK-RHA50 exposed to high temperatures.

In this study, UPV values decreased with an increasing rate of RHA substitution. It agrees with the existing results, and it is because of a material with a low density has more voids and UPV will be longer in the material [12]. In the study, RHA, which had lower density, produced more voids in the mortar, and as a result, the lower UPV and flexural strength values were obtained.

According to the results obtained in the first stage, the geopolymer mortar with 50 wt% RHA substitution (MK-RHA50) was selected for the second stage. The results from the second stage of experimental studies are given in Table 4 and Figure 10.

According to the results given in Table 4, the geopolymer mortar with 50 wt% RHA substitution has better high temperature endurance. In Liang et al. (2019) [18], there is indicated that the pores of geopolymer were refined by the filling effects of RHA and enrichment of gel phases, which was the primary reason for the optimization of geopolymer thermal stability.

5. CONCLUSION

The current study was aimed to investigate the usability of rice husk ash (RHA) on the production of metakaolin-based geopolymer mortars. For this, it was determined ultrasonic pulse velocity, compressive strength, flexural strength and high temperature endurance of the geopolymer mortars, where RHA was used at rate 25%, 50% and 75% in the sand. The results have shown that RHA could be used as a filling material in metakaolin-based geopolymer mortars. On the other hand, it was seen that metakaolin-based geopolymer mortar containing 50 wt% RHA can be an alternative to pure metakaolin-based mortar and it will be beneficial in terms of the economic use of aggregate/sand.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

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