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Efficiency of rice husk ash and fly ash as reactivity materials in sustainable concrete

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Abstract

Many environmental problems occur due to rice husk burning and emissions from coal-fired power stations. This paper presents the recycling of rice husk ash (RHA) and fly ash (FA) from power plants as reactivity materials for producing sustainable (green) concrete. This research aims to investigate the efficiency of RHA and FA replacement ratios on fresh and hardened properties of concrete mixtures. The experimental program consisted of 21 concrete mixtures, which were divided into three groups. The cementitious material contents were 350, 450 and 550 kg m^{-3} for groups one, two and three, respectively. The replacement ratios from the cement content were 10, 20 and 30% respectively, for each recycle material (RHA and FA). The slump and air contents of fresh concrete were measured. The compressive strength, splitting tensile strength, flexural strength, modulus of elasticity and bond strength of hardened concrete as mechanical properties were also analyzed. The compressive strength was monitored at different ages: 3, 7, 28, 60 and 90 d. The water permeability test of hardened concrete as physical properties was conducted. Test results showed that the RHA and FA enhanced the mechanical and physical properties compared with the control mixture. The cementitious content of 450 kg m^{-3} exhibited better results than other utilized contents. In particular, the replacement ratios of 10 and 30% of RHA presented higher mechanical properties than those of FA for each group. The water permeability decreased as the cementitious content increased due to the decrease in air content for all mixtures. The water permeability loss ratios increased as the cementitious content decreased.

Keywords: Sustainable concrete, Rice husk ash, Fly ash, Air content, Mechanical properties, Water permeability

Introduction

Rice husk ash (RHA) is an agricultural waste byproduct, and its disposal presents a major challenge by waste managers. RHA from parboiling plants exerts critical environmental threat; thus, approaches for its reduction are urgently needed. RHA material is considered a real super pozzolan due to its richness in silica, the content of which is approximately 85–90% [1]. The incorporation of high-volume fly ash (FA) (60% by binder weight) in cement paste/mortar physically and chemically influences the microstructure of the cementitious system. The replacement of cement with FA increases the water-to-cement ratio and causes low early age strength. Xu and Sarkar [2] indicated that such replacement is responsible for producing 1–3 μm spaces between particles in the paste at the early ages. The usage of FA as pozzolan in the Thai concrete industry has significantly increased during the past decade because of its enhancement of concrete features. The mechanism responsible for the enhancement has been well documented [2–4]. The degree of hydration of the cement paste is low at low water/cement (w/c) ratios. At the age of 7 d, approximately 50% of the cement is hydrated; at 7–90 d, the degree of hydration is increased by a few percent [4]. Chopra et al. [5] concluded that the increases in strength of approximately 25% at 7 d, 33% at 28 d and 36% at 56 d are attributed to the increases in RHA content from the control mixture to the 15% cement alteration. The increase in RHA content of up to 15% increases the compressive strength of the concrete, but above this value, the strength is reduced due to the decreased hydration reaction and cement content [5]. Habeeb and Mahmud [6] conducted the X-ray diffraction graph and showed that the ash from burning husk at a temperature less than 690 °C is in amorphous form because of the broad peak on the 2θ angle of 22° [6]. Provis [7] stated that alkali-activated materials are inorganic binders resulting from the reaction of an alkali metal source (solid or dissolved) with a solid silicate

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powder-like FA and slag. FA has been increasingly regarded as an appropriate raw material for alkali-activated concrete because of its availability and adequate composition of silica and alumina [8–10]. Alkali-activated FA mortars, regardless of the type of activator used, are generally more durable than ordinary Portland cement mortars under experimental conditions [11, 12]. Also, alkali-activated FA concrete when cured at an elevated temperature has excellent mechanical and durability features [9–19]. Cement and concrete production has resulted in environmental burdens. For example, the cement-producing trade accounts for 5–7% of the total carbon dioxide phylogenesis emissions [20]. One of the foremost pressing challenges that the housing industry faces is the deterioration of concrete structures. Thus, the scientific community should promote industrial ecology (utilization of commercial by-products) and establish the principles of property management in concrete production. These goals will attain a 'green' combined style and brand-new rigorous approach towards the construction of sturdy structures (for a given service life) with minimum environmental burden [21]. The pozzolanic activity of RHA depends on the silicon oxide content, silicon oxide crystallization and size and area of ash particles. In general, ash should contain a restricted quantity of unburnt carbon. RHAs with amorphous silicon oxide content and huge specific surface area are often made through the combustion of rice husk at controlled temperature, and these factors are principally liable for its high reactivity [22–24]. As the advanced evolution of associated reactions with cement is not entirely represented, accelerated pozzolanic tests can be used to approximate the RHA reactivity. This case can be provided that inherent characteristics, such as reactive silicon oxide, cannot be rated as an absolute index of RHA reactivity in amalgamated cement [25].

This study aims to solve various environmental problems, such as RHA and FA, and preserve the natural resources simultaneously in the cement industry. The properties of sustainable concrete containing high replacement ratios of RHA and FA (up to 30% of cement) are analysed. Furthermore, this work monitors the effect of these replacement ratios with various contents of cement (reaching 550 kg m^{-3}).

Materials and methods

Materials

Cement

Portland cement CEM I–52.5 N was used in all mixtures. The cement was tested in accordance with the ES 4756–1/2013 [26]. Table 1 presents the physical and chemical features of cementitious materials.

Table 1 Properties of cementitious materials

Properties	CEM I	Rice husk ash	Fly ash
Specific gravity	3.15	2.21	2.40
Specific area, $cm^2\ g^{-1}$	3250	–	3900
Color	Grey	Light grey	Light grey
Chemical compositions (%)			
Silicon dioxide (SiO_2)	19.70	96.20	61.06
Aluminum oxide (Al_2O_3)	6.46	0.26	28.55
Ferric oxide (Fe_2O_3)	3.66	0.57	3.15
Calcium oxide (CaO)	62.15	0.47	1.41
Magnesium oxide (MgO)	2.10	0.35	1.32
Sulphur trioxide (SO_3)	2.51	0.15	1.06
Potassium oxide (K_2O)	0.75	0.67	1.15
Titanium dioxide (TiO_2)	–	–	0.35
Sodium oxide (Na_2O)	0.85	0.12	0.71
Loss on ignition (LOI)	1.73	1.15	1.19

Aggregate

The fine aggregate (clean and rounded) utilized in this experiment was natural siliceous sand with a particular specific gravity of 2.67, bulk unit weight of 1680 kg m^{-3} and fineness modulus of 2.85. The coarse aggregate was local crushed limestone (dolomite) with a specific gravity of 2.70, bulk unit weight of 1700 kg m^{-3} and maximum nominal size of 13 mm, according to ES 1109/2008 [27]. The ratio of fine to coarse aggregate is approximately 1:2.

RHA

RHA was obtained by burning husk under an uncontrolled temperature. The gathered ash was sifted through a British Standard (BS) sieve with a size of 75 μm to remove large particles. The produced RHA exhibited a grey color. Energy-dispersive X-ray (EDX) composition analysis and transmission electron microscopy (TEM) analyses were applied on the produced RHA. EDX test showed that produced ash contains 96.2% silicon dioxide (SiO_2) and 0.47% calcium oxide (CaO), as presented in Table 1. The result indicates that RHA is a more reactive material than cement and FA. The chemical compositions of RHA in this study are comparable with those of Akeke et al. [1]. The TEM test indicated that particle size varies between 15 and 52 μm.

FA

FA is an industrial by-product of coal-fired power stations; the FA utilized in the current study is categorized as class F in accordance with the requirements of ASTM C618–19 [28]. Table 1 presents the chemical composition of FA as determined via X-ray fluorescence.

Superplasticizer (high rang water-reducing admixtures)

A high-performance superplasticizer admixture of the aqueous solution of modified polycarboxylate basis (Viscocrete-5930) was used to increase the workability of concrete mixtures. Viscocrete-5930 complies with ASTM

C494/C494M-17 [29], with a specific gravity of 1.11. The dosage was approximately 3% to compensate the reduced water and enhance the workability of mixtures with cementitious contents of 450 and 550 kg m^{-3}.

Water

As shown in Table 2, the water-to-cementitious material ratio (w/c) was set to 0.55 for mixtures with 350 kg m^{-3} cementitious content. The w/c was reduced to 0.25 to improve the compressive strength of concrete mixtures with cementitious contents of 450 and 550 kg m^{-3}.

Mixture proportions

Twenty-one concrete mixtures were prepared in this study and divided into three groups. Each group consisted of seven mixtures. This experimental work used three cement contents: 350, 450 and 550 kg m^{-3} for groups one, two and three, respectively. RHA and FA were used for all series as replacements of cement with various ratios. The mixtures in every group were classified as follows: control mixture; three mixtures containing 10, 20 and 30% of RHA; and three mixtures using 10, 20 and 30% of FA. The ratio of fine aggregates to coarse aggregates was maintained at 1:2. The mixtures were designed to use 0.55 w/c with 350 kg m^{-3} of cementitious materials. The w/c was reduced to 0.25 for groups two and three to improve the compressive strength of the concrete. Superplasticizer was added to the concrete with 3% of cementitious contents for groups two and three to compensate the reduced water. Table 2 shows the mixture proportions.

The experimental mixing steps are explained as follows: The fine and coarse aggregates were initially mixed for 1 min. Then, cementitious materials were added, and the quantities were remixed for 3 min. Water was added to the mixture through the mixing process with respect to the superplasticizer addition. Subsequently, the mixing process was continued for 3 min.

Test procedure

The consistency of fresh concretes was measured in terms of slump values (ASTM C143/C143M-15a) [30] and air content values (ASTM C231/C231M-17a) [31]. The compressive strength of concrete was evaluated on cube-shaped specimens (150 mm) at 3, 7, 28, 60 and 90 d (BS 1881–116) [32]. The splitting tensile test was conducted at 28 d on cylinder samples (150 × 300 mm) (ASTM C496/C496M-17) [33]. The

Table 2 Proportions of concrete mixes

Group	Mix No.	Cementitious materials			Aggregates		Superplasticizer %	w/c
		Cement kg m^{-3}	Rice husk ash %	Fly ash %	Fine %	Coarse %		
I	M1	350	0	0	33	67	0	0.55
	M2	315	10	0	33	67	0	0.55
	M3	280	20	0	33	67	0	0.55
	M4	245	30	0	33	67	0	0.55
	M5	315	0	10	33	67	0	0.55
	M6	280	0	20	33	67	0	0.55
	M7	245	0	30	33	67	0	0.55
II	M8	450	0	0	33	67	3	0.25
	M9	405	10	0	33	67	3	0.25
	M10	360	20	0	33	67	3	0.25
	M11	315	30	0	33	67	3	0.25
	M12	405	0	10	33	67	3	0.55
	M13	360	0	20	33	67	3	0.25
	M14	315	0	30	33	67	3	0.25
III	M15	550	0	0	33	67	3	0.25
	M16	495	10	0	33	67	3	0.25
	M17	440	20	0	33	67	3	0.25
	M18	385	30	0	33	67	3	0.25
	M19	495	0	10	33	67	3	0.25
	M20	440	0	20	33	67	3	0.25
	M21	385	0	30	33	67	3	0.25

flexural strength test was performed at 28 d (ASTM C78/C78M-18) [34]. The prism specimens (100 × 100 × 500 mm) were utilized for the flexural strength test. The average values of the three specimens for each testing age and all strengths were recorded. Cylinder forms (150 × 300 mm) were prepared to determine the modulus of elasticity at 28 d (ASTM C469/C469M-14) [35]. The bond strength was tested by pulling steel bar from cylinder samples. Permeability was measured at 28 d on specimens with a diameter of 150 mm and length of 150 mm to determine the depth of water penetration in concrete.

Results and discussion

Table 3 presents the fresh and hardened properties of concrete mixtures. The fresh properties include slump and air content results. The hardened properties consist of mechanical and physical properties. The mechanical features include the compressive, splitting tensile, flexural and bond strengths and modulus of elasticity. The water penetration (permeability) is the only physical feature tested in this investigation.

Slump results

The slump test was conducted to study the effect of RHA and FA replacement ratios on the slump of concrete mixtures. In group one, the slump was decreased by 12, 18 and 24% for mixtures M2, M3 and M4 with RHA replacement ratios, respectively, compared with the control mixture. By contrast, the slump of mixtures with FA replacement ratios was decreased by 6, 12 and 18% for mixtures M5, M6 and M7, respectively, compared with control mixture M1. In group two, the slump was increased by 11, 22 and 28% for mixtures M9, M10 and M11 with RHA replacement ratios, respectively, compared with control mixture M8. Contrarily, the slump for mixtures with FA replacement ratios was increased by 22, 28 and 33% for mixtures M12, M13 and M14, respectively, compared with control mixture M8. In group three, the slump was increased by approximately 21, 26 and 37% for mixtures M16, M17 and M18 with RHA replacement ratios, respectively, compared with control mixture M15. However, the slump of mixtures with FA replacement ratios was increased by 26, 32 and 42% for M19, M20 and M21, respectively, compared with control mixture M15. Generally, the slump

Table 3 Fresh and hardened properties of test results

Group	Mix No.	Slump (mm)	Air content (%)	Compressive strength (MPa)					Splitting tensile strength (MPa)	Flexural strength (MPa)	Bond strength (MPa)	Modulus of elasticity (GPa)	Water permeability $\times 10^{-10}$ (cm s^{-1})
				3 d	7 d	28 d	60 d	90 d	28 d	28 d	28 d	28 d	28 d
I	M1	85	2.3	12.4	23.3	31.1	32.9	34.5	3.1	4.5	5.0	22.4	8.5
	M2	75	1.9	15.2	28.2	37.5	39.8	41.7	3.7	5.5	6.0	27.0	5.6
	M3	70	1.7	14.4	26.9	35.7	37.9	39.7	3.5	5.2	5.7	25.7	5.3
	M4	65	1.6	12.9	24.2	32.1	34.2	35.8	3.2	4.7	5.2	23.1	4.8
	M5	80	2.0	14.1	26.2	34.9	37.3	39.1	3.4	5.0	5.6	25.1	5.9
	M6	75	1.9	14.6	27.2	36.1	38.8	40.5	3.5	5.3	5.8	26.0	5.5
	M7	70	1.8	12.8	23.9	31.7	33.9	35.5	3.1	4.6	5.1	22.8	5.1
II	M8	90	1.9	37.1	55.2	73.5	78.6	82.3	6.7	10.8	12.2	41.0	5.2
	M9	100	1.5	46.3	67.5	89.3	95.7	100.1	8.1	13.1	14.8	45.3	3.9
	M10	110	1.3	45.3	66.0	87.1	93.4	97.6	7.9	12.9	14.5	44.1	3.8
	M11	115	1.2	41.1	59.8	78.9	84.6	88.5	7.2	11.6	13.1	42.3	3.6
	M12	110	1.6	45.1	65.6	86.8	93.8	98.1	7.7	12.8	14.4	43.9	4.2
	M13	115	1.5	45.6	66.5	87.9	95.1	99.4	8.0	13.0	14.6	44.7	4.0
	M14	120	1.4	40.5	58.9	77.9	84.3	88.1	7.1	11.5	13.0	42.1	3.8
III	M15	95	1.7	43.0	61.1	80.8	87.2	91.2	6.9	11.9	13.7	42.4	4.2
	M16	115	1.4	52.1	72.7	94.7	102.4	107.0	7.9	14.1	16.1	46.5	3.0
	M17	120	1.2	50.8	70.6	92.2	99.6	104.2	7.7	13.7	15.7	45.8	2.8
	M18	130	1.1	48.1	66.8	87.2	94.3	98.6	7.3	13.0	14.8	44.5	2.7
	M19	120	1.5	49.9	69.4	90.8	98.9	103.5	7.6	13.5	15.4	45.4	3.4
	M20	125	1.3	51.1	70.8	92.9	101.3	105.9	7.8	13.8	15.8	46.1	3.1
	M21	135	1.2	47.7	66.1	86.7	93.7	98.9	7.2	12.9	14.7	43.9	3.0

value is increased by using a superplasticiser with cementitious materials of 450 and 550 kg m^{-3}. The greatest slump occurred in mixture M21 due to the usage of 550 kg m^{-3} of cementitious materials containing 30% FA. Figure 1 presents the slump test results.

Air content

The experimental results showed that the RHA and FA replacement ratios cooperated in reducing the air content. In addition, the air content decreased with the increase in cementitious materials. The RHA replacement ratio of 30% from a cement content of 550 kg m^{-3} significantly reduced the air content by 1.1% compared with all mixtures.

Compressive strength

The results from three cubes were averaged to determine the compressive strength of each concrete mixture. The compressive strength test was conducted at five different ages: 3, 7, 28, 60 and 90 d. The results showed a good early compressive strength wherein all mixtures containing 450 and 550 kg m^{-3} of cementitious materials achieved structural concrete at 3 d. By contrast, the mixtures using 350 kg m^{-3} of cementitious material achieved structural concrete at 7 d. Figure 2 shows the effects of RHA and FA replacement ratios from cement content on the compressive strength at various ages. The maximum RHA replacement ratio was 10% of cement content. The increment percentages at 28 d were 21, 22 and 17% for mixtures M2, M9 and M16, respectively, compared with the control mixture of each group. On the contrary, the maximum FA replacement ratio was 20% of cement content for all groups. Subsequently, the compressive strength at 28 d increased by 16, 20 and 15% for mixtures M6, M13 and M20, respectively, compared with the control mixture of each group. However, the 10% replacement ratio of RHA from cement contents improved the compressive strength compared with that of FA. Figure 3 presents that the compressive strength at 60 d increased by around 6–9%

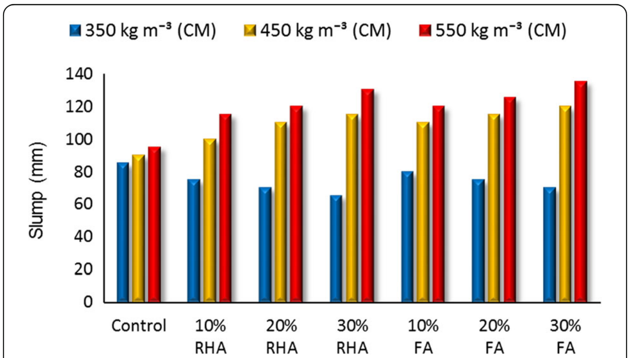

Fig. 1 Effect of using cementitious materials (CM) on the slump test of concrete mixes

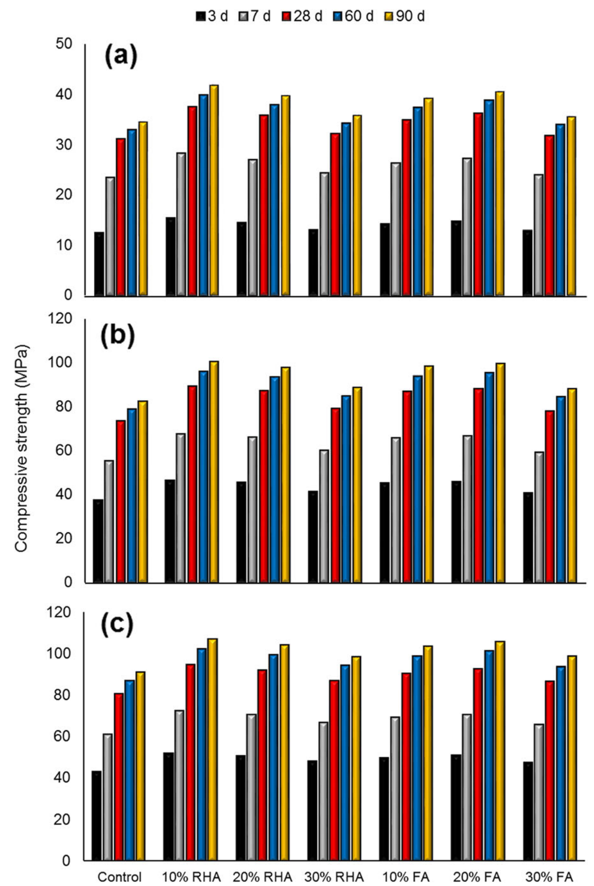

Fig. 2 Compressive strength of concrete mixtures (**a**) 350 kg m^{-3} CM, (**b**) 450 kg m^{-3} CM, (**c**) 550 kg m^{-3} CM

compared with that at 28 d. The increasing ratio of the compressive strength at 90 d was between 11 and 14% compared with that at 28 d. The compressive results at different ages agreed with those of Chopra et al. [5]. The increasing percentage of compressive strength was referred to the interaction of SiO_2 in the RHA with free calcium hydroxide, thereby reducing the internal air voids in concrete structure. The RHA contains a higher ratio of SiO_2 (approximately five times) than cement.

Tensile strength

Cylindrical specimens were tested to determine the tensile strength of concrete mixtures using RHA and FA as replacements of cement content. Figure 4a presents the effect of RHA and FA replacement ratios on the tensile strength of mixtures with 350 kg m^{-3} of cementitious materials. The concrete mixtures containing RHA recorded a higher tensile strength than that incorporated with FA. The increment percentages were 19, 13 and 3% for mixtures M2, M3 and M4 using RHA ratios, respectively, compared with control mixture M1. In group two, the tensile strength of mixture M13 which contained

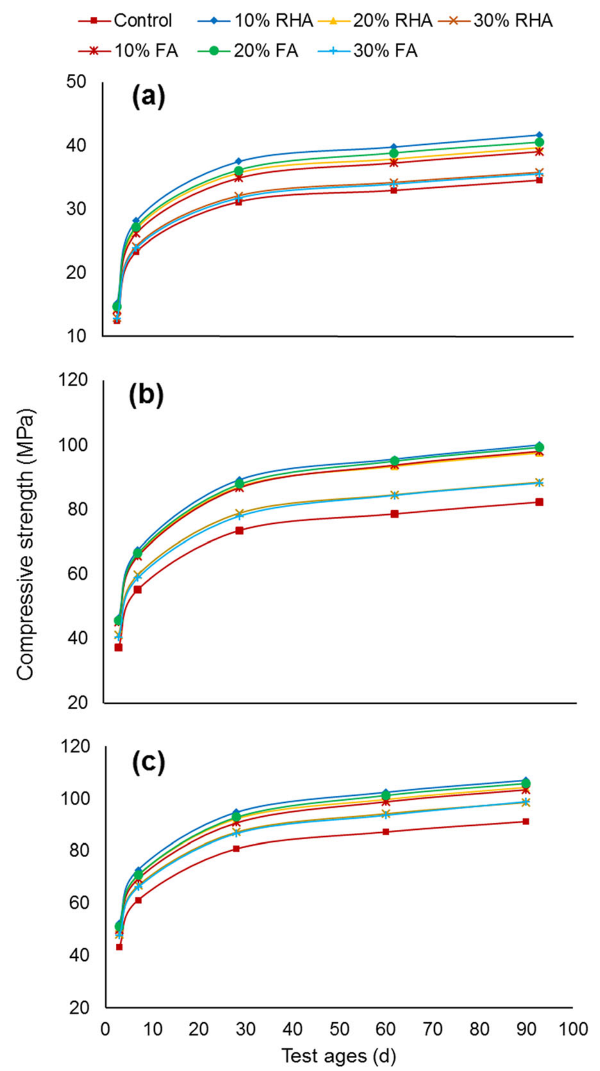

Fig. 3 Development of compressive strength (**a**) group I, (**b**) group II, (**c**) group III

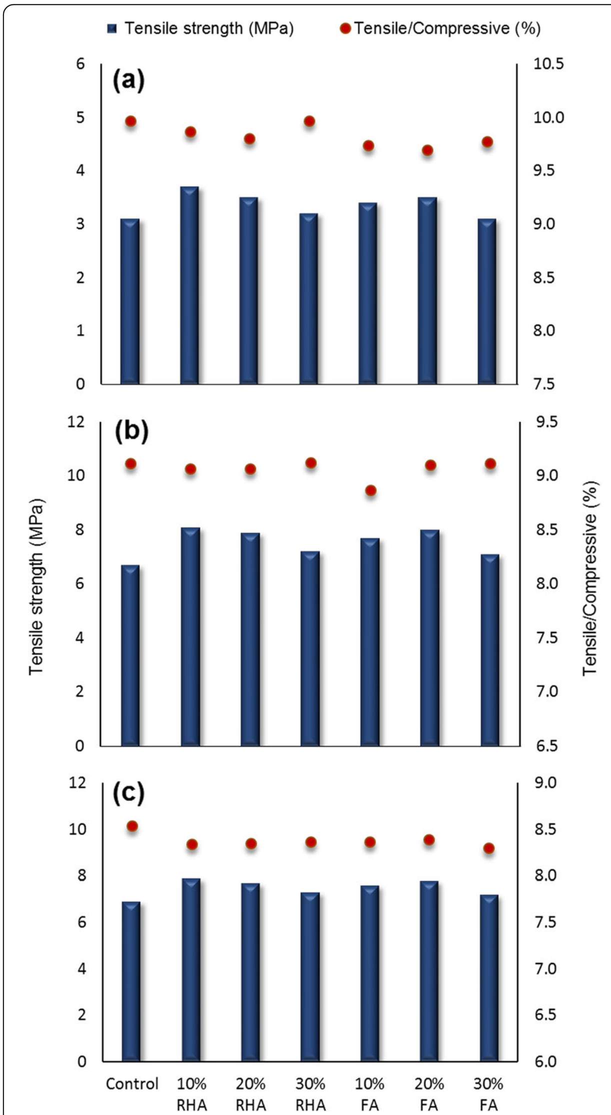

Fig. 4 Tensile strength of concrete mixes (**a**) 350 kg m^{-3} CM, (**b**) 450 kg m^{-3} CM, (**c**) 550 kg m^{-3} CM

20% of FA was closed up to the tensile strength of mixture M9 which used 10% of RHA as replacement for cement content. The highest tensile strength of group two was 8.1 MPa for mixture M9, which increased by 21% from control mixture M8, as shown in Fig. 4b. In group three, the tensile strength was close to the tensile results in group two, as displayed in Fig. 4c. Finally, the tensile results showed that the best cement content was 450 kg m^{-3}, which was used in group two for comparison with other cementitious contents. In addition, the replacement ratio of 20% of FA agreed with the tensile results of 10% of RHA in all groups. The tensile strength ratio from the compressive strength showed that the increment ratio of tensile strength decreased as the cementitious materials increased. The highest tensile strength ratio was approximately 10% from compressive strength for mixture with 30% of RHA and a cementitious content of 350 kg m^{-3}.

Flexural strength

The 10% replacement ratio of RHA with all cementitious contents improved the flexural performance of concrete mixture. Figure 5a presents similar flexural strength for M1 and M7, which indicates the insignificant effect of using 30% of FA with cement content of 350 kg m^{-3}. On the contrary, the 30% replacement ratio of FA improved the flexural strength of concrete with cement contents of 450 and 550 kg m^{-3}, as exhibited in Fig. 5b and c. Thus, a significant enhancement in flexural strength was achieved by using RHA and FA with 550 kg m^{-3} cement content. The percentage of flexural strength to compressive strength ranged from 14.3 to 14.9%, indicating that fine materials contributed to the enhancement of the flexural strength and compressive strength.

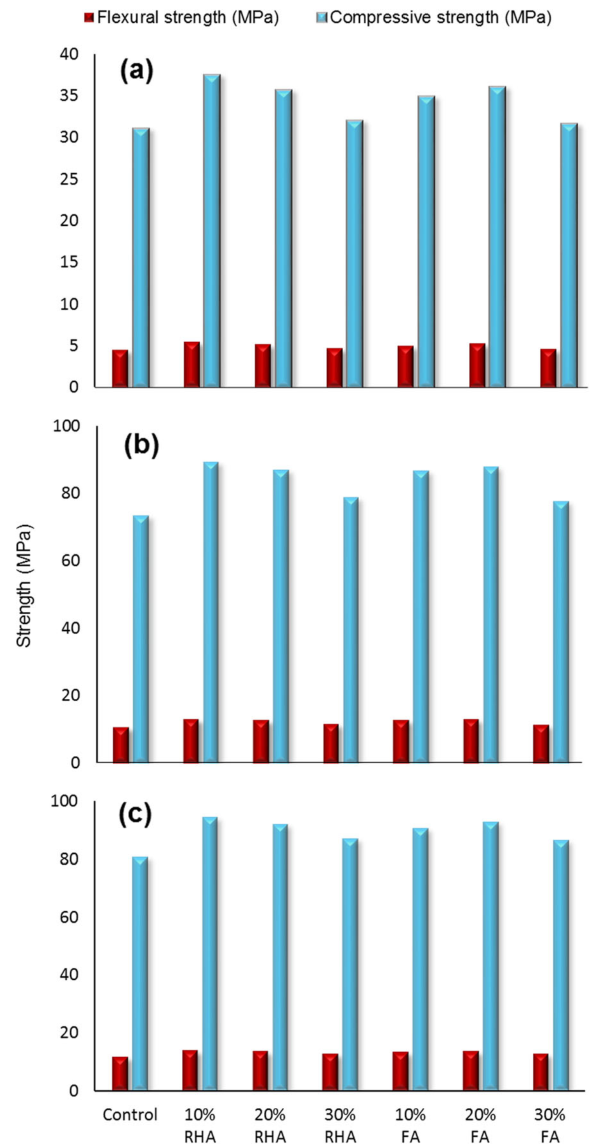

Fig. 5 Flexural strength of concrete mixes (**a**) 350 kg m^{-3} CM, (**b**) 450 kg m^{-3} CM, (**c**) 550 kg m^{-3} CM

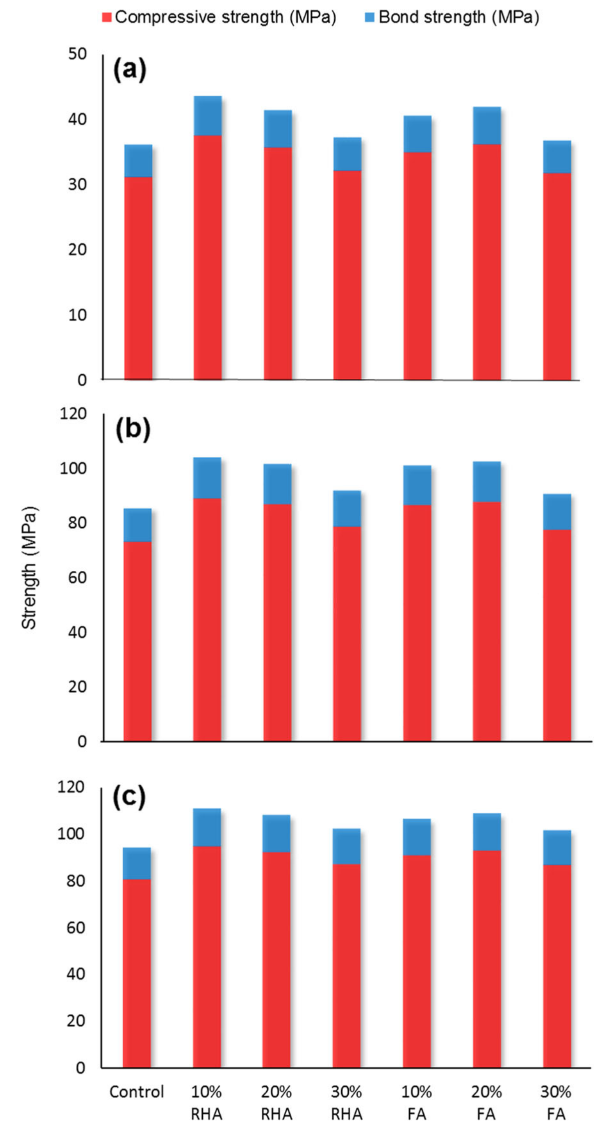

Fig. 6 Bond strength of concrete mixes (**a**) 350 kg m^{-3} CM, (**b**) 450 kg m^{-3} CM, (**c**) 550 kg m^{-3} CM

Bond strength

For reinforced concrete, a suitable bond between steel bars and the surrounding concrete must be developed. The RHA and FA ratios contributed to the improvement of the bond strength between the steel and concrete. The bond strength was increased by approximately 20, 14 and 4% for mixtures containing 10, 20 and 30% of RHA, respectively, with 350 kg m^{-3} cement content compared with control mixture M1. However, the bond strength using FA replacement ratios was 5.6, 5.8 and 5.1 MPa for mixtures M5, M6 and M7, respectively, whereas that of control mixture M1 was 5 MPa, as presented in Fig. 6a. The bond strength between steel and concrete was developed by using cement contents of 450 and 550 kg m^{-3}, as shown in Fig. 6b and c. The 10% replacement ratio of RHA improved the bond strength for each group, especially with a cement content of 550 kg m^{-3}. On the contrary, the 20% replacement ratio of FA enhanced the bond strength of concrete, which agreed with mixtures using 10% of RHA. The bond/compressive strength percentage was calculated to evaluate the efficiency of pozzolanic materials (RHA and FA). The bond/compressive strength ratios were approximately 16.1, 16.6 and 17.0% for cementitious contents of 350, 450 and 550 kg m^{-3}, respectively. The correlation showed that the bond strength of concrete mixtures improved with the increase in cementitious contents.

Modulus of elasticity

The cylinder specimens were tested to determine the modulus of elasticity of concrete mixtures using RHA and FA replacement ratios. The elasticity test was conducted by recording the strain values corresponding compressive loads. Figure 7 shows the effect of RHA and FA replacement ratios on the modulus of elasticity of concrete mixtures. The modulus of elasticity of mixtures containing 450 kg m^{-3} of materials was slightly similar to that of mixtures containing 550 kg m^{-3} of materials. The replacement with RHA and FA from cement content improved the modulus of elasticity of concrete mixtures by various percentages. The best replacement ratios were 10% of RHA and 20% of FA for each cement content. The highest modulus of elasticity was 46.5 GPa for mixture M16, which contained 450 kg m^{-3} of cementitious materials, with 10% of RHA replacement ratio.

Water permeability

Permeability is a key factor influencing the durability of concrete. This parameter is particularly important in reinforced concrete, because the concrete must prevent water from reaching the steel reinforcement. Therefore, the durability, corrosion resistance and resistance to chemical attack of concrete are directly related to its permeability. The permeability of mixtures using 350 kg m^{-3} of cementitious materials indicated that using 30% of RHA reduced the permeability of concrete by 44% from control mixture M1. This reduction was due to the decrease of the air content in this mixture compared with all mixtures with the same cement content, as shown in Fig. 8a. The best replacement ratio is 30% RHA with cement contents of 450 and 550 kg m^{-3}, which decreases the water permeability of concrete mixtures due to the lowest air content, as presented in Fig. 8b and c. The RHA and FA replacement ratios from cement contents were beneficial for decreasing the air content and water permeability of concrete mixtures.

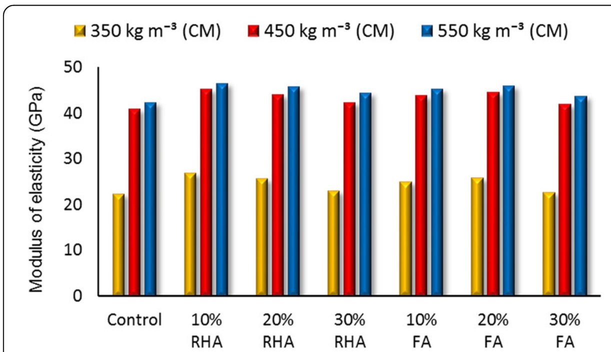

Fig. 7 Modulus of elasticity for mixes using 350, 450 and 550 kg m^{-3} CM

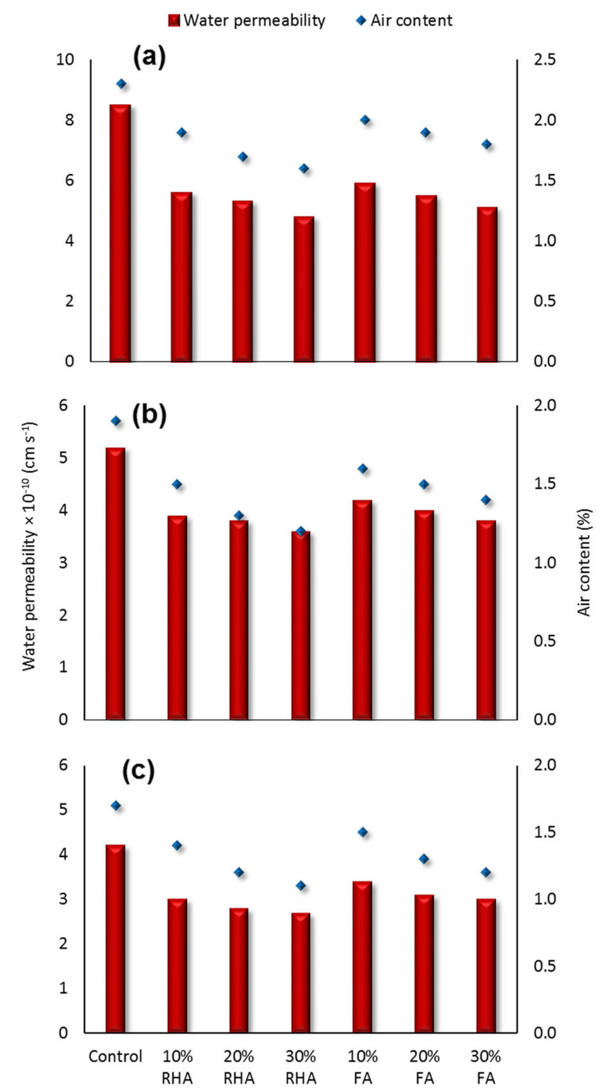

Fig. 8 Permeability of concrete mixes (**a**) 350 kg m^{-3} CM, (**b**) 450 kg m^{-3} CM, (**c**) 550 kg m^{-3} CM

Conclusions

– The percentage of SiO_2 in RHA is 96.2%, which is higher than that in FA.
– The slump results of concrete mixtures increased with the increase in cementitious contents, especially by using RHA and FA.
– The best replacement ratios of RHA and FA were 10% and approximately 20% with cement contents of 350, 450 and 550 kg m^{-3}. The mixtures with RHA exhibited a higher compressive strength than those containing FA. The increment percentages of compressive strength at 28 d were 21, 22 and 17% for mixtures M2, M9 and M16, respectively, compared with the control mixture of each group (RHA mixtures). Furthermore, the improvements of

compressive strength were 16, 20 and 15% for mixtures M6, M13 and M20, respectively (FA mixtures).

- The concrete mixtures containing RHA presented higher tensile strength than those with FA. In addition, the tensile results showed that the best cement content was 450 kg m^{-3}, which was used in group two, compared with other cementitious contents. The tensile strength ratio from compressive strength revealed that the increment rate of tensile strength decreased as the cementitious materials increased.
- The flexural strength was significantly enhanced by using RHA and FA replacement ratios with 550 kg m^{-3} cement content. The percentage of flexural strength to compressive strength ranged from 14.3 to 14.9%, indicating that fine materials contributed to the enhancement of the flexural strength and compressive strength.
- The 10% replacement ratio of RHA achieved a high bond strength for each group, especially with a cement content of 550 kg m^{-3}. On the contrary, the 20% replacement ratio of FA enhanced the bond strength of concrete, which agreed with the mixtures using 10% of RHA. The bond/compressive strength ratios were approximately 16.1, 16.6 and 17.0% for cementitious contents of 350, 450 and 550 kg m^{-3}, respectively. The correlation showed that the bond strength of concrete mixtures improved with the increase in cementitious contents.
- The replacement with RHA and FA from cement content improved the modulus of elasticity of concrete mixtures by various percentages. The best replacement ratios were 10% of RHA and 20% of FA for each cement content. The highest modulus of elasticity was 46.5 GPa for mixture M16, which contained 550 kg m^{-3} of cementitious materials with 10% of RHA replacement ratio.
- The permeability of mixtures using 350 kg m^{-3} of cementitious materials indicated that the usage of 30% of RHA reduced the permeability of concrete by 44% from control mixture M1. This reduction was due to the decrease of the air content in this mixture compared with all mixtures with the same cement content. In addition, the best replacement ratio is 30% of RHA with cement contents of 450 and 550 kg m^{-3}, which decreased the water permeability of concrete mixtures due to the lowest air content.
- The RHA and FA replacement ratios from cement contents were beneficial for decreasing the air content and water permeability of concrete mixtures. This result achieved the main goal by using high replacement ratios of RHA and FA for improving the durability of concrete.

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Authors' contributions
The manuscript was mainly based on a draft written by MA and BAA, and written through contributions of all authors. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are available in Egypt.

Competing interests
The authors declare they have no competing interests.

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