



Comparative study of pozzolanic and filler effect of rice husk ash on the mechanical properties and microstructure of brick aggregate concrete



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ABSTRACT

The aim of this study was to investigate the pozzolanic effect (PE) and filler effect (FE) of rice husk ash (RHA) on the mechanical properties and microstructure of brick aggregate concrete (BAC). For this, concrete cylinders (100 mm × 200 mm) were prepared with 0–25% RHA with water-to-binder ratios of 0.50 at a constant mix-ratio of 1:1.5:3 and cured in water. Test results revealed that the mean particle size of RHA decreases with increasing grinding time. The compressive strength (f_c) of BAC due to filler effect are 58.56–94.62% less compared to the pozzolanic effect of RHA for the 10%–25% replacement of cement. Meanwhile, the 15% RHA showed the maximum f_c of BAC due to pozzolanic effect of RHA. The tensile strength (f_{sp}) and flexural strength (f_r) of BAC due to pozzolanic effect are 60%–150% and 25%–150% higher than that of filler effect of RHA for the 10%–25% replacement of cement respectively. The modulus of elasticity (E_c) and Poisson's ratio (ν) of BAC due to pozzolanic effect are 2%–29% and 27%–43% greater than that of filler effect of RHA for the 10%–25% replacement of cement respectively. BAC with 10–20% RHA shows a dense and homogeneous microstructure. Therefore, inclusion of RHA as a partial replacement of cement possesses a significant pozzolanic effect than the filler effect on the mechanical properties and microstructure of BAC.

1. Introduction

Rice husk is an agricultural waste. When this husk is completely burnt, about 25% of rice husk ash (RHA) is generated [1]. It was proven that the RHA contains about 85–95% of amorphous silica [2, 3, 4]. However, this silica is not easily biodegradable and mostly used for landfill. It was also well-documented that RHA shows both filler and pozzolanic effect in mortar and concrete. These effects of RHA vary from one sample to another due to the differences in the type of paddy, crop year, climate and geographical conditions. Several researchers reported that the production of silica, reduction of carbon content, silica structure, fineness, loss on ignition and growing filler and pozzolanic activity of RHA depend on its incineration technique, temperature and burning time [4, 5, 6, 7]. It is expected to add pozzolanic values in cement hydration and consequently enhance strength [8]. RHA concrete, though not altogether new concepts are in the forefront of building materials. Rukzon et al. [9] found that the finer particles of RHA show a higher pozzolanic

reaction in mortar. Rambabu et al. [1] also reported that the fine particle of RHA shows greater pozzolanic activity and strength when it is used partially with cement. Many attempts have been made to produce and use RHA in concrete researches [7, 8, 10, 11, 12, 13]. It has been reported that concrete provides a notable microstructural changes due to its pozzolanic and filler action of RHA [10, 14]. In addition, Zhang et al. [15] found that the calcium hydroxide and calcium silicate hydrates was the major hydration and reaction products for the RHA paste. The authors [15] also found that the width of interfacial zone between the paste and the aggregate was reduced due to the use of RHA. Recently, some important studies have been performed on the filler effect, pozzolanic effect and microstructure of RHA in mortar and concrete [14, 15, 16]. However, the crushed brick as coarse aggregate with RHA as a partial replacement of cement in making concrete was not studied. In contrast, a couple of studies [17, 18] used RHA in making clay brick and found that the clay bricks having RHA are more feasible and inexpensive for construction. Moreover, several studies [19, 20, 21, 22] have already been

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conducted on the properties of BAC. However, they did not use RHA as cement replacement materials in making concrete. In addition, the comparative study of pozzolanic and filler effect of RHA on the mechanical properties of brick aggregate concrete (BAC) was not investigated. From the research gaps, the focus of the present study was to investigate and compare the pozzolanic effect (PE) and filler effect (FE) of RHA on the mechanical properties such as compressive strength (f'_c), tensile strength (f_{sp}), flexural strength (f_r), modulus of elasticity (E_c) and Poisson's ratio (ν) and microstructure of BAC.

2. Background

2.1. Filler and pozzolanic effect in concrete

The strength and durability is the most important parameter of concrete. Both of them depend more on the cement paste than the aggregate. Cement matrix is more prone to damage by the environmental than that of aggregate due to its pore, which permits water and dissolved ions to move in. It is well-known that pozzolans present in concrete exerts both filler and pozzolanic effects on the properties of concrete but it is challenging to evaluate the performance of pozzolanic and filler effect of concrete separately. It will be helpful if the mechanism of filler effect is known that could help recognize the PE of pozzolans in concrete. To know the FE of pozzolans in concrete, previous researchers [23, 24, 25, 26, 27] used limestone or carbon black as non-reactive fillers materials as a substitute of pozzolans with a replacement of cement. Those filler materials were chemically inactive and nearly similar in particle sizes and fineness of pozzolanic materials. Detwiler and Mehta [23] used fine carbon black as a filler material with a partial replacement of cement to produce concrete cylinders (100 mm \times 200 mm). Where the BET surface area of carbon black is 25 m²/g. The authors [23] reported that the development of strength of concrete at early age is due to the FE of pozzolan. In addition, Goldman and Bentur [25] used three types of fine carbon black (0.025- μ m, 0.073- μ m and 0.33- μ m mean particle sizes) as a microfiller material with a partial replacement of cement to produce 70 mm \times 70 mm \times 70 mm cubes and 70 mm \times 70 mm \times 280 mm beams. The author [25] used silica fume containing 92.8% SiO₂ with specific surface area of 18.3 m²/g. The authors [25] found that carbon black fillers show similar effects on the strength of concrete compared to the matrix strength as like as silica fume due to only the particle size that was smaller than 0.073- μ m. The authors [25] also reported that this influences arise only due to a microfiller effect of carbon black caused by the mechanism of transition zone which reduces bleeding in the interfacial transition zone of concrete becomes denser, generates a composite material that helps the aggregate to dynamically enhance the strength. Meanwhile, Isaia et al. [24] used limestone as a filler material with a partial replacement of cement to produce concrete cylinders sizes 100 mm in diameter and 200 mm in height with several water-to-cement ratios with the average particle sizes of limestone is 4- μ m. The authors [24] concluded that the FE is more important in the high strength concrete mixtures at later ages. The author [24] also stated that the microstructure of paste not only depends on the pozzolanic reactions but also filler performance to provide a denser, more homogeneous and uniform paste. In addition, Mohammed et al. [26] used locally available natural limestone as a filler material with a partial replacement of cement to produce 100 mm concrete cube with several water-to-cement ratios with the average particle sizes of limestone being less than 65- μ m. The authors [26] concluded that the filler materials did not affect the nature of the porosity (micro or macro) of self-compacting concrete while at 28-days it influences the critical pore diameter. Nonetheless, Zhang et al. [15] studied the effects of RHA on cement paste and concrete on the hydration and the microstructure of the interfacial zone between the aggregate and paste. The author [15] reported that the width of the interfacial zone between the aggregate and the cement paste reduced due to the RHA filled the porosity and reduced the Ca(OH)₂ in concrete as a result

improved the compressive strength. However, Madandoust et al. [27] stated that the development of tensile strength containing RHA at early age due to the FE of RHA but lower than that of control concrete, but it became greater at the later ages due to the PE of RHA.

2.2. Filler and pozzolanic effect in mortar

To know the filler performance of pozzolans in cement mortar, several researchers [14, 16, 28, 29, 30] used ground river sand or crushed quartz with different particle sizes of a non-reactive fillers materials as a substitute of pozzolans by replacement of cement. Even though, those fillers materials were nearly analogous physically to pozzolans but actually non-reactive in nature. As a result, they determine the FE of pozzolans in mortar by the comparison between experimental values of concrete containing NS and theoretical values of concrete without NS (control) with similar particle size, cement replacement level, water cement ratio and age of curing. Cheerarot et al. [28] used river sand (19.4- μ m and 20.6- μ m, 13.8 and 11.7- μ m, 6.3 and 6.4- μ m particle size) as a filler material with similar partial replacement of cement to produce mortar specimens. The authors [28] reported that the development of strength of mortar with pozzolanas particle sizes between 6.3 to 19.4- μ m have a slight FE but at lower replacement levels the author found slightly higher strength with particle sizes of ground river sand is smaller (6.4- μ m) compared with a coarser size (20- μ m). In addition, Jamil et al. [16] used four types of fine NS (6.72, 18.6 and 6.85, 18.9- μ m mean particle sizes) as a filler material with a partial replacement of cement to produce 50 mm mortar cube and 40 mm \times 40 mm \times 160 mm beams specimens with a constant water cement ratio 0.485. The authors [16] determine the FE of pozzolans in mortar by the comparison between strengths of mortars containing small size NS (SNS) and large size NS (LNS) as non-reactive filler material, where they used similar cement replacement level, particle size, fineness, water cement ratio and curing age to produce mortar specimens using pozzolans or non-reactive fillers. The authors [16] reported that the compressive strength or flexural strength of mortar increase or decrease due to the FE must be responsible for the particle size of the NS. Furthermore, Jaturapitakul et al. [30] used ground river sand as a filler material with three different particle sizes of (8.1- μ m, 11.5- μ m and 21.4- μ m) to prepare mortar specimens having a constant water-to-cement ratio 0.493. The authors [31] concluded that the compressive strength of mortar increase with increases in fineness of particles of filler material due to the FE of ground river sand. The author [30] also stated that during curing age between 3 to 90 days, the differences in compressive strength of mortars containing ground river sand are almost constant due to the FE of ground river sand with particle size of 8.1 and 21.4- μ m, 8.1 and 11.5- μ m, and 11.5 and 21.4- μ m. Similarly, Khan et al. [14] used locally available fine natural sand with particle sizes of 7.6- μ m that passes through the 45- μ m sieve to prepare 50 mm mortar cube with a constant water-to-cement ratio of 0.485. The authors [14] determine the FE of pozzolanas for the compressive strength of mortar by the comparison between the theoretical compressive strength of control mortar to the experimental compressive strength of fine natural sand mortars. The authors [14] concluded that when fine non-reactive filler materials used up to 10% replacement of cement, it displayed more noticeable maximum strength due to FE at 7.5% replacement of cement. Meanwhile, Cordeiro et al. [29] used crushed quartz as an insoluble and non-reactivity filler material in the preparation of mortar with the average particle sizes and Blaine fineness of crushed quartz is 29.1- μ m and 210 m²/kg respectively. The authors [29] reported that the dilution effect was the liable for the strength differences between the control mortar and crushed quartz mortar after 28-days curing. The authors [29] also reported that at early ages, the strength development of crushed quartz mortar was noteworthy due to the filler activity of crushed quartz. Therefore, it can be concluded from the above discussion that at early age, the FE is more important in the improvement of compressive, flexural and tensile strength of concrete and mortar. This effect depends on the several factors such as the filler particles size, replacement level,

Table 1
Physical properties of RHA and OPC.

Properties	Present study		Krishna et al. [33]		Ganesan et al. [32]	
	RHA	OPC	RHA	OPC	RHA	OPC
Passed through sieve (mm)	0.075	0.075	0.090	0.090	0.045	0.045
Fineness (%)	80	100	87	98	85	99
Specific gravity (dry)	2.00	3.10	1.95	3.15	2.06	3.1
Bulk density (g/cm ³)	0.435	-	0.53	1.44	0.40	1.16

- Values are not available.

curing age and water to cement ratio.

3. Materials & methods

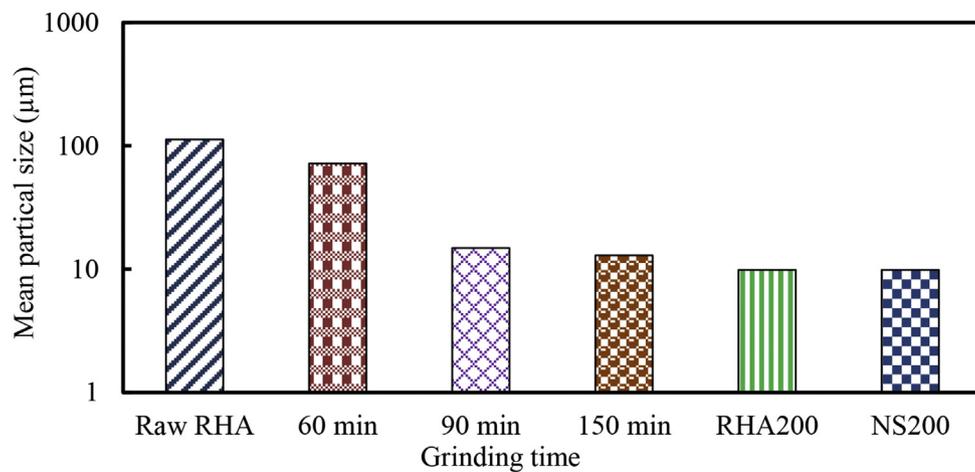
3.1. Materials

In order to conduct this experimental work, locally available RHA was

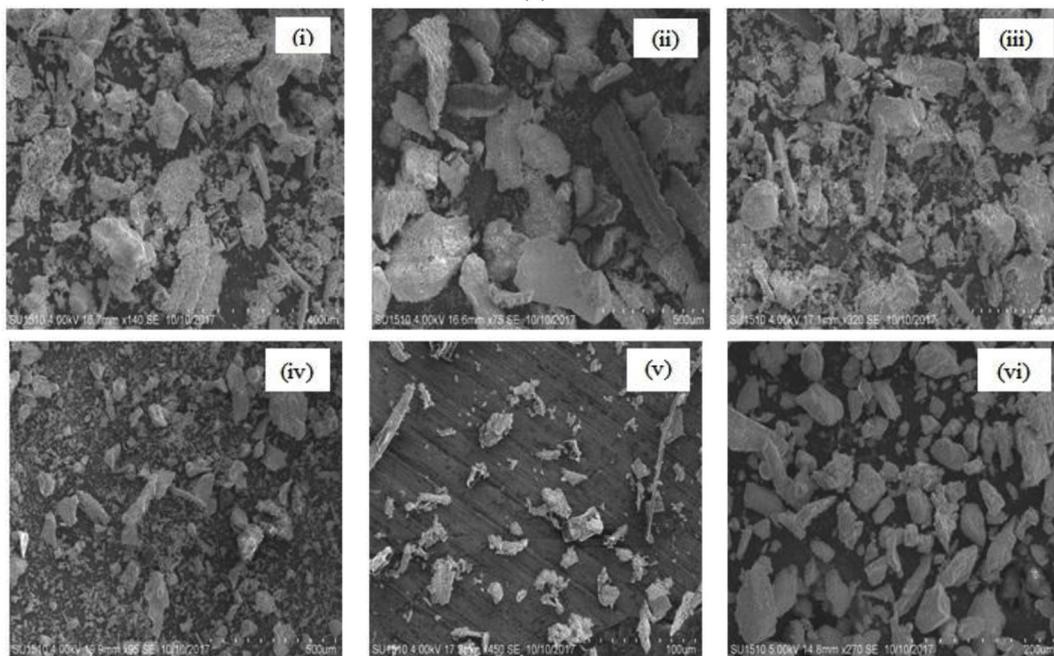
received from local rice mill. Locally available natural sand (NS) was used as a non-reactive filler material. These non-reactive NS was used as a filler representative instead of RHA. Bricks were crushed manually to make coarse aggregate and then sieved for grading. Coarse aggregates that passed through 19 mm sieve were used in this study. Locally available sand was used as fine aggregate. Ordinary Portland cement (OPC) was used for this study. Tap water available in the laboratory was used for specimen preparation and curing. The physical and chemical properties of these materials are discussed below.

3.2. Preparation of RHA and NS

A Los Angeles abrasion machine (G-128-EI42-5305/02, ELE International, Hoskin Scientific, England) were used for grinding of RHA and NS. In order to improve fineness of RHA, grinding balls (14 steel balls each of 48 mm diameter) were used with grinding duration of 60, 90 and 150 min respectively. The rotational speed of the machine was kept 30–33 rpm. In the same way, dry NS was ground by the same grinding



(a)



(b)

Fig. 1. (a) Mean particle size of RHA and NS with grinding time (b) SEM image of RHA samples: (i) Raw RHA, (ii) after 60 min, (iii) after 90 min and (iv) after 150 min of grinding; (v) RHA200 and (vi) NS200 (RHA200 and NS200 means RHA and NS passing through 75 µm or No. 200 sieve).

process with grinding duration of 150 min.

3.3. Tests on RHA and NS

For this study, the different physical and chemical properties of RHA were examined. The mean particle size of RHA and NS was evaluated by scanning electron microscopy (SEM) machine and SEM image analysis software. The chemical composition of RHA was determined using X-ray fluorescence (XRF) technique. The crystalline or amorphous phase of RHA was investigated using X-ray diffraction (XRD) analysis.

3.4. Physical properties of RHA

The different physical properties of RHA including specific gravity, bulk density and fineness were examined and are described below.

3.4.1. Specific gravity and bulk density of RHA

The specific gravity and bulk density of RHA was determined according to BS 1377 [31]. Table 1 shows the physical properties of RHA. The table indicates that the average specific gravity and bulk density of RHA was found as 2.0 and 0.435 g/cm^3 respectively. Ganesan et al. [32] reported that the specific gravity and bulk density of RHA is 2.06 and 0.40 g/cm^3 respectively. Krishna et al. [33] found the specific gravity and bulk density of RHA is 1.95 and 0.53 g/cm^3 respectively. Ganesan et al. [32] and Krishna et al. [33] found nearly similar results. Therefore, the RHA used in the present study was found to be justified in terms of the values of specific gravity and bulk density to be used in concrete construction.

3.4.2. Fineness of RHA

Los Angeles abrasion machine was used for grinding of RHA. RHA passing through 75 μm (No. 200) sieve was collected to use in this research. Keertana and Gobhiga [34] successfully used RHA passing through 75 μm sieve for research purpose. Fineness of RHA is presented in Table 1. The table indicates that 80% RHA was passed through 75 μm sieve. Fineness of RHA increases with increase in grinding time as reported in various past studies [7, 35]. Therefore, it can be concluded that fineness of RHA used in this study seems to be reasonable.

3.4.3. Mean particle size of RHA and NS

The mean particle size of RHA and NS was determined by SEM image analysis (software: image J). The mean particle size of RHA and NS are shown in Fig. 1(a). Also, the SEM images of RHA and NS samples are shown in Fig. 1(b). It can be seen that the RHA particles are irregular in shape before grinding (raw RHA). However, after 60 min of grinding, the mean particle size of RHA decreases from $112.53 \mu\text{m}$ to $72.01 \mu\text{m}$. After 90 and 150 min, the mean particle size of RHA decreases gradually $14.84 \mu\text{m}$ and $12.91 \mu\text{m}$ respectively. After that, it is noted that the mean particle size of RHA decreases with increasing grinding time. Similar results also reported in various previous studies [7, 16, 36]. Fig. 1(a) also reveals that the RHA200 and NS200 have the similar mean particle size ($9.85 \mu\text{m}$) which was passing through the 75 μm (No. 200) sieve. Therefore, it can be concluded that the RHA and NS can be used to accomplish the research objective due to the similar particle size.

3.4.4. X-ray diffraction analysis of RHA

In order to know the silica structure (amorphous and crystalline) of RHA, X-ray diffraction (XRD) analysis was performed using XRD machine (PANalytical, Empyrean, Netherland and data analysis software: Match 3.0). The 2θ (twice theta) angle ranged from 10 to 90° . The obtained XRD pattern of the RHA sample is shown in Fig. 2. The figure shows a strong broad peak at around 20.85° (2θ) which indicates the structure of silica present in RHA as amorphous form. The very sharp peak indicates the crystalline phase of quartz as trigonal (hexagonal axes) structure at about 26.97° (2θ). Nair et al. [5] reported that the very sharp peak for RHA indicates the crystalline nature of silica, whereas amorphous form due to the broad peak on 2θ angle of 22° . Therefore, from the above discussion it can be concluded that RHA led to silica in amorphous form and it contained certain amounts of quartz.

3.5. Chemical properties of RHA and OPC

The chemical properties of RHA and OPC were examined by X-ray fluorescence (XRF) machine (SHIMADZU, XRF-1800, Japan) while loss on ignition (LOI) test was done by electric muffle furnace. Table 2 presents the chemical compositions and LOI of RHA and OPC. The table shows that RHA contains about 86.29% of silica, which is responsible for the

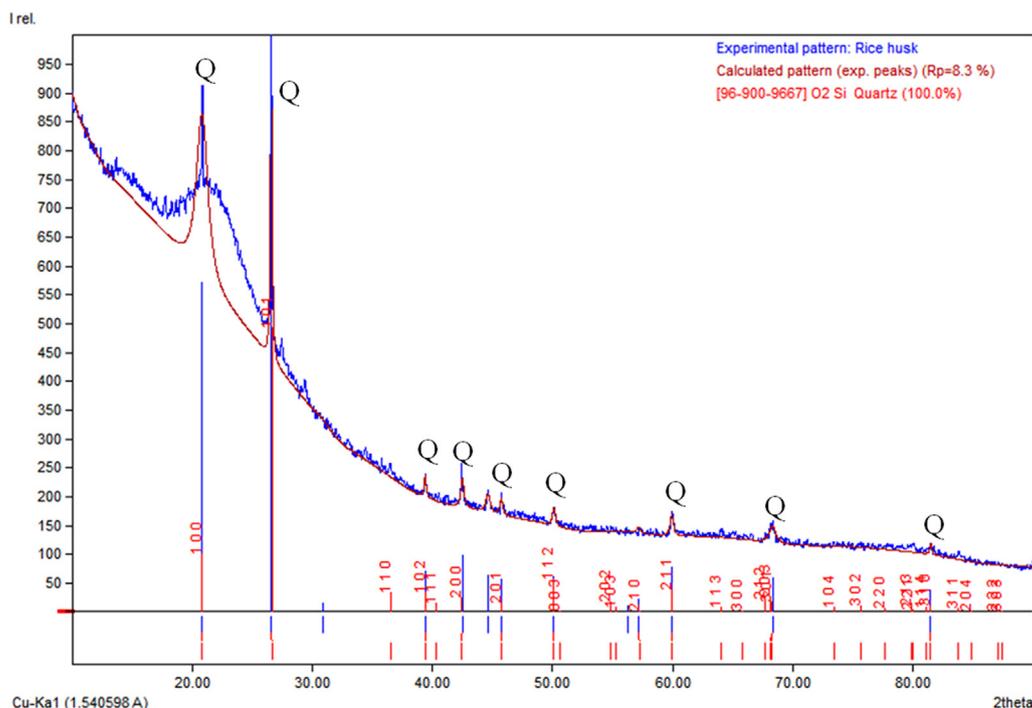


Fig. 2. XRD pattern of RHA particles [Q = Quartz (SiO_2)].

Table 2
Chemical properties of RHA and OPC.

Oxide composition (%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	SO ₃	Na ₂ O	K ₂ O	MnO	LOI	Reference
RHA	86.29	0.57	0.57	0.62	1.13	0.27	0.12	2.30	0.22	7.35	Present study
RHA	87.40	0.40	0.30	0.60	0.90	0.40	0.04	3.39	-	4.60	Van et al. [38]
RHA	87.20	0.15	0.16	0.35	0.55	0.24	1.12	3.68	-	8.55	Dakroury and Gasser [39]
OPC	20.41	5.21	3.47	1.90	64.27	2.71	0.47	0.47	-	0.77	Present study
OPC	21.60	3.70	5.10	0.60	64.30	2.40	0.36	0.17	-	0.90	Van et al. [38]
OPC	20.10	4.51	2.50	3.13	61.30	4.04	2.24	0.39	-	2.41	Dakroury and Gasser [39]

- Values are not available.

Table 3
Physical properties of fine and coarse aggregate.

Properties	Fine aggregate (Natural sand)			Coarse aggregate (Brick chips)				
	Present study			Kulkarni and Momin [41]	Rashid et al. [21]	Present study	Kulkarni and Momin [41]	Rashid et al. [21]
	Sylhet sand	Local sand	Combined sand					
Passed through sieve (mm)	4.75	4.75	4.75	-	-	19	40	19
Fineness modulus (F.M)	3.12	1.08	2.11	2.72	1.86	6.99	8.44	6.97
Specific gravity (dry)	2.67	2.67	2.75	2.64	2.5	2.56	2.48	2.73
Water absorption (%)	1.01	1.01	1.01	-	2.6	16.40	6.16	15.80
Unit weight (kg/m ³)	1503	1267	1385	-	-	924	1011	1089
Moisture content (%)	2.56	2.56	2.56	-	-	-	-	-
Bulk density (g/cm ³)	2.63	2.63	2.62	-	-	-	-	-

- Values are not available.

pozzolanic reaction or secondary hydration in concrete. However, OPC contains about 20.41% of silica. The total percentage of major oxides (SiO₂ + Al₂O₃ + Fe₂O₃) is over 87% for RHA which is greater than the minimum (70%) as specified in ASTM C618 [23]. On the other hand, total percentage of major oxides for OPC (SiO₂ + Al₂O₃ + Fe₂O₃) is 29.09%. The sulfur trioxide (SO₃) content for RHA is less than 5% which is the maximum allowable content as prescribed by the ASTM C618 [37] standard. RHA also contains less than 3% of K₂O. Van et al. [38] denoted RHA as class F pozzolan in their study due to presence of 88.1% of major oxides, 0.4% SO₃ and 3.39% K₂O. The table also shows that the LOI of RHA and OPC is 7.35% and 0.77% respectively. Velupillai et al. [40] reported that the LOI value of RHA varies between 1-35%. According to ASTM C618 [23], in laboratory evaluation the LOI of Class F pozzolanic materials are not more than 12%. Dakroury and Gasser [39] found the LOI value for RHA as 8.55. Therefore, from the above discussion, it can be concluded that properties of RHA used in this study are similar to Class F pozzolan.

3.6. Physical properties of fine and coarse aggregates

The physical properties of fine and coarse aggregate are shown in

Table 4
Engineering and mechanical properties of OPC.

Normal consistency (%)	Setting time (min.)		Compressive strength (MPa)		Tensile strength (MPa)		Reference
	Initial	Final	(3-day)	(28-day)	(3-day)	(28-day)	
30	120	315	28.4	33.8	0.13	0.39	Present study
28–32	≥45	≤375	12.0	28.0	-	-	ASTM C150 [42]
30.0	55	320	-	-	-	-	Kulkarni and Momin [41]
33.2	191	254	26.0	46.8	-	-	Tiwari and Patel [43]

- Values are not available.

Table 3. The table shows that properties of aggregates are similar to the past research results [21, 41]. Kulkarni and Momin [41] found the fineness modulus (FM), specific gravity of fine aggregate as 2.72 and 2.64 respectively. The authors [41] also found fineness modulus (FM), specific gravity, water absorption and unit weight of brick aggregate as 8.44, 2.48, 6.16% and 1011 kg/m³ respectively. On the other hand, Rashid et al. [21] found FM, specific gravity and water absorption of fine aggregate as 1.86, 2.50 and 2.60% respectively. The authors also [21] found FM, specific gravity, water absorption and unit weight of brick aggregate as 6.97, 2.73, 15.80% and 1089 kg/m³ respectively. Therefore, properties of aggregates used in this study are considered to be customary.

3.7. Engineering and mechanical properties of OPC

The engineering and mechanical properties of cement are shown in **Table 4**. The table shows that the engineering and mechanical properties of cement satisfy the ASTM C150 [42] limit and similar to the past research results [30, 41]. Kulkarni and Momin [41] found the normal consistency, initial setting time and final setting time as 30%, 55 min and 320 min respectively. Tiwari and Patel [43] found the initial setting time, final setting time as 191 min, 254 min and compressive strength for 3 days and 28 days as 26.0 MPa and 46.8 MPa respectively and normal consistency as 33.2%. Therefore, from the above discussion it can be concluded that properties of cement used in this study satisfies the requirements as prescribed for ordinary Portland cement (Type-I).

3.8. Mix proportion of concrete specimens

All materials were taken percentage by mass (% by mass) at constant mix proportion of 1:1.5:3 as presented in **Table 5**. Concrete mixture had a binder content of 409.1 kg/m³ with a constant water-to-binder (w/b) ratio of 0.50.

3.9. Mixing and casting of concrete specimens

The fresh concrete was prepared as per designed mix (**Table 5**) in a drum type mixture machine. The fresh concrete was placed in the Cylindrical mould of 100 mm × 200 mm in size in three layers and

Table 5Mix proportion (1:1.5:3) for 1 m³ of concrete for w/b of 0.50.

Mix No.	RHA/NS (%)	RHA/NS (kg)	OPC (kg)	Fine aggregate (kg)		Coarse aggregate (kg)	Water (kg)
				Sylhet sand	Local sand		
BACR0/BACNS0	0	0.0	409.1	307.4	259.1	755.8	204.6
BACR10/BACNS10	10	40.9	368.2	307.4	259.1	755.8	204.6
BACR15/BACNS15	15	61.4	347.7	307.4	259.1	755.8	204.6
BACR20/BACNS20	20	81.8	327.3	307.4	259.1	755.8	204.6
BACR25/BACNS25	25	102.3	306.8	307.4	259.1	755.8	204.6

compacted according to ASTM C31 [44]. The fresh concrete specimen was kept in the laboratory without any disturbance for 24 h within room temperature. Then specimens were marked to identify and placed in the water tank for desired curing age.

3.10. Tests on concrete specimens

3.10.1. Compressive strength (f'_c)

At the desired testing age (7, 28 and 90 days) of concrete, the concrete cylinders were subjected to f'_c test by 3000 kN capacity compression testing machine (Matest s. r.l. Treviolo 24048, C089PN448, Italy) following the ASTM C39 [45] specifications. Compressive strength test was performed by maintaining a loading rate of 0.24 MPa/s according to ASTM C39 [45] testing standard, which specified the loading rate varies from 0.15 to 0.35 MPa/s. The f'_c was calculated based on the average result of three specimens.

3.10.2. Split tensile strength (f_{sp})

The f_{sp} test was carried out as per ASTM C496 [46]. After 28 days, the concrete cylinders were subjected to f_{sp} test using universal testing machine (TORSEE, Capacity: 200 kN, Tokyo Testing Machine Mfg. Co. Ltd., Japan). Split tensile strength test was conducted by maintaining a loading rate of 1.0 MPa/min according to ASTM C496 [46] testing standard and stated that the rate varies from 0.7 to 1.4 MPa/min. The average f_{sp} values were recorded from the average value of three specimens for each set of data.

3.10.3. Flexure strength (f_r)

The f_r was determined by center-point loading test methods according to ASTM C293 [47] standard. The f_r was measured on a 100 mm × 100 mm × 500 mm concrete beam using universal testing machine (TORSEE, Capacity: 200 kN, Tokyo Testing Machine Mfg. Co. Ltd., Japan) at 28 days of curing age. Flexure strength test was made by maintaining a loading rate of 1.0 MPa/min according to ASTM C293 [47] testing standard, which indicated that the loading rate keep in about 0.9–1.2 MPa/min. The average f_r values were calculated based on the average value of three specimens.

3.10.4. Modulus of elasticity (E_c)

The E_c test was carried out as per ASTM C469 [48] standard on the concrete cylinders using universal testing machine (UTM 100, Capacity: 3000 kN, Fuel Instruments & Engineers Pvt. Ltd., India). Modulus of elasticity test was performed with a loading rate of 248 ± 10 kPa/s according to ASTM C469 [48] testing standard and specified the loading rate keep in about 241 ± 34 kPa/s. One dial gauge were used to measure the axial deformation. For E_c test of each mix, three specimens were used and their average value was recorded.

3.10.5. Poisson's ratio (ν)

The ν test was carried out as per ASTM C469 [48] using universal testing machine (UTM 100, Capacity: 3000 kN, Fuel Instruments & Engineers Pvt. Ltd., India). Poisson's ratio test was performed keeping a loading rate of 248 ± 10 kPa/s according to ASTM C469 [48] testing standard and specified the rate would be about 241 ± 34 kPa/s. Two dial gauges were used to measure the lateral deformation of the cylinder. The

collected data from three specimens was used to calculate the average value of ν .

3.11. Strength activity index (SAI) of RHA

The pozzolanic performance of RHA in BAC was investigated by SAI method as prescribed in ASTM C311 [49]. The SAI of RHA in BAC is calculated as the ratio of the f'_c of the mortar cube containing RHA in relation to the f'_c of the control mortar cube (0% RHA) at 7 and 28 days. Therefore, $SAI = A/B \times 100$; where, $A = f'_c$ of mortar cube containing RHA and, $B = f'_c$ of control mortar cube. The values of the SAI correspond to the average of three specimens for each mix.

3.12. Pozzolanic effect (PE) of RHA

The PE of RHA on mechanical properties of BAC was evaluated by the comparison between properties of concrete containing RHA and natural sand (NS) with similar particle size (Fig. 1), cement replacement level and age of curing. The main purpose of using NS in this study is due to its role as a filler representative of RHA. Jamil et al. [16] successfully determined PE of RHA by this method for mortar specimen. Thus, the PE of RHA on mechanical properties of BAC at 28 days was determined using the above technique, $PE = \alpha - \beta$; where, PE = pozzolanic effect of BAC due to the pozzolanic action of RHA; α = properties of BACR (f'_c, f_{sp}, f_r, E_c and ν); β = properties of BAC with NS (f'_c, f_{sp}, f_r, E_c and ν).

3.13. Filler effect (FE) of RHA

The FE of RHA has been calculated based on a method proposed by Khan et al. [14]. Locally available NS was used as a non-reactive filler material instead of RHA with similar particle size at cement replacement level. FE of RHA on mechanical properties of BAC was evaluated by the comparison between experimental values of BAC with NS (BACNS) and theoretical values of concrete properties at 28 days of curing age. For example, the value for f'_c of concrete with 10% NS is "X" MPa and that of theoretical value of control (90% OPC only) is "Y" MPa, then FE of 10% RHA on $f'_c = (X - 0.9 \times Y)$ MPa. The values of any property (f'_c, f_{sp}, f_r, E_c

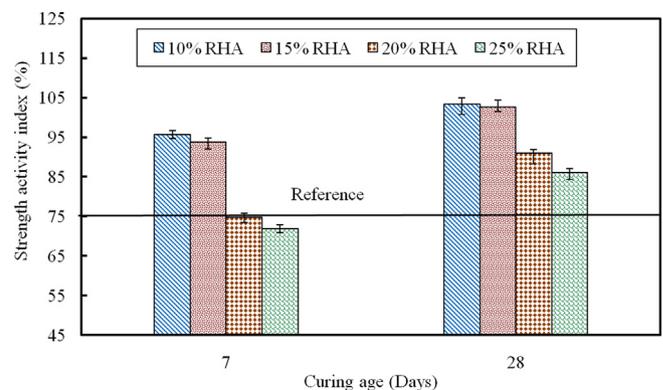


Fig. 3. Strength activity index (SAI) of RHA in BAC at 7 and 28 days.

and ν) correspond to the average of three specimens for each mix.

3.14. Microstructure of concrete

After 28 days of curing, specimens were cut into 10 mm × 10 mm size and ground to expose a fresh surface. Then the microstructure of the concrete sample was evaluated by scanning electron microscopy (SEM) analysis using the JEOL brand SEM machine (JSM-7600F model).

4. Results & discussions

4.1. Strength activity index (SAI) of RHA

The SAI was performed to know the pozzolanic effect of RHA in BAC. The SAI of RHA is shown in Fig. 3. The reference line corresponds to the threshold value indicated in the ASTM C618 [37] standard. It was observed that the f'_c of control mortar was found as 28.4 MPa and 33.8 MPa at 7 and 28 days respectively. The f'_c of mortar containing 10%,

15%, 20% and 25% RHA were found 27.2, 26.6, 21.2 and 20.4 MPa respectively at 7 days of curing age, while these values were found is 34.89, 34.63, 30.74 and 29.1 MPa for those mixes respectively at 28 days of curing age.

Fig. 3 shows that the SAIs of RHA mortar were obtained as 95.7%, 93.8%, 74.7% and 71.9% of the strength of control mortar for using 10, 15, 20 and 25% RHA respectively at 7 days. The SAIs of RHA mortar were found as 103.4%, 102.6%, 91.1%, and 86.1% of the control mortar strength for using 10, 15, 20 and 25% RHA respectively at 28 days. The SAIs of RHA are higher than the minimum requirement of 75% as specified in ASTM C618 [37] for 28 days. On the other hand, only 10% and 15% RHA meet the ASTM C618 [37] requirements at 7 days. The test results revealed that 10% and 15% RHA increased the SAI in comparison to the 20% and 25% RHA replacement at 7 days which may be due to the FE of RHA. However, SAI was found higher than the minimum requirement of 75% for using up to 25% RHA at 28 days. This could be attributed to the delayed start of pozzolanic reaction of RHA with $\text{Ca}(\text{OH})_2$. It is well-documented that pozzolanic reaction starts to proceed, which

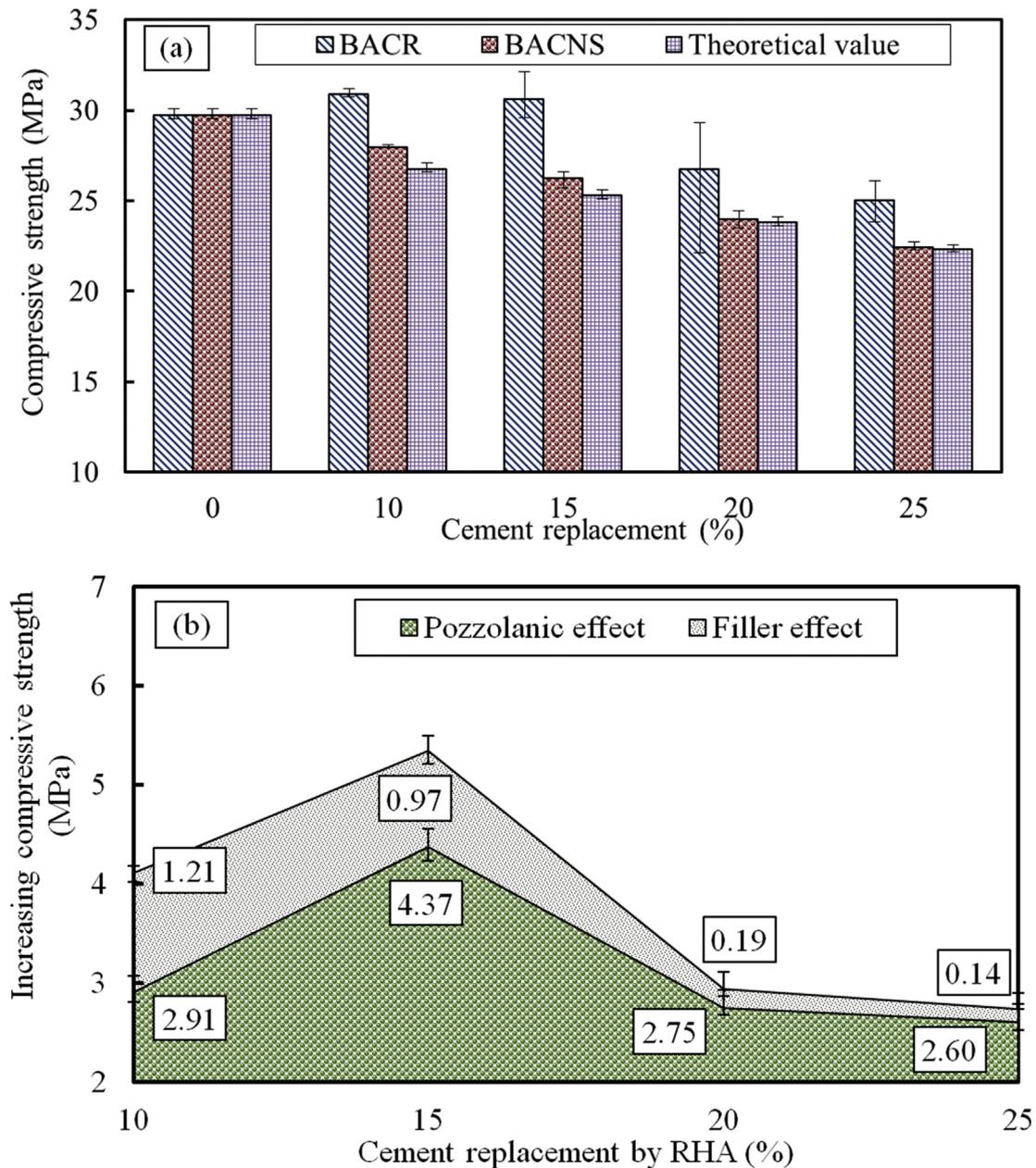


Fig. 4. (a) Experimental and theoretical value of f'_c with RHA and NS (b) Increasing f'_c of BAC for PE and FE of RHA at 28 days.

decreases the amount of CH and improves the microstructure through densification at later ages, after 28 days [15, 50, 51]. Therefore, it can be concluded that RHA shows a significant PE and FE on BAC up to 25% replacement of cement after 28 days.

4.2. The PE of RHA on f'_c of BAC

The PE of RHA on f'_c of BAC was evaluated to do the comparative study on PE and FE of RHA on f'_c in BAC. The f'_c of brick aggregate concrete containing RHA (BACR) has been shown to be influenced by PE and FE whereas f'_c of BAC with NS (BACNS) is influenced by FE as shown in Fig. 4. The hydration effect for both concrete can be considered constant because percentages of replacement of cement and w/b ratio are kept constant in preparation of BAC. Therefore, improvement of f'_c of BAC due to pozzolanic reaction of RHA is calculated from the difference between f'_c of BACR and BACNS (Fig. 4(a)) with similar particle size and RHA replacement level at 28 days of curing age [16]. For example, f'_c of

BACR10 is 30.90 MPa and f'_c of BACNS10 is 27.99 MPa at 28 days of curing age. Therefore, increment of f'_c of BAC due to pozzolanic reaction of RHA is 2.91 MPa (30.90–27.99) at 28 days of curing age, which is triggered by the pozzolanic reaction of RHA. All of these PE values are presented in Fig. 4(b). Fig. 4(b) also indicates that enhancement of f'_c due to pozzolanic reaction of the RHA that increases with increasing cement replacement with RHA up to 15%. The maximum increment of f'_c of BACR due to pozzolanic reaction of RHA is found to be 4.37 MPa for 15% cement replacement of cement. Jamil et al. [16] concluded that RHA shows a less effect to increase the f'_c of mortar due to pozzolanic reaction at early age (7 and 14 days). The authors also reported that the PE of RHA not only depends on particle size but also depends on age and cement replacement level. Therefore, from the above discussion it can be concluded that BAC gains a significant strength due to pozzolanic reaction of RHA at 28 days of curing age.

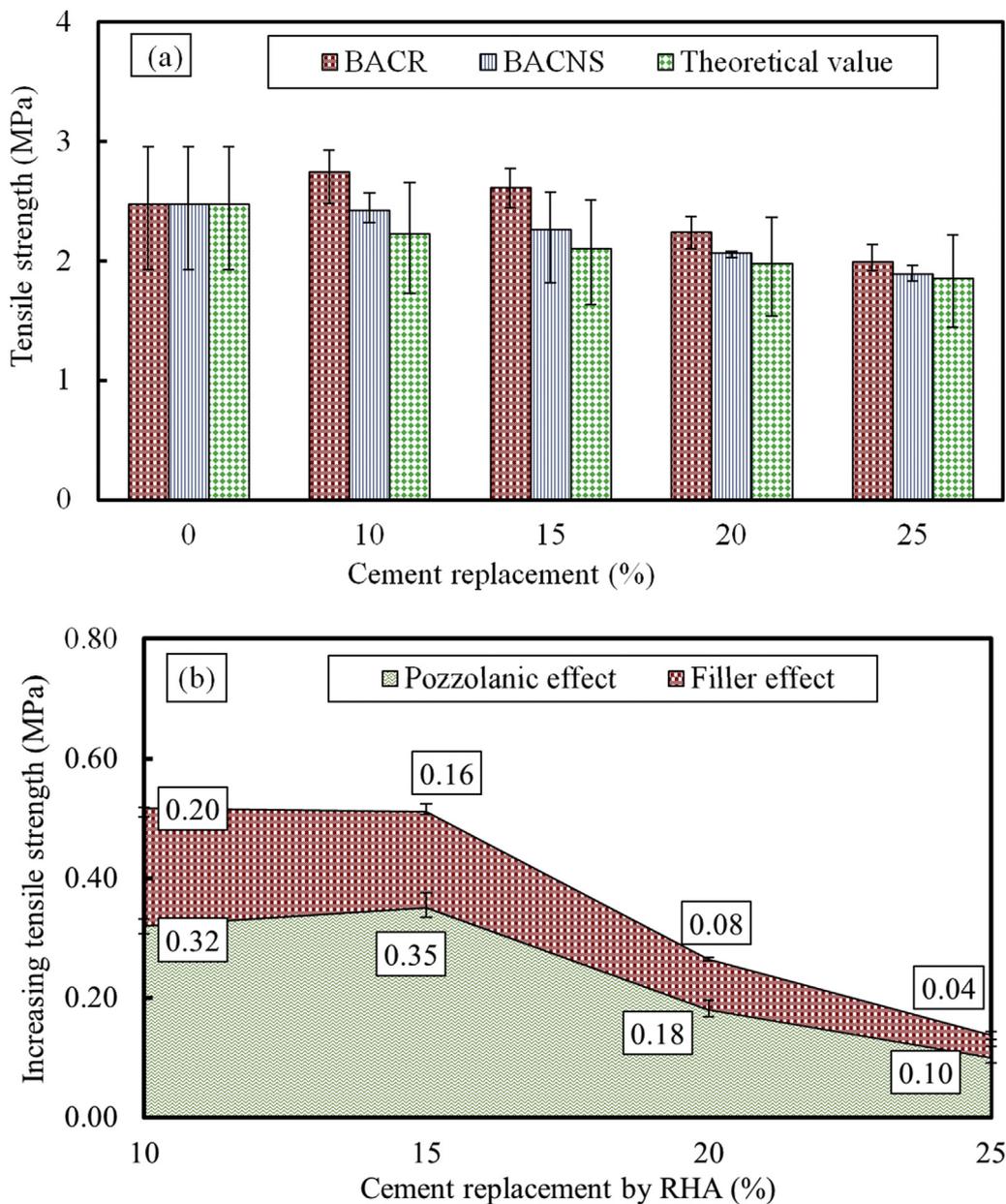


Fig. 5. (a) Experimental and theoretical value of f'_c with RHA and NS and (b) Increasing f'_c of BAC for PE and FE of RHA at 28 days.

4.3. The FE of RHA on f_c of BAC

The FE of RHA on f_c of BAC was evaluated to determine the comparative performance of PE and FE of RHA on f_c in BAC. Fig. 4(a) presents the theoretical and experimental values of f_c of BAC (BACNS) due to cement replacement by NS. Fig. 4(a) shows the f_c of BACNS0 (100% OPC) are 29.76 MPa at 28 days, thus the theoretical value of f_c for BACNS10 (amount of available cement 90%) would be $29.76 \times 90\% = 26.78$ MPa. On the other hand, the experimental value of f_c of BACNS10 was found as 27.99 MPa at 28 days curing. Therefore, the increases in f_c of BAC due to FE of 10% NS should be $27.99 - 26.78 = 1.21$ MPa. All of these values of FE are shown in Fig. 4(b). It is also clearly seen that the additional f_c achieved by the FE and there is no possibility of strength gain from any chemical involvement of NS. Fig. 4(b) reveals that increment of f_c due to FE of RHA decreases gradually with increase in replacement of cement. Jamil et al. [16] reported that the f_c of mortar increases or decreases due to FE depending on the particle size of the NS.

The maximum increment of f_c of BAC due to FE of RHA was found 1.21 MPa for 10% RHA replacement of cement at 28 days of curing age. Consequently, it can be concluded that the RHA particles contribute to increase the f_c of BAC by the FE at 28 days of curing.

4.4. Comparative study of PE and FE of RHA on f_c of BAC

Fig. 4(b) shows the enhancement of f_c due to pozzolanic reaction as 2.91, 4.37, 2.75 and 2.60 MPa for the mixes BACR10, BACR15, BACR20 and BACR25 respectively at 28 days of curing age. On the other hand, Fig. 4(b) also shows that the enhancement of f_c due to FE are 1.21, 0.97, 0.19 and 0.14 MPa for the mixes BACNS10, BACNS15, BACNS20 and BACNS25 respectively at 28 days of curing. Hence, the f_c due to FE are 58.56%, 77.71%, 93.02% and 94.62% lower compared to the PE of RHA for the mixes BACR10, BACR15, BACR20 and BACR25 respectively at 28 days of curing age. Therefore, it can be concluded that at 28 days the f_c of BAC due to PE increased significantly than the FE of RHA up to 25%

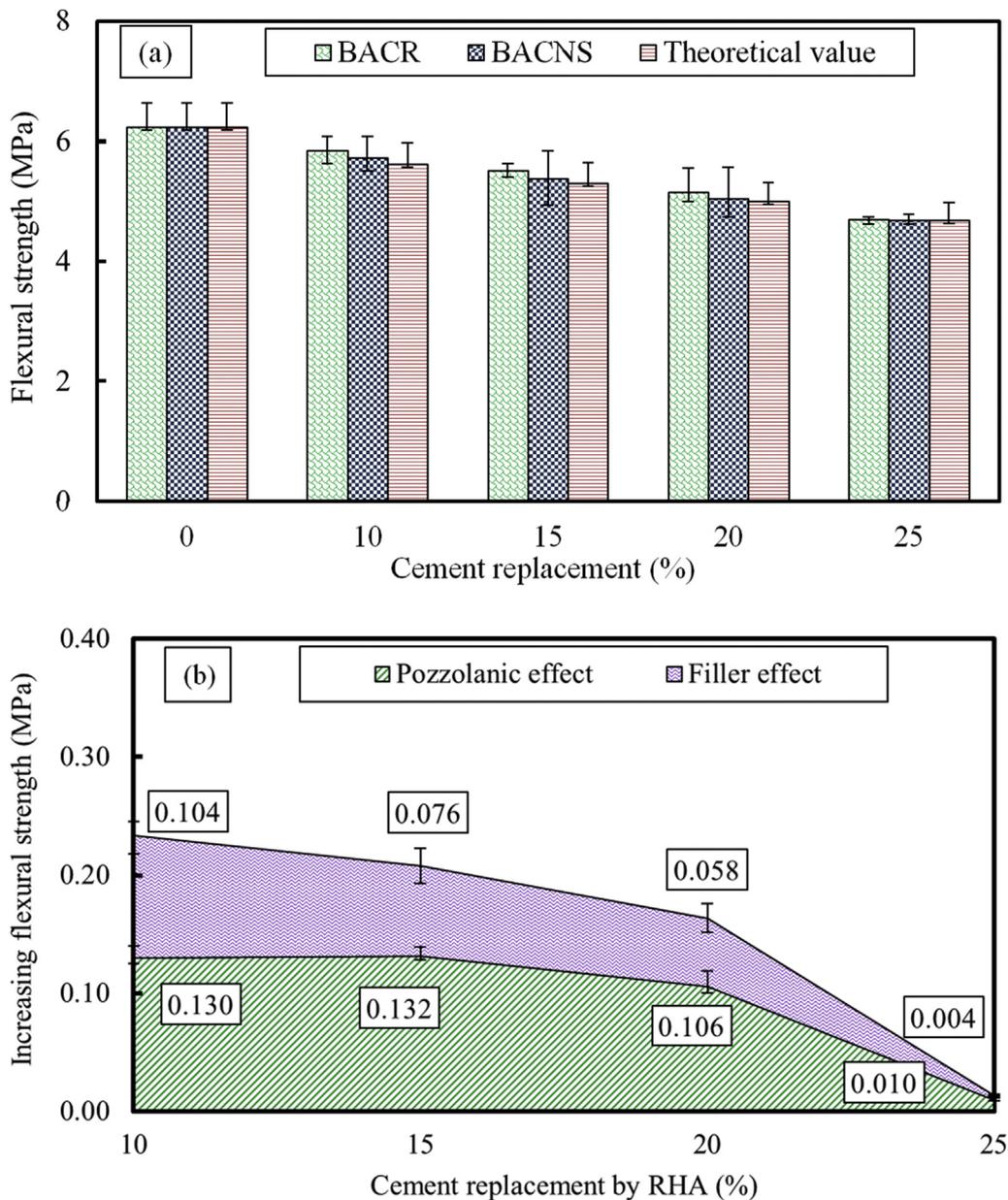


Fig. 6. (a) Experimental and theoretical value of f_r with RHA and NS and (b) Increasing f_r of BAC due to PE and FE of RHA at 28 days.

replacement. It may be due to the production of additional C-S-H gel in concrete which can decrease the pore of concrete and increase in the f'_c .

4.5. The PE of RHA on f_{sp} of BAC

The PE of RHA on f_{sp} of BAC was evaluated to work out the comparative performance of PE and FE of RHA on f_{sp} in BAC. The values of f_{sp} of BACR and BACNS at 28 days of curing age are presented in Fig. 5(a). The figure shows that the f_{sp} of BACR10 is 2.74 MPa and f_{sp} of BACNS10 is 2.42 MPa at 28 days of curing age. Therefore, enhancement of f_{sp} in BAC due to pozzolanic reaction of RHA is 0.32 MPa (2.74–2.42) at 28 days of curing age, which is induced from pozzolanic reaction of RHA. Fig. 5(b) shows the PE of RHA for all replacement level on f_{sp} of BAC after 28 days curing age. Fig. 5(b) reveals that the increment of f_{sp} due to pozzolanic reaction was 0.32, 0.35, 0.18 and 0.10 MPa for the mixes BACR10, BACR15, BACR20, BACR25 respectively at 28 days of curing age. Fig. 5(b) also reveals that the increment of f_{sp} due to pozzolanic reaction of RHA increased with the increase in RHA replacement level up to 15%

and then decreased which may be due to the use of locally available RHA that are responsible for the higher LOI. The maximum improvement of f_{sp} of BAC due to pozzolanic reaction of RHA was found 0.35 MPa for 15% replacement of cement by RHA at 28 days of curing age. Therefore, from the above discussion, it can be concluded that the RHA particles contribute to growth of f_{sp} of BAC by the PE at 28 days of curing.

4.6. The FE of RHA on f_{sp} of BAC

The FE of RHA on f_{sp} of BAC was evaluated to determine the comparative performance of PE and FE of RHA on f_{sp} in BAC. Fig. 5(a) presents the theoretical and experimental values of f_{sp} (BACNS) due to cement replacement by NS. Fig. 5(a) illustrates that the f_{sp} of BAC containing 100% OPC is 2.47 MPa at 28 days, thus the theoretical value of f_{sp} for 90% available cement should be $2.47 \times 90\% = 2.22$ MPa and the experimental value of f_{sp} of BAC with 10% NS was 2.42 MPa. Thus, the FE of RHA on f_{sp} of BAC for 10% RHA is $2.42 - 2.22 = 0.20$ MPa. By the same way all of these values of FE of RHA on f_{sp} of BAC after 28 days curing are

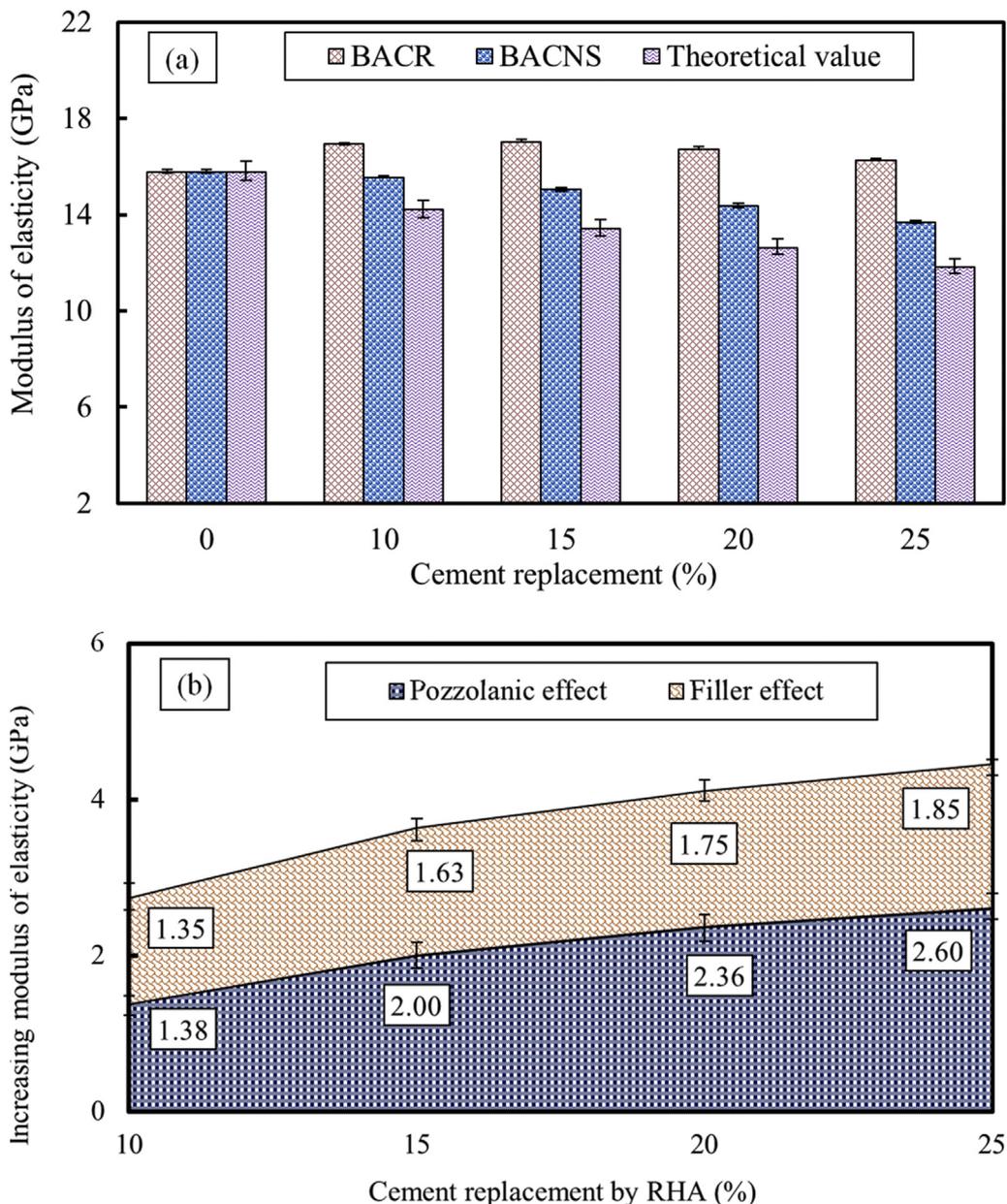


Fig. 7. (a) Experimental and theoretical value of E_c with RHA and NS and (b) Increasing E_c of BAC due to PE and FE of RHA at 28 days.

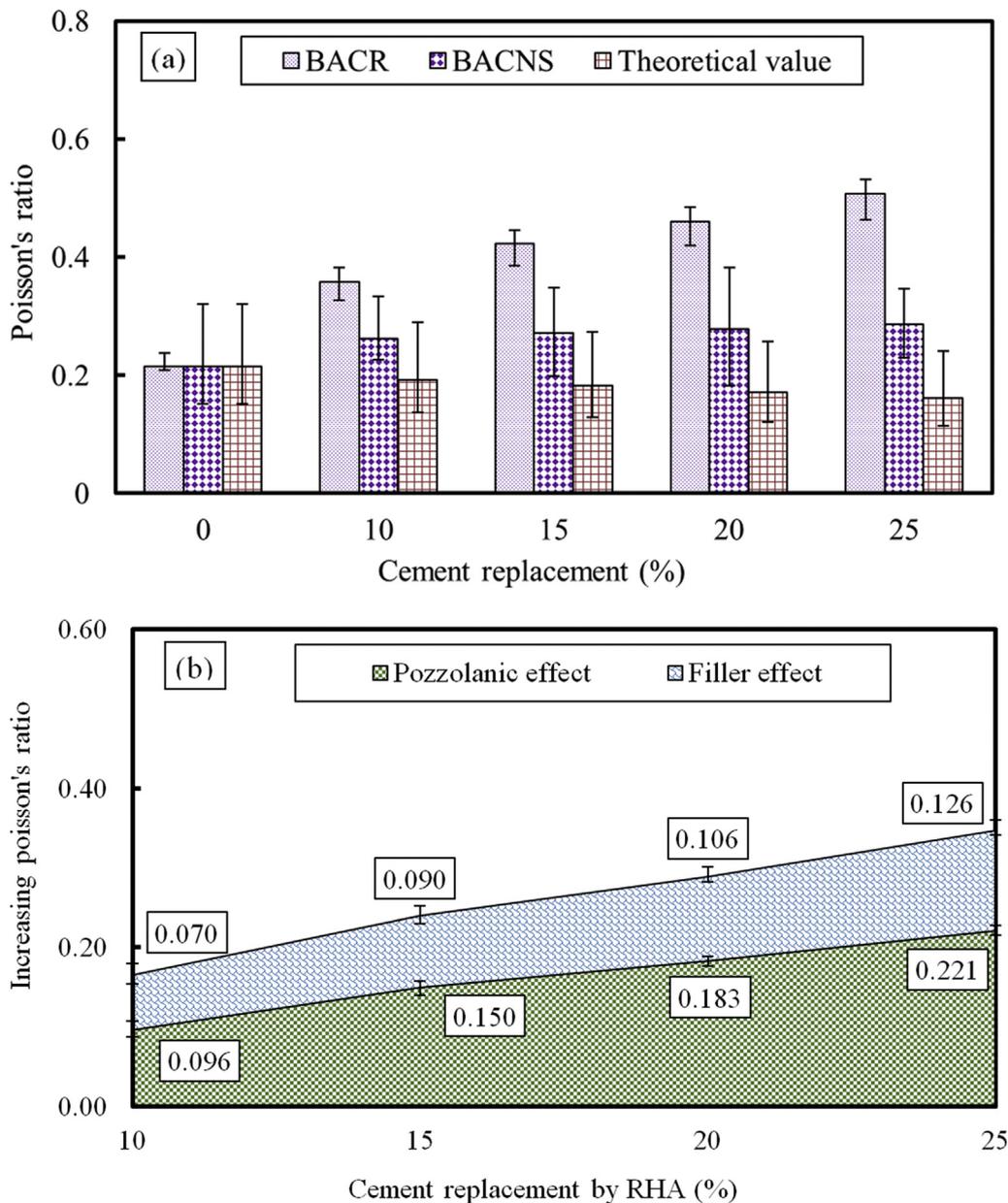


Fig. 8. (a) Experimental and theoretical values of ν with RHA and NS and (b) Increasing ν of BAC for PE and FE of RHA at 28 days.

presented in Fig. 5(b). It also clearly shows the additional f_{sp} achieved by the FE and there is no chemical involvement of NS for the increment of strength. Moreover, Fig. 5(b) reveals that the FE of the NS has a tendency to decrease gradually with increase in the amount of cement replacement level. This may be due to the inclusion of NS which creates extra amount of silica into the BAC that was not contributing to chemical reaction with the hydration product of cement. Thus, the BAC shows the maximum increment of f_{sp} due to FE of RHA is 0.20 MPa for 10% replacement of cement by RHA at 28 days of curing. Therefore, it can be concluded that the RHA particles also contribute to increase in the f_{sp} of BAC by the FE at 28 days of curing.

4.7. Comparative study of PE and FE of RHA on f_{sp} of BAC

Fig. 5(b) shows that the enhancement of f_{sp} due to pozzolanic reaction is 0.42, 0.35, 0.18 and 0.10 MPa for the mixes BACR10, BACR15, BACR20 and BACR25 respectively at 28 days of curing. On the other hand, Fig. 5(b) also indicates that the development of f_{sp} in BAC due to FE

of RHA is 0.20, 0.16, 0.08 and 0.04 MPa for the 10%, 15%, 20% and 25% replacement of NS at 28 days of curing respectively. Hence the f_{sp} due to PE are 60%, 118%, 125% and 150% more than the FF of RHA for the mixes BACR10, BACR15, BACR20 and BACR25 respectively at 28 days of curing. Therefore, from the above discussion it can be concluded that at 28 days the f_{sp} of BAC due to PE increased markedly than the FE of RHA up to 25% replacement.

4.8. The PE of RHA on f_r of BAC

The PE of RHA on f_r of BAC was evaluated to know the comparative performance of PE and FE of RHA on f_r in BAC. Experimental values of f_r with RHA and NS are presented in Fig. 6(a). The figure indicates that the f_r of BAC with 10% RHA was found 5.85 MPa and f_r of BAC with 10% NS was obtained 5.72 MPa at 28 days of curing age. Therefore, the increase in f_r of BAC due to pozzolanic reaction of RHA is 0.13 MPa (5.85–5.72) at 28 days of curing age, which is initiated by pozzolanic reaction of RHA. Fig. 6(b) shows all of the PE of RHA on f_r of BAC for different replacement level after 28 days curing age. Fig. 6(b) reveals that increment of f_r due to

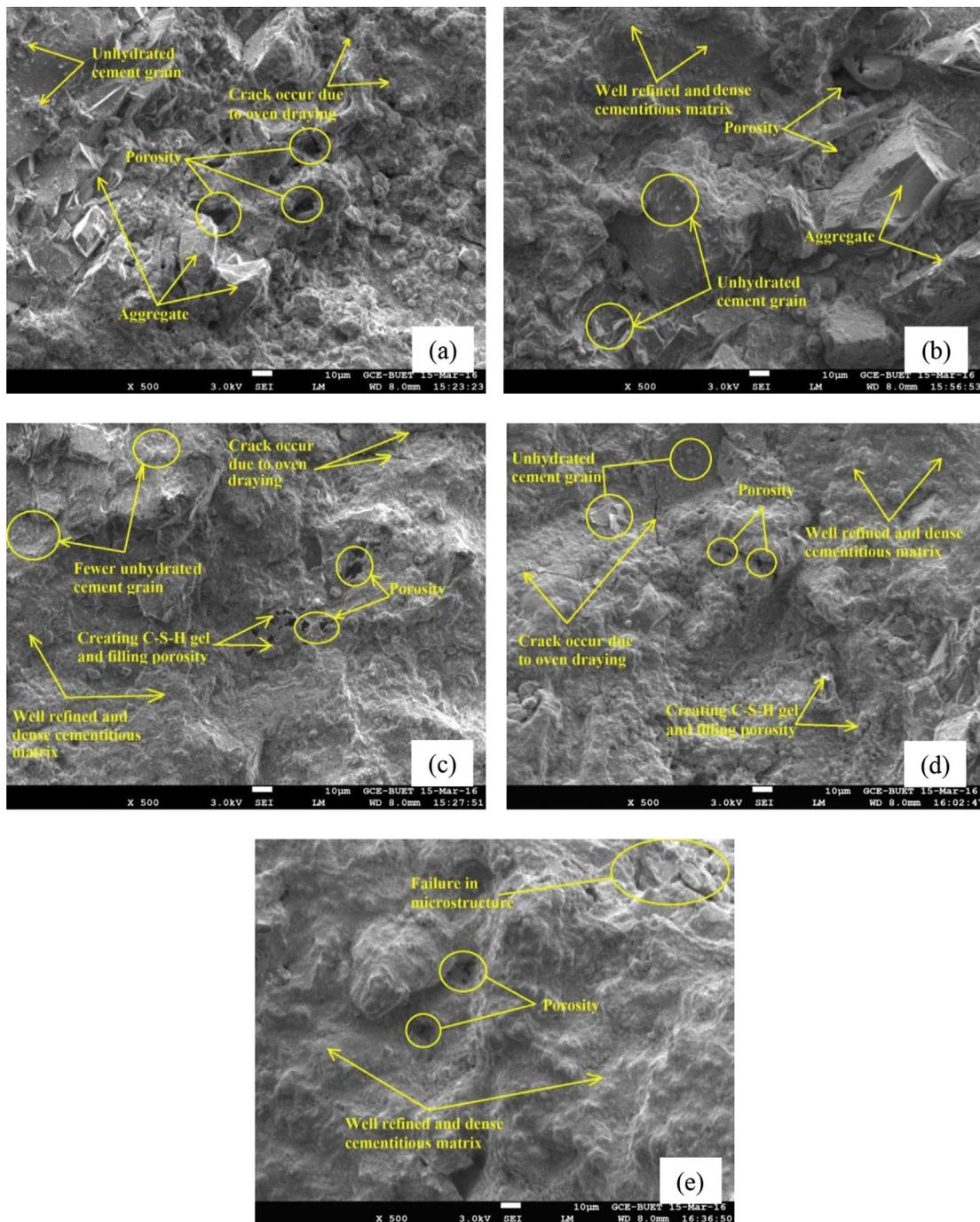


Fig. 9. Microstructure of (a) 0% RHA (b) 10% RHA (c) 15% RHA (d) 20% RHA and (e) 25% RHA concrete after 28 days.

pozzolanic reaction of the RHA increases with increase in replacement level up to 15%, thereafter decreases. But, the RHA particles help to develop the f_r of BAC by the PE at 28 days of curing. The maximum increment of f_r of BAC due to pozzolanic reaction of RHA was found 0.14 MPa for 15% replacement of cement by RHA at 28 days of curing age. Habeeb and Fayyadh [52] reported that f_r of RHA concrete increases with the decreasing RHA particle sizes. This may be due to the increment of pozzolanic reaction and filler ability of finer RHA particles as reported by Zhang et al. [15].

4.9. The FE of RHA on f_r of BAC

The FE of RHA on f_r of BAC was evaluated to find the comparative performance of PE and FE of RHA on f_r in BAC. Fig. 6(a) presents the

theoretical and experimental values of f_r (BACNS) due to cement replacement by NS. Fig. 6(a) shows that the f_r of BAC containing 0% NS (100% OPC) are 6.24 MPa at 28 days. Thus, the theoretical f_r for 90% cement should be $6.24 \times 90\% = 5.62$ MPa. On the other hand, the experimental value of f_r of BAC with 10% NS was found 5.72 MPa at 28 days curing. Thus, the FE of RHA on f_r of BAC for 10% RHA is $5.72 - 5.62 = 0.10$ MPa. All of these values of FE of RHA are presented in Fig. 6(b). From the results, it is obvious that these additional f_r achieved by the FE and there is no possibility of strength gain from any chemical contribution of NS. Fig. 6(b) reveals that increment of f_r due to FE of RHA decreases gradually with increase in replacement of cement. The maximum increment of f_r of BAC due to FE of RHA was found 0.10 MPa for 10% replacement of cement by RHA at 28 days of curing. Therefore, it can be concluded that the RHA particles help develop the additional f_r of BAC by

the PE at 28 days of curing.

4.10. Comparative study of PE and FE of RHA on f_r of BAC

Fig. 6(b) shows that the enhancement of f_r due to pozzolanic reaction is 0.130, 0.132, 0.106 and 0.010 MPa for the mixes BACR10, BACR15, BACR20 and BACR25 respectively at 28 days of curing age. On the other hand, Fig. 6(b) also shows that the enhancement of additional f_r due to FE is 0.104, 0.076, 0.058 and 0.004 MPa for the mixes BACNS10, BACNS15, BACNS20 and BACNS25 respectively at 28 days of curing age. Therefore, the f_r due to PE are 25%, 74%, 83% and 150% more than that of FE of RHA for the mixes BACR10, BACR15, BACR20 and BACR25 respectively at 28 days of curing age. The results also reveals that the f_r of BAC due to PE increased significantly than the FE of RHA up to 25%. Therefore, it can be inferred that the BACR up to 25% replacement exhibited the higher f_r by the PE which is greater than the FE at 28 days curing. This may be due to the production of C–S–H glue by RHA particles.

4.11. The PE of RHA on E_c of BAC

The PE of RHA on E_c of BAC was evaluated to determine the comparative performance of PE and FE of RHA on E_c in BAC. The E_c of BAC with RHA and NS are presented in Fig. 7(a). The figure indicates that the E_c of BAC with 10% RHA was recorded as 16.94 GPa and E_c of BAC with 10% NS was found as 15.56 GPa at 28 days of curing age. Therefore, the increment of E_c due to pozzolanic reaction of RHA is calculated as 1.38 GPa (16.94–15.56), which is induced by pozzolanic reaction of RHA. Fig. 7(b) shows the PE of RHA on E_c of BAC for different replacement of RHA after 28 days of curing age.

Fig. 7(b) reveals that enhancement of E_c due to pozzolanic reaction of the RHA increases with replacement of cement by RHA (up to 25%). The maximum improvement of E_c of BAC due to pozzolanic reaction of RHA was obtained as 2.60 GPa at 28 days of curing age for 25% replacement of cement by RHA. Mehta [53] reported that ultimate strength of concrete containing pozzolans will result in significant gain in the E_c after 28 days of curing age. The increase in E_c due to pozzolanic reaction of RHA may be due to the production of additional C–S–H gel in concrete which can reduce the strain of concrete. In addition, Noaman et al. [13] reported that the E_c of BAC with RHA marginally grows with the increase in RHA replacement compared to the control may be due to the PE of the RHA.

4.12. The FE of RHA on E_c of BAC

The FE of RHA on E_c of BAC was evaluated to work out the comparative performance of PE and FE of RHA on E_c in BAC. Fig. 7(b) presents the theoretical and experimental values of E_c due to cement replacement by NS. Fig. 7(b) shows that the E_c of BAC containing 0% NS (100% OPC) is 15.79 GPa at 28 day. Thus the theoretical value of E_c for 10% replacement of cement by RHA (amount of available cement 90%) should be $15.79 \times 90\% = 14.21$ GPa. However, the experimental value of E_c of BAC with 10% NS was found as 14.96 GPa. Therefore, the increment in E_c of BAC due to FE of 10% NS should be $15.56 - 14.21 = 1.35$ GPa. Similarly, the results of E_c are shown in Fig. 7(b), which represent the increase in E_c of BAC due to FE of RHA after 28 days curing. Finally, the figure clearly shows the extra E_c achieved by the FE and there is no possibility of increasing the E_c from any chemical involvement of NS. Fig. 7(b) reveals that the increment of E_c increases gradually due to FE of RHA with increase in replacement of cement. The maximum increment of E_c of BAC due to FE of RHA was found 1.85 GPa for 25% replacement of cement at 28 days of curing. Therefore, it can be concluded that the RHA particles contributed to increase in E_c of BAC by the FE at 28 days of curing age.

4.13. Comparative study of PE and FE of RHA on E_c of BAC

Fig. 7(b) shows that the enhancement of E_c due to pozzolanic reaction

are 1.38, 2.00, 2.36 and 2.60 MPa for the mixes BACR10, BACR15, BACR20 and BACR25 respectively at 28 days of curing age. On the other hand, Fig. 7(b) also shows that the enhancement of E_c due to FE are 1.35, 1.63, 1.76 and 1.85 GPa for the mixes BACNS10, BACNS15, BACNS20 and BACNS25 respectively at 28 days of curing age. Hence, the E_c due to PE are 2%, 19%, 26% and 29% greater than the PE of RHA for the mixes BACR10, BACR15, BACR20 and BACR25 respectively at 28 days of curing age. Therefore, from the above discussion it can be concluded that at 28 days the E_c of BAC due to PE increased significantly than the FE of RHA up to 25% replacement.

4.14. The PE of RHA on Poisson's ratio (ν) of BAC

The PE of RHA on ν of BAC was evaluated to learn about the comparative performance of PE and FE of RHA on ν in BAC. Experimental values of ν with RHA and NS are presented in Fig. 8(a). The figure indicates that the ν of BACR10 is 0.359 and ν of BACNS10 is 0.263 at 28 days of curing age. Therefore, the increase in ν due to pozzolanic reaction of RHA at 28 days of curing age is calculated from the difference between ν of BACR10 and BACNS10. The calculated value is 0.096 (0.359–0.263), which is induced by pozzolanic reaction of RHA. Fig. 8(b) shows all of the PE of RHA on ν of BAC for different replacement level after 28 days curing age.

Fig. 8(b) reveals that ν due to pozzolanic reaction of the RHA increases with increasing RHA content up to 25%. The maximum ν due to pozzolanic reaction of the RHA exhibited for 25% RHA replacement with cement. The maximum increment of ν of BAC due to pozzolanic reaction of RHA was 0.221 at 28 days of curing age. The increase in ν of BAC due to pozzolanic reaction of RHA may be obtained for the production of additional C–S–H gel, which can participate to increase elastic properties of concrete. Similarly, Noaman et al. [13] stated that, the use of RHA in concrete can lead to increase in elastic properties of concrete, as a result, the ν of BAC containing RHA increases.

4.15. The FE of RHA on Poisson's ratio (ν) of BAC

The FE of RHA on ν of BAC was evaluated to find the comparative performance of PE and FE of RHA on ν in BAC. Fig. 8(a) presents the theoretical and experimental values of ν due to cement replacement by NS. Fig. 8(a) shows that the ν of BAC containing 100% OPC (0% NS) is 0.215 at 28 day. Thus the ν for 90% available cement should be $0.215 \times 90\% = 0.194$ and the experimental value (BACNS) of BAC with 10% NS was 0.263. For example, the differences in ν between the experimental value of BACNS10 and the theoretical value of 90% OPC concrete is $0.263 - 0.194 = 0.070$ at 28 days curing. All of the results are shown in Fig. 8(b), which represent the increase in ν of BAC due to FE of RHA after 28 days curing. It also clearly shows the additional ν achieved by the FE with no chemical contribution of NS involved. Moreover, Fig. 8(b) reveals that the RHA have a tendency to increase ν gradually with increase in the amount of cement replacement level which may be due to the FE of RHA. The maximum increment of ν of BAC due to FE of RHA was found 0.126 for 25% replacement of cement at 28 days of curing. Therefore, it can be concluded that the RHA particles contributed to increase the ν of BAC by the FE at 28 days curing.

4.16. Comparative study of PE and FE of RHA on ν of BAC

Fig. 8(b) shows that the enhancement of ν due to pozzolanic reaction were 0.096, 0.150, 0.183 and 0.221 for the mixes BACR10, BACR15, BACR20 and BACR25 respectively at 28 days of curing age. On the other hand, Fig. 8(b) also indications the development of ν in BAC due to FE of RHA was 0.070, 0.090, 0.106 and 0.126 for the 10%, 15%, 20% and 25% replacement of NS respectively at 28 days of curing. Hence, the ν due to PE were 27%, 40%, 42% and 43% more than the FE of RHA for the mixes BACR10, BACR15, BACR20 and BACR25 respectively at 28 days of curing age. Therefore, from the above discussion it can be inferred that at

28 days the ν of BAC due to the PE increased significantly than the FE of RHA up to 25% replacement.

4.17. Microstructure of BAC with RHA

The SEM analysis was conducted to scrutinize the microstructural condition of BAC with 0–25% RHA as a partial replacement of cement. The microstructural studies of BACR were conducted by SEM observation which is shown in Fig. 9. Fig. 9 represents the microstructure of BACR0 (control), BACR10, BACR15, BACR20 and BACR25 at w/b ratio of 0.50 after 28 days curing. The microcracks observed in some specimens are primarily due to artifacts during the specimen preparation process and hence, may not be given much attention. Fig. 9(a) shows that the control concrete was characterized by large number of pores in its matrix, with significantly large-sized and numerous unhydrated cement grains. On the contrary, the BACR10 specimens are identified by Fig. 9(b) that could be characterized by denser paste with very minimal porosity and fewer unhydrated cement grains compared to control concrete. A comparison among Fig. 9(a), (b) and (c) containing 0%, 10% and 15% RHA respectively indicates that the presence of RHA contributes to achieving the lower internal porosity (created by the RHA grains), total porosity and unhydrated cement grains compared to the control concrete. It also presents that refined microstructure is due to good PE and FE of RHA particles. This result shows a good agreement with mechanical properties (f'_c , f_{sp} , E_c and ν) of BACR. In addition, comparison between Fig. 9(a) and (b) indicates that the presence of pores and unhydrated cement grains decreases with increasing percentage of RHA.

Again, a comparison among Fig. 9(a), (d) and (e) containing 0%, 20% and 25% RHA respectively indicates that the presence of RHA contributes towards achieving little internal porosity (created by the RHA grains) and less unhydrated cement grains compared to the control concrete. However, BACR25 indicates that the presence of RHA adds little internal porosity (created by the RHA grains). As there is no unhydrated cement grains compared to the control concrete, it creates well refined and dense cementitious matrix. Even somewhere it shows failure of microstructure. Up to 15% cement replacement level, BACR shows a dense and homogeneous microstructure due to both PE and FE. Karim et al. [10] reported that the presence of RHA in mortar and concrete provides a significant microstructural changes due to its PE and FE. Earlier, Zhang et al. [15] reported that the addition of RHA was found to improve both hydration and microstructure of this zone, in which the porosity and the $\text{Ca}(\text{OH})_2$ amount is reduced, so does the thickness of this zone, compared to that in the Portland cement paste. Up to 20% cement replacement level, BACR shows a dense and homogeneous microstructure because of both PE and FE. But the internal bonding of particles collapsed due to addition of higher RHA replacement. From the above discussion, it is hypothesized that the fine RHA grains present in the BAC would have completely took part in the pozzolanic reaction to form C–S–H gel given the amorphous silica content of RHA particles.

5. Conclusions

The major findings of the research are summarized below for a constant mix ratio of 1:1.5:3 and water-to-binder ratio of 0.50:

- The RHA used in this study is similar to Class F pozzolan and exists in an amorphous form that contained certain amounts of crystalline silica as quartz phase. Also, the mean particle size of RHA decreases with increase in grinding time.
- SAI of RHA shows a significant PE and FE on BAC up to 25% replacement of cement than the minimum requirement of 75% (SAI) after 28 days of curing.
- At 28 days, the rates of development of f'_c of BAC due to FE are 58.56–94.62% are found lower compared to the PE of RHA for the

10%–25% replacement. The 15% RHA shows the maximum f'_c of BAC due to PE which is better compared to the FE of RHA.

- The rates of development of f_{sp} due to PE are 60%–150% are higher compared to the FE of RHA for the 10%–25% replacement after 28 days of curing. Also, the 15% RHA shows the maximum f_{sp} of BAC as 0.35 MPa due to PE which is larger compared to the FE of RHA.
- After 28 days, the increments of f_r due to PE are 25%–150% higher than that of FE of RHA for the 10%–25% replacement. Also, the 15% RHA shows the maximum f_r of BAC as 0.14 MPa due to PE which is greater than the FE of RHA.
- After 28 days, the E_c of BAC increases by 2%–29% due to the PE compared to the FE of RHA with replacement of cement by 10%–25%. The 25% RHA shows the maximum E_c of BAC due to PE that is higher than the FE of RHA.
- Poisson's ratio (ν) increases 27%–43% due to PE compared to the FE of RHA with increasing RHA by 10%–25% after 28 days of curing. However, BAC containing 25% RHA shows the maximum ν due to PE that is greater than the FE of RHA.
- Up to 20% cement replacement level, BAC with RHA shows a dense and homogeneous microstructure that may be due to both PE and FE after 28 days of curing.

Declarations

Author contribution statement

Md Abu Noaman: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Md. Rezul Karim, Md. Nazrul Islam: Conceived and designed the experiments; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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