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ARTICLE

Effects of the tensile strength and elastic modulus of low-strength brick aggregate concrete on the ultimate shear strength of short reinforced concrete columns

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Abstract
Ultimate shear strength of reinforced concrete columns made with low-strength brick aggregate concrete (BAC) is estimated using Mohr's circle and relevant failure criterion. Compressive tests and splitting tensile tests on concrete cylinders show that the material properties of BAC are distinctly different from those of stone aggregate concrete (SAC). In contrast to the well-known dependence between the splitting tensile strength and the square root of the compressive strength of concrete, a linear relationship between the splitting tensile strength and the compressive strength is proposed for BAC. The splitting tensile strength of BAC was lower than that of SAC of the same grade when the concrete compressive strength was below 25 MPa. Independent of the concrete strength, the elastic modulus of BAC was 70% of that calculated with the ACI code equation and 50% of that of SAC of the same grade. Twenty-six column specimens under constant vertical and cyclic horizontal loads are cited from a preliminary report of this research group (see Kabir et al. (2020)) for comparison with the estimated shear strength. A column specimen made with 13.0 MPa BAC exhibited a lower shear strength than that made with a similar grade of SAC. In the 22–23 MPa compressive strength range no distinct difference was observed. The difference in the tested shear strength originates from the distinct differences in the elastic modulus and splitting tensile strength.

KEYWORDS
brick aggregate concrete, column shear strength, compressive strength, elastic modulus, Mohr's circle, splitting tensile strength, stone aggregate concrete

1 | INTRODUCTION

The scarcity of natural rocks in the recent deltaic deposits of Bangladesh[1] and India necessitated the use of crushed bricks as coarse aggregates in past concrete constructions.[2–5] Surprisingly, a direct field survey conducted by Japan International Cooperation Agency[6] revealed that reinforced concrete (RC) buildings constructed between 1960 and 2006

Discussion on this paper must be submitted within two months of the print publication. The discussion will then be published in print, along with the authors' closure, if any, approximately nine months after the print publication.

and made with low-strength brick aggregate concrete (BAC) are widely distributed in Bangladesh. Nakajima et al.[7] found that the concrete compressive strength (f'_c) of 44% of the cores taken from 20 buildings in Dhaka was below 10 MPa. However, the structural load bearing elements of these building stocks must perform adequately not only under vertical loads but also under lateral seismic loads due to the anticipated risks of seismic events in the vicinity of moderately active tectonic faults.[8–11] Unfortunately, in contrast, Bangladesh has had catastrophic building collapses in recent history under only vertical loads (Miller[12] for 2005 Spectrum Sweater Factory collapse, Yardley[13] for 2013 Rana Plaza collapse) due to poor construction quality with BAC. Even though the Bangladesh construction industry can transition toward better construction practices with SAC using imported stone aggregates, the significant stocks of old RC construction from BAC demand a thorough performance assessment for disaster risk mitigation.[6]

Previous studies on BAC and its effects on structural performance were generally performed for f'_c above 15 MPa. Several studies revealed significant differences in fundamental material properties,[14,15] axial behavior[4,16] and flexural behavior[3] compared with those of SAC. In this context, the legacy paper from Akhtaruzzaman and Hasnat[2] on BAC between 13.8 and 35 MPa can be cited. Their conclusions on the difference between BAC and SAC in terms of modulus of elasticity, E_c (30% lower for BAC), and splitting tensile strength, f_t (11% higher for BAC), were drawn by considering only the data points above 15 MPa. Moreover, the uniqueness of the f_t of BAC was not derived from direct comparisons of test results of samples of BAC and SAC but was instead derived from test results of BAC and the value of SAC calculated using the ACI equations.[17] In the 30–60 MPa range, Mansur et al.[5] reported a higher f_t for BAC than for SAC. Furthermore, Akhtaruzzaman and Hasnat[18] studied the shear strength of RC beams made with BAC with an f'_c value of 13–40 MPa and found tested shear strength ($\tau_{\max}$) to be higher than that predicted by the 1983 ACI Building Code[17] developed for SAC. Islam et al.,[4] Choudhury et al.[16] and Hasnat et al.[3] later studied the performance of structural members made with BAC with an f'_c value above 20 MPa. Recently, Mohammad et al.[19,20] studied the shear and flexural behavior of RC beams made with recycled BAC. However, the mechanical properties of low-strength BAC samples and their influence on structural performance have never been discussed.

Shear strength is one of the most important indicators of the performance of structural members, particularly columns that are under lateral loads while simultaneously bearing large vertical loads. In a recent communication, Pujol et al.[21] utilized Mohr–Coulomb failure criterion to calculate the ultimate shear capacity τ_{ul}(computed ultimate shear strength divided by the cross-sectional area of the concrete core of columns). Their approach was mentioned by them to be too conservative for columns under high axial stress ($>0.4f'_c$) with small transverse reinforcement ratio ρ_w values, which is typical for older BAC columns. An equation was proposed for shear strength estimation with low-quality column members,[22] but they mainly pertain to SAC. Kabir et al.[23] recently validated the applicability of this equation for a lower bound of tested shear strength, $\tau_{\max}$, but the origin of their observations related to material strength parameters was not studied there.

This study is the first attempt to estimate the $\tau_{\max}$ of low-strength short BAC column specimens by considering f_t and E_c as the fundamental material properties. To do this, f_t and E_c of BAC and SAC were obtained from cylindrical concrete specimens in the 5–40 MPa f'_c range. The results were correlated with the τ_{ul} values of columns specimens. In this process, Mohr's circle[24] and related failure criterion were adopted to link the material properties and structural behavior using a similar method proposed by Pujol et al.,[21] Hibino and Yamaki,[25] and Hanai et al.[26] Figure 1 illustrates the fusion process. The elastic modulus E_c and splitting tensile strength f_t are the parameters used to describe the size and position of Mohr's circle. After reaching the failure criterion in tension, f'_t, the corresponding ultimate shear strength τ_{ul} is obtained and is examined by comparing with the test results of the BAC and SAC column specimens.

2 | COMPRESSIVE STRENGTH AND SPLITTING TENSILE STRENGTH

2.1 | Test plan

Two series of tests were performed at the Concrete Laboratory of Bangladesh University of Engineering and Technology. In the first series, compressive tests and splitting tensile tests were performed on BAC and SAC cylinder specimens with a 10–40 MPa target f'_c using a compressive testing method ASTM C39/C39M-03[27] and a splitting tensile testing method ASTM C496/C496M-04,[28] respectively. In the second series, stress–strain curves were obtained from the same stock of ingredient materials. A very slow loading rate (~0.15 MPa/s) was chosen for each of the tests.

Specimens with diameters of 100 mm and heights of 200 mm were cast and cured for 7–60 days. Well burnt clay bricks with an average crushing strength of 28.2 MPa and 18.4% absorption capacity, meeting the BDS 208[29] specifications for Grade A bricks, were crushed, sieved, and washed before they were used as the

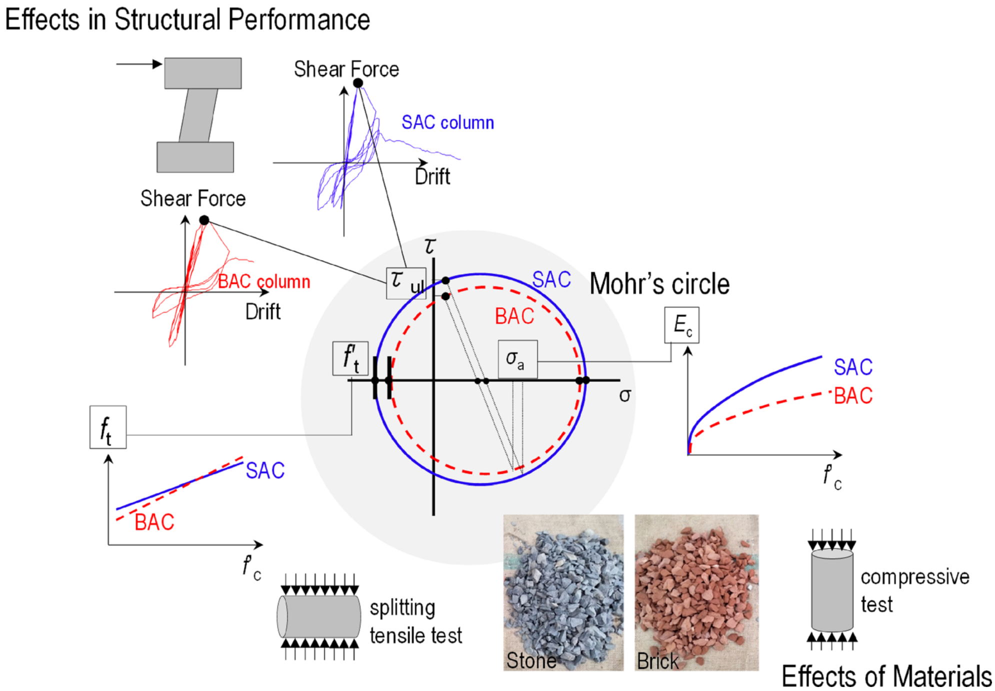


FIGURE 1 Schematic representation of the effect of materials on the structural response seen as the computed ultimate shear strength, τ_{ul}.

TABLE 1 Mixing proportions of the BAC and SAC samples

Target strength and type of coarse aggregate	Mixing proportions (w/w) Cement	FA[a]	CA[a]	VFFS[a]	Water/cement ratio
10 MPa BAC	1	2.22	4.44	0.11	0.85
10 MPa SAC	1	2.11	4.22	0.05	0.80
20 MPa BAC	1	1.5	3	-	0.70
20 MPa SAC	1	1.5	4	-	0.63
30 MPa BAC	1	1.25	2.5	-	0.48
30 MPa SAC	1	1.25	2.5		0.48
40 MPa BAC	1	1.15	2.3		0.45
40 MPa SAC	1	1.15	2.3		0.45

Abbreviations: BAC, brick aggregate concrete; FA: fine aggregate, CA: coarse aggregate; SAC, stone aggregate concrete; VFFS: very fine fraction of sand.
[a]Coarse aggregates of sizes 19–25 mm: 12–19 mm: 6–12 mm, 1.24 : 1.67 : 1 are used; see also Table 2 of Reference [4] conducted in same laboratory, VFFS can pass through a 200 μm sieve.

coarse aggregate of BAC. Natural stones collected from quarries were used as the stone aggregate of SAC. Sylhet sand was used as the fine aggregate in both the SAC and BAC. A very fine fraction of sand (VFFS, smaller than 200 μm sieve) was used in BAC to simulate the limitations of the past construction processes in Bangladesh resulting in low-strength concrete, for example, improper washing of aggregate or use of turbid water.

2.2 | Mixing proportions

The mixing proportions of the concretes are outlined in Table 1. The target f'_c values were 10, 20, 30, and 40 MPa. To obtain a 10 MPa grade of BAC and SAC with a sufficient slump, VFFS were added.

2.3 | Relationship between f'_c and f_t

The compressive strength, $f_c{}'$, and splitting tensile strength, f_t, of the same batch of specimens were correlated, as shown in Figure 2 with two relationships. Each data point represents the average of three specimens. Figure 2a shows the linear dependence of f_t on $\sqrt{f'_c}$. The relationships between f_t and $\sqrt{f'_c}$ were noticeably different for BAC and SAC (R^2 of 0.89 for BAC and 0.83 for SAC) at $\sqrt{f'_c}$ values above and below 5. Up to a $\sqrt{f'_c}$

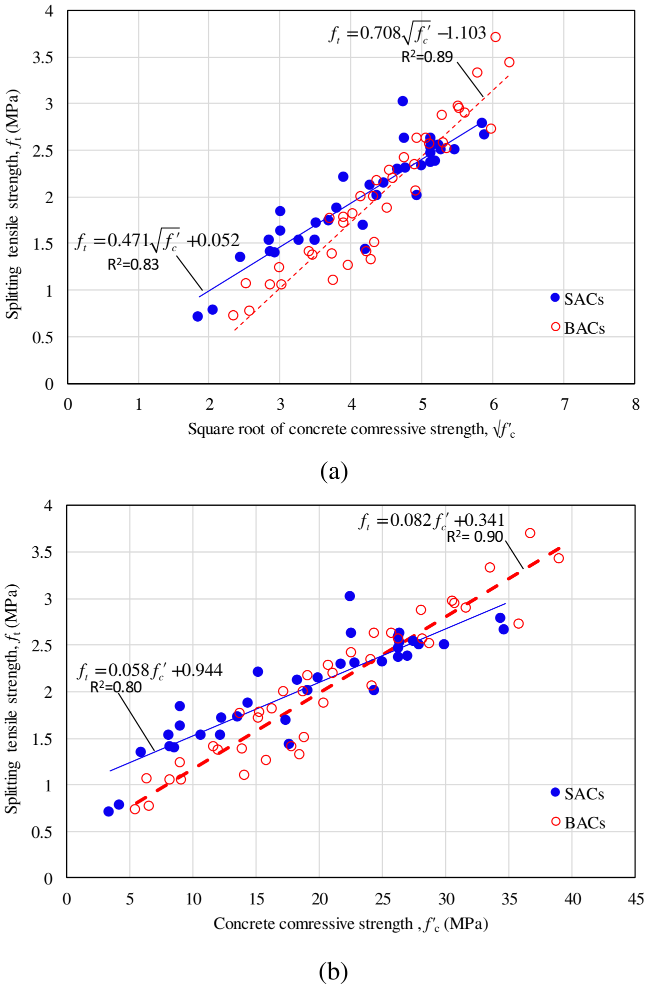


FIGURE 2 Relationships between compressive strength and splitting tensile strength observed from experiments. (a) Relation between f_t and $\sqrt{f_c'}$. (b) Relation between f_t and f_c'.

value below 5, the f_t of BAC was lower than that of SAC, while a reverse trend was seen above a $\sqrt{f_c'}$ value of 5. However, this striking observation of a lower f_t for BAC than for SAC for f_c' values below 25 MPa is missing in the legacy data available from Akhtaruzzaman and Hasnat.[2] Their observation, f_t of BAC being 11% higher than that of SAC, is based on a partial data set from BAC with an f_c' of 24 MPa and higher, which limits the applicability of the findings to low-strength BAC. Another finding of Mansur et al.[5] is in agreement for f_c' values above 25 MPa, but no data were reported for f_c' values below 25 MPa, an obvious shortcoming with respect to the current studies. However, the f_t of BAC was found to be higher than that of SAC for f_c' values of 30–60 MPa, in agreement with the data set presented here and with those available from Akhtaruzzaman and Hasnat.[2]

Figure 2b shows the linear dependence of f_t on f_c' (R^2 of 0.90 for BAC and 0.80 for SAC). A comparison between Figure 2a, b and the corresponding R^2 values suggested a more confident fit in f_t versus f_c' relation for BAC but a more confident fit in f_t versus $\sqrt{f_c'}$ for SAC. In addition, all BAC plots with $\sqrt{f_c'}$ value below 3.5 on Figure 2a lie above the regression line, therefore, the regression line is not suitable for the estimation of f_t on low strength BAC. On the other hands, the BAC regression line on Figure 2b is intermediate of such low strength BAC plots. This important observation of the current study motivated the authors to use f_c' as an alternative horizontal axis instead of the widely used $\sqrt{f_c'}$, as shown in Figure 2b. Although further fundamental studies are needed, in this paper, f_c' is used instead of $\sqrt{f_c'}$ to estimate f_t for BAC. The authors use the well-justified term $\sqrt{f_c'}$ in estimations for SAC. According to the discussion herein and the regression line of the corresponding plots, the f_t values of the SAC and BAC samples were estimated by Equations (1) and (2), respectively.

$$f_{t,SAC} = 0.471\sqrt{f'_{c,SAC}} + 0.052 \tag{1}$$

$$f_{t,BAC} = 0.082 f'_{c,BAC} + 0.341 \tag{2}$$

2.4 | Stress–strain behavior and elastic modulus

The stress–strain responses in the compressive tests on four BAC (named B1, B2, B3, and B4 in descending order of the target f_c') and four SAC (named S1, S2, S3, and S4 in descending order of the target f_c') specimens are shown in Figure 3a. The changes in E_c with respect to f_c' for BAC and SAC are compared in Figure 3b. Two points on the stress–strain curve at a strain of 50×10^{-6} and one-third of the maximum strength f_c' are taken, and the slope between those two points is defined as E_c.[30] The SAC specimens have a higher elasticity than BAC specimens with a similar f_c', for example, comparisons of the S2 versus B1, S3 versus B2 and S4 versus B3 responses (Figure 3b). In each of the cases, $E_{c,BAC}$ is approximately half (50%) of $E_{c,SAC}$ (see Figure 3b). A similar trend was found in the study by Akhtaruzzaman and Hasnat,[2] with f_c' values between 24 and 34.5 MPa. They concluded that $E_{c,BAC}$ is approximately 30% lower than $E_{c,SAC,ACI}$ calculated from the ACI 318–77 equation, which is shown in Equation (3a). Then, Equation (3b), used to calculate $E_{c,BAC}$, is proposed (the authors modified the factor of Equation (3b) to be in SI units).

$$E_{c,SAC,ACI} = 4700\sqrt{f_c'} \tag{3a}$$

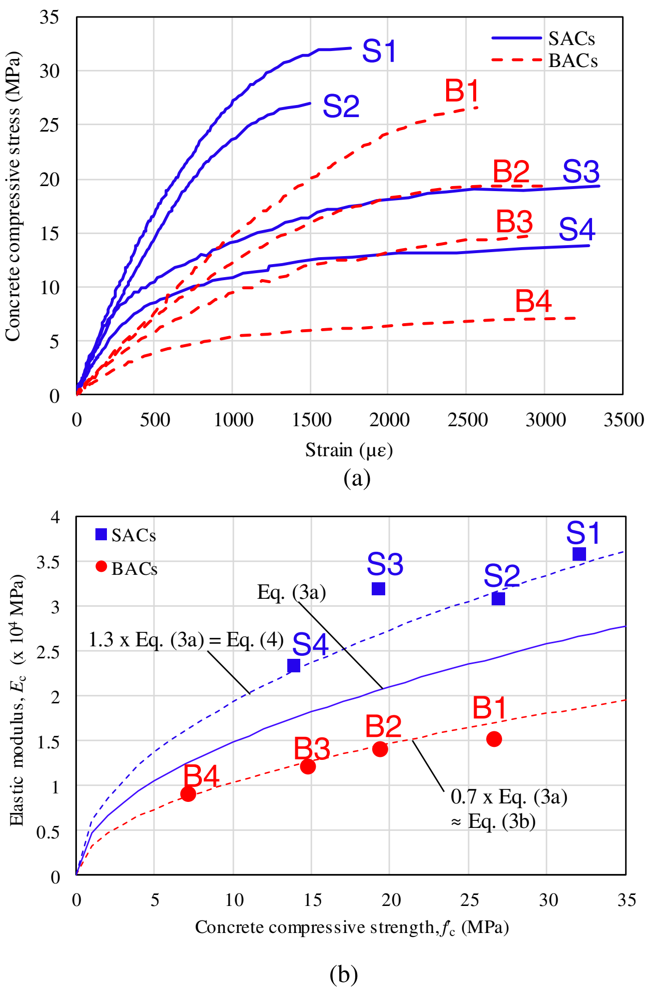


FIGURE 3 Stress–strain responses and elastic modulus seen for grades of brick aggregate concrete (BAC) and stone aggregate concrete (SAC) in experiments. (a) Stress–strain responses. (b) Variation of E_c with f'_c.

$$E_{c,BAC} = 3323\sqrt{f'_c} \tag{3b}$$

To see the consistency of the observed results, predictions from Equation (3a) and Equation (3b) are plotted in Figure 3b to show the fits for SAC and BAC, respectively. The E_c values of the above-mentioned eight typical specimens were also compared with predictions from Equations (3a) and (3b) in Figure 3b. This 30% lower boundary of $E_{c,SAC,ACI}$ from Equation (3a) shows good agreement with the BAC test results, even in the low-strength concrete zone. This firmly supports the applicability of the Akhtaruzzaman and Hasnat[2] equation in the low-strength concrete zone. Regarding $E_{c,SAC,ACI}$, Equation (3a) underestimates the test results for $E_{c,SAC}$ by 30%, as seen from the upper line of the plot in Figure 3b, because Equation (3a) is an equation for design (as Vakhshouri[31] reported, the ACI equation tends to underestimate the tested $E_{c,SAC}$). According to the results presented here, the use of Equations (4) and (3b) for the estimation of mean $E_{c,SAC}$ and $E_{c,BAC}$, respectively, appears to be realistic and justifiable:

$$E_{c,SAC} = 1.3 \cdot 4700\sqrt{f'_c} \tag{4}$$

3 | BEHAVIOR OF COLUMN SPECIMENS UNDER LATERAL LOADS WITH A SUPERIMPOSED VERTICAL LOAD

3.1 | Test plan

The material properties of concrete are not only discernible from the structural response observed in the tests but also need to be adequately addressed with a modified assessment procedure if the experimental evidence demands it. To this end, tests on 22 BAC and four SAC column specimens were carried out. A preliminary report from this research group can be found in Kabir et al.[23] Scaling in cross-sectional dimensions was avoided to eliminate obscurity due to the scale factors of the specimens of less-studied BAC. The column specimen dimensions were 240 mm × 240 mm, similar to those generally encountered in studies performed in Bangladesh (Project for Capacity Development on Natural Disaster Resistant Techniques of Construction and Retrofitting for Public Buildings).[32,33] The clear height was 480 mm (Figure 4a), so a short column with a shear span-to-effective depth ratio of 1.17 could be simulated in the tests. The geometric details of the 26 specimens are mentioned in Table 2. The longitudinal reinforcements and transverse reinforcements were 16 and 6 mm diameter deformed bars, respectively. The f_c' of the BAC columns ranged from 8.5 to 37.9 MPa and that of the SAC columns ranged from 13.0 to 40.3 MPa. The same mixing proportion and the same batch of materials are used in both the cylindrical test (previous section) and structural test (this section). The transverse reinforcement ratio ρ_w was kept low (0.11%–0.33%) to replicate the conditions found in Bangladesh field surveys under CNCRP.[32] Specimens were first loaded to the designated axial load and then subjected to sequences of horizontal cyclic loading according to the loading protocol shown in Figure 4b. The loading system designed to reproduce the double curvature on the column is shown in Figure 4c. Further details are available in the corresponding study by Kabir et al.[23] Four of the tested specimens after failure are shown in Figure 4d–g.

The test results for the maximum shear loads (Table 2) sustained by the 22 column specimens of BAC

TABLE 2 Specimen information

Specimen	Transverse reinforcement ratio, ρ_w (%)	Coarse aggregate	Testing day $f_c{}'$ (MPa)	Axial load (kN)	Axial load ratio	Maximum shear load (kN)
B10BD01 (0.1)	0.11	Brick	8.5	340.6	0.70	106.7
B15BD02 (0.1)	0.11	Brick	14.8	340.8	0.40	139.7
B25BD03 (0.1)	0.11	Brick	29.6	340.6	0.20	161.4
B30BD04 (0.1)	0.11	Brick	34.1	339.8	0.17	157.5
B10BD05 (0.2)	0.22	Brick	10.0	342.1	0.59	117.5
B15BD06 (0.2)	0.22	Brick	15.6	341.9	0.38	151.2
B25BD07 (0.2)	0.22	Brick	29.5	340.1	0.20	180.0
B30BD08 0.2)	0.22	Brick	37.9	340.9	0.16	163.9
B15BD09 (0.2)	0.22	Brick	15.3	339.8	0.39	147.5
B10BD10 (0.2)	0.22	Brick	14.6	179.8	0.21	108.0
B15BD11 (0.2)	0.22	Brick	14.8	182.8	0.21	128.4
B10BD12 (0.1)	0.11	Brick	11.2	180.9	0.28	87.1
B15BD13 (0.1)	0.11	Brick	14.2	187.0	0.23	108.5
B15BD14 (0.1)	0.11	Brick	17.7	179.9	0.18	129.2
B25BD15 (0.1)	0.11	Brick	30.5	180.7	0.10	166.3
B10BD16 (0.1)	0.11	Brick	12.3	187.0	0.26	116.0
B10BD17 (0.1)	0.11	Brick	10.1	338.1	0.58	96.7
B15BD18 (0.1)	0.11	Brick	14.2	340.9	0.42	119.7
S20BD19 (0.2)	0.22	Stone	20.5	181.0	0.15	139.5
B20BD20 (0.1)	0.11	Brick	22.2	340.8	0.27	139.1
B20BD21 (0.2)	**0.22**	**Brick**	**23.9**	**344.4**	**0.25**	**166.3**
B20BD22 (0.2)	0.22	Brick	23.0	179.8	0.14	144.0
S20BD23 (0.2)	**0.22**	**Stone**	**22.2**	**340.1**	**0.27**	**176.7**
S40BD24 (0.1)	0.11	Stone	40.3	186.0	0.08	181.8
S10BD25 (0.3)	**0.33**	**Stone**	**13.0**	**441.3**	**0.59**	**170.2**
B10BD26 0.3)	**0.33**	**Brick**	**13.0**	**441.9**	**0.59**	**139.7**

Note: The bold font denotes the specimens discussed for comparison.

and four column specimens of SAC show a gradual, consistent and general increase in load capacities with the increase in ρ_w and $f_c{}'$.[23] However, a comparison between the BAC and SAC results indicates distinct dissimilarities in the recorded capacities, even with the same geometry and steel reinforcements. This difference must originate from the characterizable difference in the SAC and BAC performance over the investigated f_c' ranges. The following subsections focus on this topic.

3.2 | Comparisons between SAC and BAC specimens

Two combinations for each pair of specimens were selected from a test database (Table 2, in bold font) constructed by the same laboratory with the same material and test conditions. There was no mentionable difference in the four specimens except for the coarse aggregates (BAC vs. SAC) used in each combination. Specimens B20BD21 (0.2) and S20BD23 (0.2) had similar $f_c{}'$ values (23.9 and 22.2 MPa, respectively), the same ρ_w value (0.22%) and similar applied axial load ratios (0.25 and 0.27, respectively), but the coarse aggregates (brick and stone) were different. Specimens B10BD26 (0.3) and S10BD25 (0.3) had similar $f_c{}'$ values (13.0 and 13.0 MPa, respectively), the same ρ_w values (0.33%) and similar applied axial load ratios (0.59 and 0.59, respectively), but the coarse aggregates (brick and stone) were different (Table 2, in bold font). The load-deflection curves for these four specimens are shown in Figure 5. These specimens exhibited sharp capacity

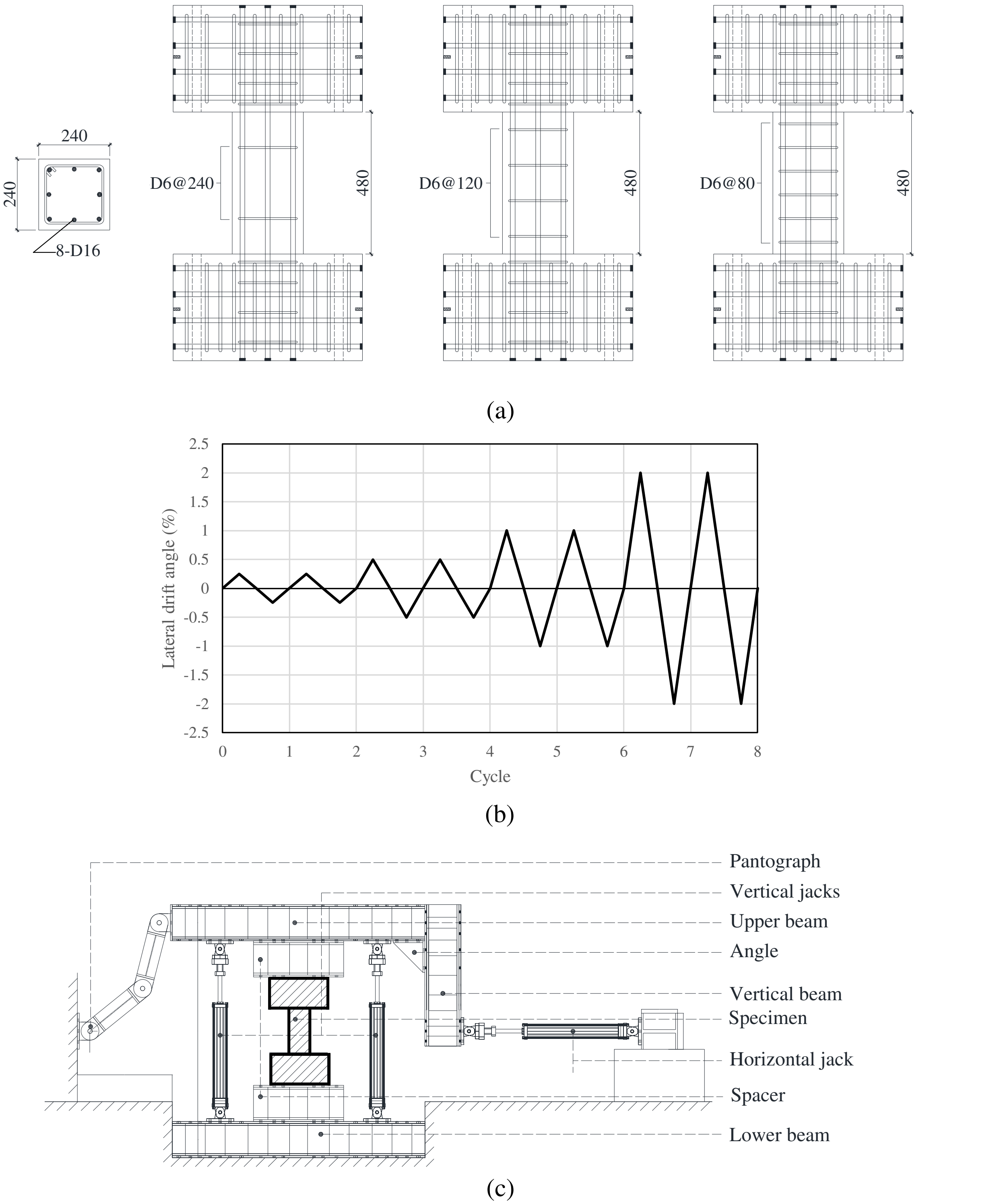
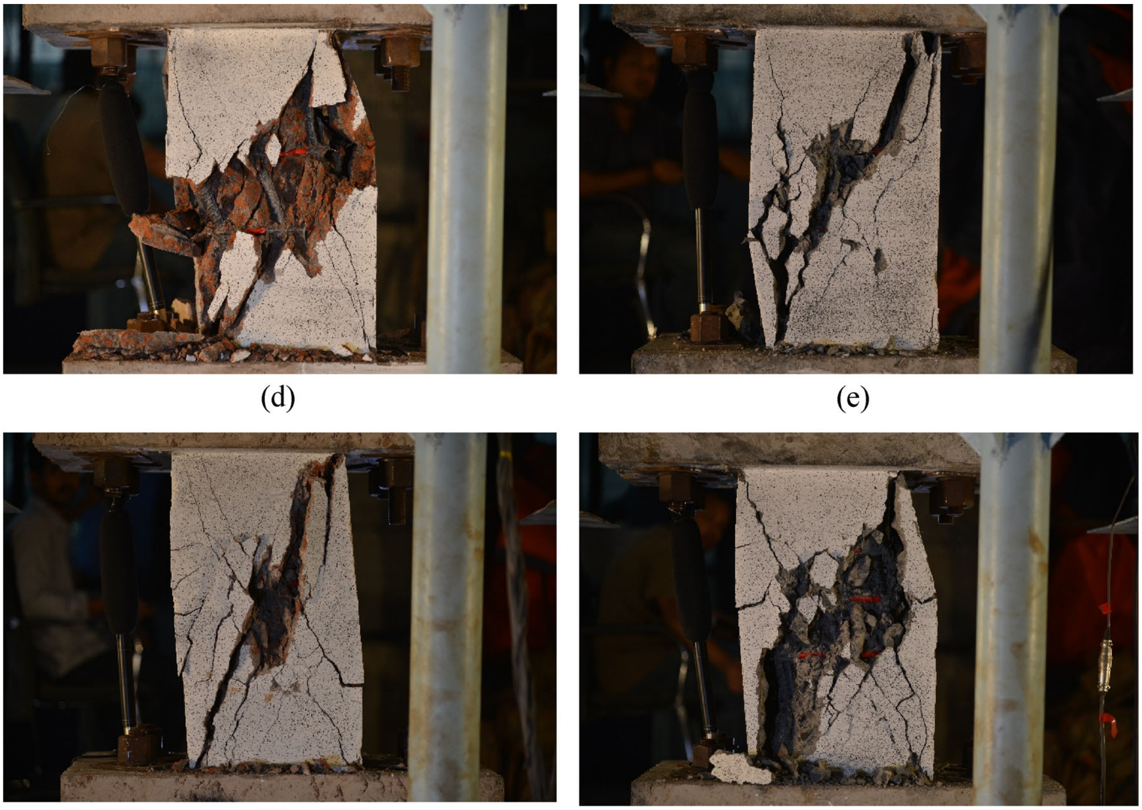


FIGURE 4 Testing of specimens from brick aggregate concrete (BAC) and stone aggregate concrete (SAC). (d–g) Typical failure patterns in tested specimens. (a) Specimen geometry and rebar details. (b) Applied loading history on each of the specimens. (c) Specimen in the test setup as seen in the elevation view. (d) B20BD21(0.2). (e) S20BD23(0.2). (f) B10BD26(0.3). (g) S10BD25(0.3).

deterioration after reaching their maximum capacity due to brittle shear failure.

The tested shear strength $\tau_{\max}$ (observed maximum shear strength normalized by the cross-sectional area of concrete core of the column) is plotted against f_c' in Figure 6a. The difference in the $\tau_{\max}$ values of B20BD21 (0.2) and S20BD23 (0.2) was small; however, a relatively large difference between B10BD26 (0.3) and S10BD25 (0.3) was observed. The BAC specimen with an f_c' of 13.0 MPa (B10BD26 (0.3)) exhibited a distinctly lower



(d) (e) (f) (g)

FIGURE 4 (Continued)

$\tau_{\max}$ than the SAC specimen (S10BD25 (0.3)) with the same $f_c{}'$. The difference in the material properties of SAC and BAC, namely, E_c and f_t, were estimated as main reasons of difference in $\tau_{\max}$. This point is further addressed in the next section.

4 | SHEAR STRENGTH ESTIMATION CONSIDERING THE DIFFERENCES IN MATERIAL PROPERTIES

4.1 | Estimation method

The equation derived from Mohr's circle and relevant failure criterion can consider the effects of differences in properties, for example, f_t and E_c, between BAC and SAC. Although Mohr's circle was developed to estimate the stresses of plain concrete, it has been employed to estimate the shear strength of RC columns and beams in design guidelines (e.g.,AIJ[34]) and recent studies (e.g., Pujol et al., Safi and Hibino[21,35]). The effects of longitudinal and transverse reinforcements were considered by adopting an approach similar to those of Pujol et al.[21] and Hibino and Yamaki.[25] Pujol et al[21] provided simple formulations of mean axial stress σ_a based on several sectional analyses and transverse stress σ_t on column section. From σ_a, σ_t, and a failure criterion, the size and position of the Mohr's circle and corresponding shear stress at the failure (in this paper, τ_{ul}) were determined. In this paper, the ultimate shear strength τ_{ul} was calculated using Equation (5). The mean axial stress of the concrete, σ_a, was calculated using Equation (6), instead of the suggested equation[21] because the equation is derived from the sectional analysis of column made with SAC and may not be applicable for all the specimen here. Pujol et al.[21] assumed $f' = 1/12_t \sqrt{f_c{}'}$ as a failure criterion (failure at the stress circle reaching f_t', as shown in Figure 7a,b) and, Hibino and Yamaki and Hanai et al.[25,26] assumed Equation (7) which provides higher f_t' value than above. In this attempt, Equation (7) was employed because most of the specimens here seemed to reach shear capacity at (or a little later) the appearance of diagonal shear crack where f_t' value did not deteriorates as suggested in the equation $f_t' = 1/12\sqrt{f_c{}'}$. Equations (1) and (2) were used to calculate the f_t values of the SAC and BAC specimens, respectively. Equations (4) and (3b) were used to calculate the E_c values of the SAC and BAC specimens, respectively. The mean transverse stress σ_t was calculated using Equation (8) as well as Pujol et al.[21] Since several parameters of Coulomb's criterion (Limit 1) for low-

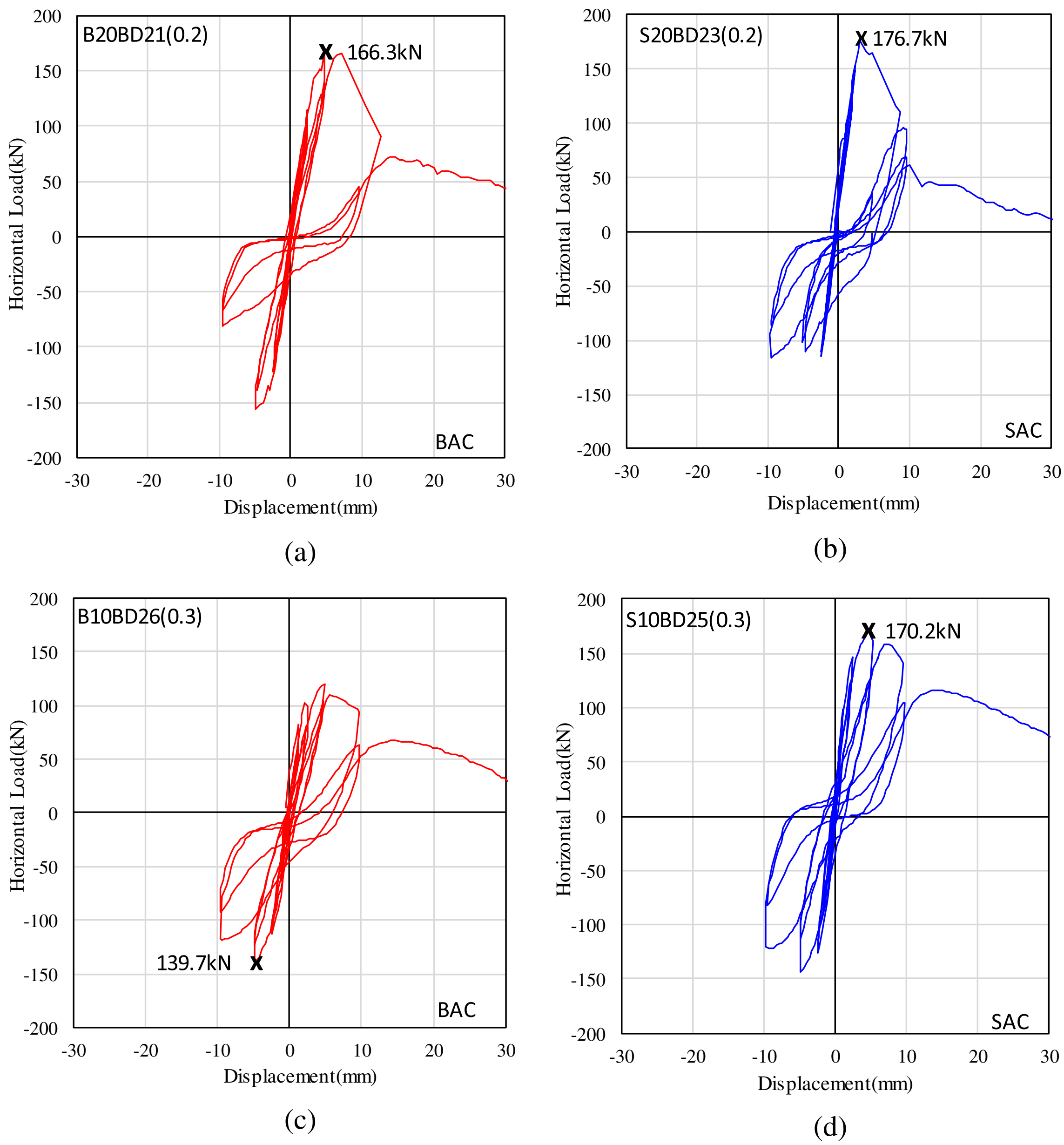


FIGURE 5 Load–deflection curves of four selected specimens. (a) B20BD21(0.2). (b) S20BD23(0.2). (c) B10BD26(0.3). (d) S10BD25(0.3).

strength BAC are unknown, only Limit 2 was considered in this attempt.

$$\tau_{ul} = \sqrt{(\sigma_a + f_t')(\sigma_t + f_t')} \tag{5}$$

$$\sigma_a = \left(\frac{E_c A_c}{E_s A_s + E_c A_c}\right)\frac{P}{A_c} \tag{6}$$

$$f_t' = 0.6 f_t \tag{7}$$

$$\sigma_t = \rho_w \sigma_{wy} \tag{8}$$

where τ_{ul} is the computed ultimate shear strength of a column, σ_a is the mean axial stress on concrete core, E_c and E_s are the elastic modulus of concrete and longitudinal bars ($=2.1 \times 10^5$ MPa), respectively, A_c and A_s are the cross-sectional areas of the concrete core and longitudinal reinforcements, respectively, $f_t{}'$ is the failure criterion in tension, σ_t is the mean transverse stress, ρ_w is the transverse reinforcement ratio, and σ_{wy} is the yield strength of the transverse reinforcement.

4.2 | Estimation of the strength of compatible specimens

The $\tau_{\max}/\tau_{ul}$ (tested/calculated) values of the four specimens are shown in Figure 6b. The $\tau_{\max}/\tau_{ul}$ values of the four specimens made with BAC and SAC ranged from

0.7–0.9. Clearly, the $\tau_{\max}$ values of the BAC columns were estimated in the same accuracy as those of the SAC columns if the differences in f_t and E_c were adequately considered.

As shown in Figure 7, for low-strength BAC specimens, f_t was lower than that of SAC. $E_{c,BAC}$ was approximately half of $E_{c,SAC}$. Considering the difference in E_c, the axial stress, σ_a, was also lower in the BAC than in the SAC specimens; therefore, the diameter of Mohr's circle that reaches the failure criterion f_t' was significantly smaller. As a result, the corresponding τ_{ul} of BAC was lower than that of SAC. When these differences in material properties were considered, the accuracies of shear strength estimations for the BAC and SAC specimens became much more similar, as shown in Figure 6b. The f_t and f_t' of mid-strength ($f_c' \approx 23$ MPa) BAC specimens was very close to that of SAC because its f_c' was close to 25 MPa. Regardless of f_c', $E_{c,BAC}$ was half of $E_{c,SAC}$. Therefore, only the difference in σ_a influenced the diameter and the position of Mohr's circle and the corresponding τ_{ul}. As Figure 7 shows, the difference in σ_a resulted in a minor difference in τ_{ul}, as well as in the tested strength shown in Figure 6a.

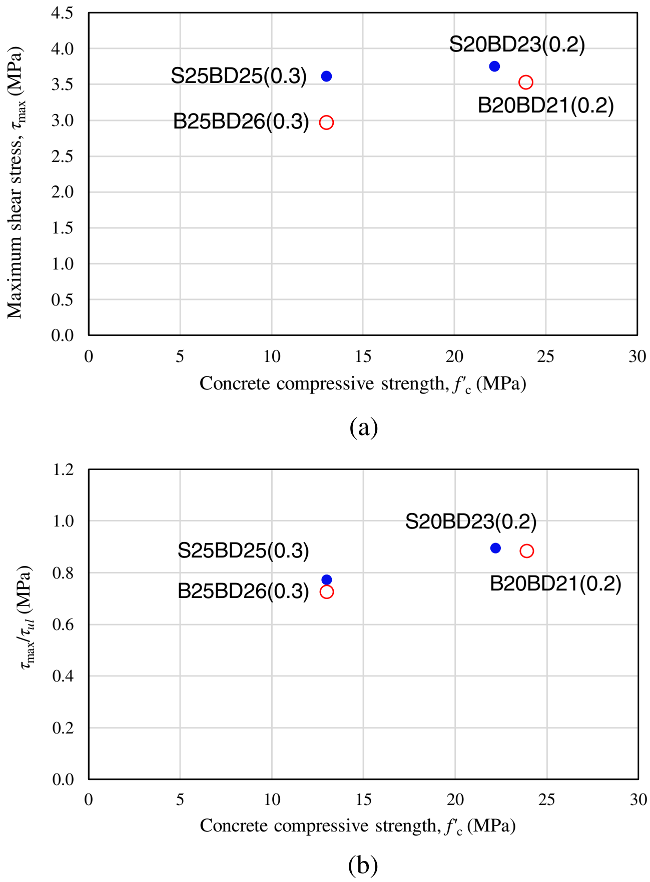


FIGURE 6 Assessment of results obtained from experiments. (a) Normalized tested shear strength (shear stress) $\tau_{\max}$. (b) Accuracy of the shear strength estimation.

4.3 | Performance evaluation for other column specimens

The procedure attempted in this study to calculate τ_{ul} was examined using all 26 specimens reported in Kabir et al.[23]; see also Table 2. Figure 8 shows the $\tau_{\max}/\tau_{ul} \approx 1.0$ values of those specimens along with the transverse reinforcement ratio ρ_w. The observations and findings from Figure 8 are as follows: (1) Reasonable accuracy ($\tau_{\max}/\tau_{ul}$) was achieved for BAC specimens with ρ_w equal to 0.22% or below and f_c' below 25 MPa, which is typical for old existing buildings in Dhaka; (2) SAC specimens were plotted as intermediate ($\rho_w = 0.11, 0.22\%$) or near ($\rho_w = 0.33\%$) the BAC specimens, so the applied procedure could provide similar accuracy for both BAC and SAC; and (3) When ρ_w increases, the $\tau_{\max}/\tau_{ul}$ values of the specimens tend to decrease. Two specimens (one from BAC and the another from SAC) with ρ_w of 0.33% were plotted for $\tau_{\max}/\tau_{ul}$ below 1.0, that is, overestimation is observed. This might be due to Equation (8),

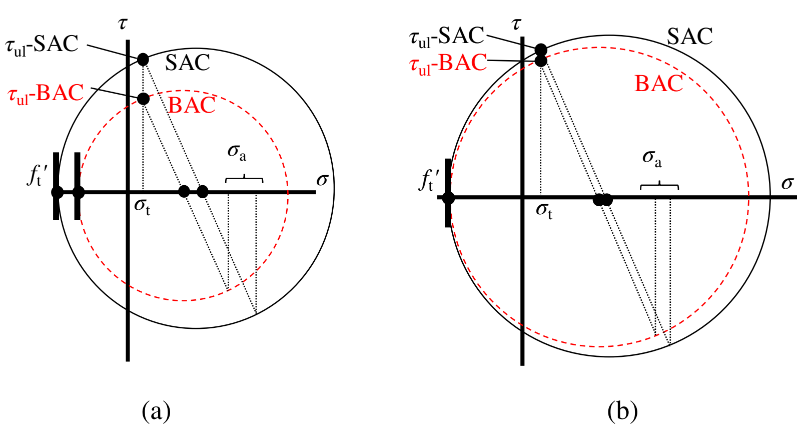


FIGURE 7 Conceptual diagrams of Mohr's circle at the computed ultimate shear strength considering the difference in materials. (a) low-strength ($f_c' \approx 13$ MPa) specimens. (b) mid-strength ($f_c' \approx 23$ MPa) specimens.

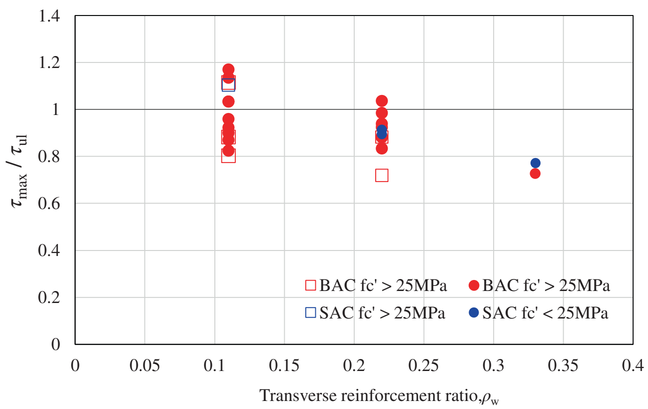


FIGURE 8 Shear strength calculation results for all the specimens

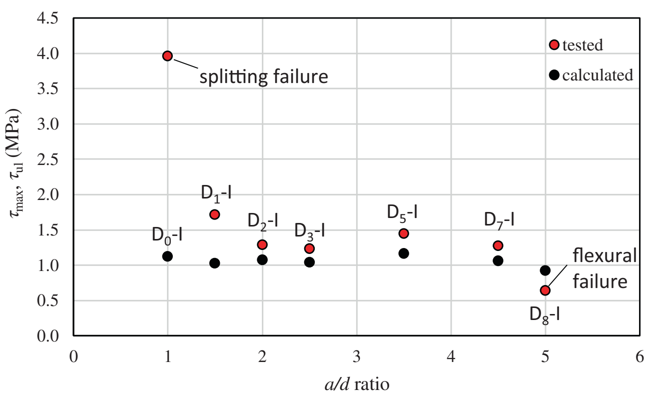


FIGURE 9 Comparison between tested strength (τ_{max}) and estimated strength (τ_{ul}) for the specimens and test results presented in Akhtaruzzaman and Hasnat.[18]

which assumes that all the transverse reinforcements fully develop yield stress. In the specimens with $\rho_w = 0.33\%$, their transverse reinforcements might not fully yield and this may be a reason of the overestimation. Although further studies are needed to address this point, the main objectives of this study were to reasonably estimate the τ_{max} of columns made with low-strength BAC from a fundamental standpoint, which has not been studied previously in detail. From the discussions above, the procedures could estimate the τ_{max} of BAC specimens as well as SAC specimens with ρ_w equal to 0.22% or below and $f_c{}'$ below 25 MPa with reasonable accuracy.

Akhtaruzzaman and Hasnat[18] tested 48 RC beams made with BAC. Eight (the Series D specimens) out of the 48 specimens had identifiable strengths and were used in this examination due to the availability of the full data set. The main test parameter was the a/d ratio (shear span-to-effective depth ratio) of the specimens. The a/d ratio ranged from 1.0 to 5.0, and $f_c{}'$ ranged from 14.01 MPa (2030 psi) to 18.49 MPa (2680 psi). Transverse reinforcement was not provided for these specimens.

The τ_{ul} values of these eight specimens were calculated using Equation (5) considering the BAC properties, and the results are shown with the tested strength in Figure 9. In this comparison, A_c was assumed to be 2/3 of cross-sectional area of the beams for the calculation of τ_{max}. Except for D_0-I and D_8-I, the tested and calculated strengths of these specimens were in reasonable match. Specimens D_0-I and D_8-I had the lowest and highest a/d ratios (1.0 and 5.0, respectively) and are reported to have different failure patterns (splitting failure and flexural failure, respectively). Naturally, the calculated strength did not match when the failure pattern was different. Thus, the shear strength estimation procedure for BAC specimens attempted in this paper exhibited a reasonable accuracy for predicting test results conducted more than 40 years ago in the same laboratory.[15]

5 | CONCLUSIONS

The tested shear strength, τ_{max}, of RC columns made with low-strength BAC and the fundamental material properties, E_c and f_t, were estimated using Mohr's circle. The findings are summarized as follows.

1. The splitting tensile strength, f_t, of BAC was lower than that of SAC of the same grade when the concrete strength was below 25 MPa. Although the square root of the concrete compressive strength, f_c', was generally correlated to f_t for normal-weight SAC, the relationship between f_c' and f_t for BAC identified in this study was predominantly linear.
2. The elastic modulus E_c of BAC was 70% that of the ACI code equation and 50% that of SAC of the same grade.
3. The difference in coarse aggregate properties affected the shear strength of low-strength concrete. Shear strength of columns made with BAC were relatively lower in low f_c' zone, than columns made with the same grade of SAC.
4. The tested shear strength, τ_{max}, of the BAC specimens with low- to mid-strength and a small transverse reinforcement ratio were accurately estimated when different E_c and f_t values were appropriately considered.
5. The attempted procedure was confidently evaluated with previously published results.

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NOTATIONS

A_c,A_s	cross-sectional areas of the concrete core (surrounded by centre lines of transverse reinforcement) and longitudinal reinforcements, respectively
a/d	shear span-to-effective depth ratio
E_c,$E_{c,SAC}$,$E_{c,BAC}$	elastic modulus of concrete, stone aggregate concrete, and brick aggregate concrete
$E_{c,SAC,ACI}$	calculated elastic modulus of stone aggregate concrete using an ACI 318 equation.
$f_c{}'$	concrete compressive strength
f_t	splitting tensile strength
f_t'	failure criterion in tension
ρ_w	transverse reinforcement ratio
$\tau_{\max}$	tested shear strength (normalized by A_c)
τ_{ul}	computed ultimate shear strength (normalized by A_c)
σ_a	axial stress on concrete
σ_t	mean transverse stress
σ_{wy}	yield stress of transverse reinforcements

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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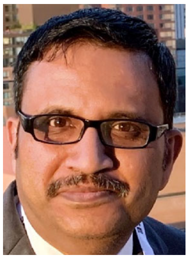

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