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Microstructure of Structural Lightweight Concrete Incorporating Coconut Shell as a Partial Replacement of Brick Aggregate and Its Influence on Compressive Strength

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Abstract: In this study, coconut shell aggregate (CSA) was used in brick aggregate concrete (BAC) to produce structural lightweight concrete. Various BACs containing CSA (CSBACs) were prepared based on the volumetric mix ratio of 1:1.5:3 (cement:fine aggregate:coarse aggregate). CSA was used substituting 0−15% of brick aggregate (BA) by weight. The concrete mixes were designed based on the weight-based water to cement (w/c) ratios of 0.45, 0.50, and 0.55. All the freshly mixed concretes were tested for their workability with respect to slump. In addition, the freshly mixed concretes made with the w/c ratio of 0.50 were examined for their wet density and air content. The hardened concretes were tested for their dry density, compressive strength, and microstructural characteristics (e.g., microcrack, micropore, fissure). The microstructure of CSBACs was investigated by a scanning electron microscope (SEM). In addition, the fissure width between the cement paste and CSA was measured from the SEM images using "ImageJ" software. The correlation between the compressive strength and fissure width of CSBAC was also examined. Test results showed that the air content of CSBACs including 5–15% CSA was higher than that of the control concrete (0% CSA). In addition, the density and compressive strength of concrete decreased with the increased CSA content. Above all, the most interesting finding of this study was the presence of fissures in the interfacial transition zone between the cement paste and CSA of CSBAC. The fissure width gradually increased with the increase in CSA content and thus decreased the compressive strength of concrete. However, the fissure width decreased with the increased curing age of concrete and therefore the compressive strength of CSBAC was enhanced at later ages. Moreover, a good correlation between the compressive strength and fissure width of CSBAC was observed in this study.

Keywords: brick aggregate concrete; coconut shell aggregate; compressive strength; fissure; interfacial transition zone; lightweight concrete; microstructure

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1. Introduction

The costs of building materials are going up gradually. In addition, the amount of waste materials generated from agricultural and industrial sectors is increasing enormously all over the world. Coconut shell (CS) is one among these wastes—it is generated from fully ripe coconuts. Around 62 million tons of coconuts are produced every year in the world, including Bangladesh [1]. CS comprises around 15.6% of the whole fruit [2]. Consequently, about 9.7 million tons of CS are obtained from the coconut fruit per year. The disposal of such a huge amount of CS has become a real problem, which could be alleviated if it can be utilized in producing construction materials. CS can be used in concrete as a partial replacement of conventional coarse aggregate, thus reducing the cost of concrete production and resolving the disposal problem caused by coconut waste.

Many researchers investigated the use of CS aggregate (CSA) in normal-weight concrete [3–9]. Reddy et al. [3] produced several concretes substituting 25%, 50%, and 100% of natural coarse aggregate (NCA) by CSA. The effects of CSA on the workability and strength properties (compressive strength, splitting tensile strength, and flexural strength) of concrete were examined by them. The respective 28-day compressive strength of the concrete mixes with 25%, 50%, and 100% CSA was 22.26 MPa, 14.93 MPa, and 5.48 MPa in their study. They also showed that about 4.45%, 8.90%, and 17.81% of the cost can be reduced for 25%, 50%, and 100% CSA, respectively. Ranjith [4] used CSA as a 100% replacement of conventional granite aggregate in concrete using two sets of mix proportions and conducted tests for compressive strength, flexural strength, and modulus of elasticity. He found the 28-day compressive strength of CSA concretes in the range of 17.73–21.33 MPa. Abubakar and Abubakar [5] incorporated CSA into concrete replacing 100% NCA (gravel) with the volumetric mix ratios of 1:1.5:3, 1:2:4, and 1:3:6 (cement: fine aggregate: coarse aggregate). They showed that about 48% of the cost can be reduced when CSA is used wholly as the coarse aggregate. Moreover, the cube compressive strength at 28 days was found as 16.5 MPa, 15.1 MPa, and 11.0 MPa for these three concrete mixes with 100% CSA. Rajeevan and Shamjith [6] used CSA as 5%, 10%, 15%, 20%, 25%, 30%, and 35% replacements of NCA to produce conventional concretes. They determined the compressive strength, splitting tensile strength, and flexural strength of CSA concretes. In their study, the 28-day compressive strength of CSA concretes was found in the range 20.4–24.6 MPa. They observed that a compressive strength comparable to that of conventional concrete can be obtained using up to 15% CSA. Kamal and Singh [7] produced several normal-weight concretes using CSA as 10%, 20%, and 30% replacements of NCA along with 0% and 20% fly ash as a partial replacement of cement. They tested the concretes for workability, density, and strength properties (compressive strength, splitting tensile strength, and flexural strength). In their study, the 28-day compressive strength was found in the range of 20.12–34.10 MPa for the CSA concretes with 0% fly ash whereas the CSA concretes including 20% fly ash had the compressive strength of 19.58–24.52 MPa. Furthermore, Patel et al. [8] used CSA in several concretes replacing 10%, 20%, and 30% NCA. They also found that the replacement of NCA by CSA up to 20% provided a good compressive strength as compared to conventional concrete. In another study, Mohapatra and Parhi [9] prepared multiple concretes using 5%, 10%, 15%, and 20% CSA in place of NCA. They examined the compressive strength and splitting tensile strength of CSA concretes. In their study, the respective compressive strength at 28 days was 20.67 MPa, 17.22 MPa, 16.04 MPa, and 15.45 MPa for 5%, 10%, 15%, and 20% CSA concretes. All the above studies revealed that a normal-weight concrete with adequate strength can be produced using CSA.

CSA has also been used as a lightweight coarse aggregate to produce structural lightweight concrete (SLWC) [10–13]. In 2008, Gunasekaran et al. [10] made lightweight concretes using 100% CSA as coarse aggregate. For the CSA concretes, they obtained the dry density of 1880–1930 kg/m^3 and the compressive strength of 19.1 MPa at the age of 28 days. In another study, Gunasekaran et al. [11] investigated the physical and mechanical properties of multiple concretes made with CSA. In their study, the density of the CSA concretes at 28 days was less than 2000 kg/m^3 and satisfied the requirement of SLWC [14]. In addition, the 28-day compressive strength values were found as 26.70 MPa and 25.95 MPa for two different concrete mixes made with 100% CSA. Again in 2012, Gunasekaran et al. [12] performed a long-term study on the SLWC made with CSA. They investigated the workability, density, strength properties (compressive strength and bond strength), and microstructural characteristics of CSA concretes. The dry density at 28 days was found as 1970 kg/m^3. They also observed that most of the compressive strength development took place at the early stages although it continued to increase with the increased age of concrete. In addition, Duna and Musa [13] made multiple concretes replacing 10%, 20%, 40%, 60%, 80%, and 100% NCA by CSA. They investigated the effects of CSA on the workability, density, and strength properties (compressive strength and flexural strength) of concrete. In their study, the density and compressive strength of the CSA concretes at 28 days varied in the range of 1407–2065 kg/m^3 and 8.12–19.28 MPa, respectively. Recently, Prakash et al. [15] developed several concretes incorporating 10–30% fly ash along with 50% and 100% CSA. They found that all the concrete mixes fulfilled the density requirement of SLWC, except the 50% CSA mix without fly ash. Furthermore, the concrete mixes with 50% CSA and 10–30% fly ash provided higher workability and strength properties (compressive strength and splitting tensile strength) than all 100% CSA mixes. The above studies infer that SLWC with acceptable strength properties can be made using CSA as a partial replacement of NCA. However, it should be mentioned that none of the above studies used brick aggregate (BA) partially or fully as the coarse aggregate in concrete.

Several studies were performed to produce brick aggregate concrete (BAC) [16–21]. In 1983, Akhtaruzzaman and Hasnat [16] introduced crushed brick as coarse aggregate for use in concrete; the key mechanical properties (compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity) of various BACs were examined in their study. They found the 28-day compressive strength of BACs in the range of 16–38 MPa. Mansur et al. [17] investigated the suitability of using crushed brick as the coarse aggregate in concrete by investigating its basic properties (workability, compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, stress-strain relationship, drying shrinkage, and creep). They produced BACs with a compressive strength ranging from 64 MPa to 72 MPa at the age of 28 days. Cachim [18] produced concretes with crushed brick and investigated their workability, density, and mechanical properties (compressive strength, splitting tensile strength, and modulus of elasticity). They found the 28-day compressive strength of 24.5–32.3 MPa for different BAC mixes. Rashid et al. [19] used BA in concrete replacing 25%, 50%, 75%, and 100% of NCA. They examined the effects of BA on the density and mechanical properties (compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity) of concrete. For different BACs, they obtained the compressive strength of 31.11–45.50 MPa at 28 days. Again, Rashid et al. [20] conducted another study to produce high strength concrete using BA. They examined the density and mechanical properties (compressive strength, flexural strength, and modulus of elasticity) of various BACs. In their study, the respective 28-day compressive strength of BAC was 25.04, 24.63, 19.89, and 18.29 MPa for 25%, 50%, 75%, and 100% replacement of NCA. Furthermore, Noaman et al. [21] investigated the workability and mechanical properties (compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, and Poisson's ratio) of BAC containing rice husk ash as a partial replacement of cement. They found that the compressive strength of BAC at 28 days varied in the range of 21.5–30.9 MPa. It was also observed that some of the BACs produced in the above studies satisfied the density requirement of SLWC given by ACI Committee 213 [14]. However, none of these studies incorporated CSA into BAC as a partial replacement of BA and investigated the effects of CSA on the properties of concrete.

In this study, CSA was used as a partial replacement of BA to produce coconut shell brick aggregate concrete (CSBAC). The workability (slump), wet density, air content, dry density, compressive strength, and microstructure of various concrete mixes including 0–15% CSA were examined. The effect of microstructure on the compressive strength of CSBAC was sought. In addition, the fissure width in the interfacial transition zone (ITZ) of CSBAC was measured. The relationship between the fissure width and compressive strength of CSBAC was also derived.

2. Research Significance

The consumption of CS as coarse aggregate in CSBAC could be a cost-effective solution to the environmental problem caused by coconut waste. The incorporation of CSA reduces the weight of concrete and thus SLWC can be produced using this coarse aggregate. Although the inclusion of CSA decreases the density and compressive strength of concrete, it still possesses adequate strength for many applications. In addition, CSA affects the ITZ of concrete. It has been found that the ITZ of CSBAC includes fissures, which are mainly responsible for the decrease in the compressive strength of CSBAC. The width of fissures increases with a higher CSA content and more decrease in the compressive strength occurs with a larger fissure width. Moreover, a good correlation between the fissure width and compressive strength of CSBAC was observed. These research findings are expected to enrich knowledge on CSBAC.

3. Materials and Methods

3.1. Materials and Their Properties

In this experimental study, crushed CS and brick chips were used as coarse aggregates. BA was partially (0–15%) replaced by CSA. Locally available coarse and fine sands (1:1 by bulk volume) were used as fine aggregates. Normal (ASTM Type I) Portland cement (NPC) was used as the binding material whereas laboratory tap water was used for mixing and curing of concretes.

3.1.1. Coconut Shell Aggregate (CSA)

CS was collected as a dumped waste from Hatiya Island, Noakhali, Bangladesh. The shells were sun dried for 24 h and fibers were removed from the dried shells before being crushed. To make CSA, CS was crushed manually by steel hammers to a size such that it passed through a 19-mm sieve but was retained on a 4.75-mm (No. 4) sieve. The sieved CSA was washed with water for several times and then sun-dried again for 24 h. Some of the sun-dried CSA is shown in Figure 1. Before using in concrete mixes, sun-dried CSA was submerged in water to achieve saturated surface-dry (SSD) condition. Different properties such as gradation, unit weight, moisture content, water absorption, relative density (SSD), aggregate impact value (AIV) and aggregate crushing value (ACV), flakiness index (FI), and elongation index (EI) of CSA were tested according to ASTM C136/C136M [22], ASTM C29/C29M [23], ASTM C566 [24], ASTM C127 [25], IS 2386-IV [26], BS 812-105.1 [27], and BS 812-105.2 [28], respectively.

Figure 1. CSA used in making concrete mixes.

The properties of CSA are presented in Table 1 and the gradation of CSA is shown in Table 2. These tables show that the fineness modulus (FM), SSD relative density, water absorption, unit weight, ACV, and AIV of CSA were 6.77, 1.27, 27.65%, 595 kg/m^3, 0.98%, and 3.84%, respectively. The values of the above properties are comparable to those of preceding studies [5,10,11]. Gunasekaran et al. [11] indicated that the FM, relative density, water absorption, unit weight, ACV, and AIV of CS were 6.26, 1.05, 24%, 650 kg/m^3, 2.58%, and 8.15%, respectively. Furthermore, Abubakar and Abubakar [5] reported that the FI and

EI of CSA were 97.19% and 50.56%, respectively. In this study, the respective FI and EI of CSA were 93.65% and 50.65%. Therefore, it can be considered that the properties of CSA were suitable for concrete.

Table 1. Major physical and mechanical properties of coarse and fine aggregates.

Property	Coarse Aggregate		Fine Aggregate (Sand)		
	BA	CSA	Coarse	Fine	Combined
Flakiness index, FI (wt.%)	10.90	93.65	-	-	-
Elongation index, EI (wt.%)	12.60	50.65	-	-	-
Relative density (SSD)	2.41	1.27	2.61	2.70	2.66
Water absorption (wt.%)	12.80	27.65	2.04	1.38	1.71
Unit weight (kg/m^3)	1015	595	1515	1330	1420
Air-dry moisture content (wt.%)	5.60	2.04	0.50	0.50	0.50
Aggregate crushing value, ACV (wt.%)	31.74	0.98	-	-	-
Aggregate impact value, AIV (wt.%)	30.43	3.84	-	-	-

- Not tested.

Table 2. Particle size distributions or gradings of fine and coarse aggregates.

Sieve Size (mm)	Coarse Aggregate (% Finer)			Fine Aggregate (% Finer)			
	BA	CSA	ASTM Limit	Fine Sand	Coarse Sand	Combined Sand	ASTM Limit
37.50	100	100	100	-	-	-	-
19.00	70.6	98.8	90–100	-	-	-	-
9.50	14.4	22.2	20–55	-	–	-	-
4.75	5.00	1.80	0–10	100	100	100	95–100
2.36	0.0	-	-	100	96.8	98.4	80–100
1.18	0.0	-	-	100	87.2	94.4	50–85
0.60	0.0	-	-	99.6	43.2	73.6	25–60
0.30	0.0	-	-	65.6	9.2	40.4	10–30
0.15	0.0	-	-	18.4	1.6	11.6	0–10

- Not applicable. FM values—BA: 7.09, CSA: 6.77, coarse sand: 2.62, fine sand: 1.16, and combined sand: 1.81.

3.1.2. Brick Aggregate (BA)

Locally available first class (Grade A) bricks (compressive strength > 15 MPa, water absorption < 15%) [29], manufactured by M/S Baimail Aizuddin Bricks, were crushed manually to obtain BA for use in this study. The bricks were procured from a brickfield situated in Konabari, Gazipur, Bangladesh. Before crushing, the bricks were tested for their compressive strength and water absorption according to ASTM C67 [30], which were found as 18.15 MPa and 11.92%, respectively. After crushing the bricks, the BA obtained was sieved for its gradation. The maximum size of BA was 0.75 in. (19 mm) and it was entirely retained on No. 4 sieve. The physical properties such as the gradation, unit weight, and moisture content of BA were determined in accordance with ASTM C136/C136M [22], ASTM C29/C29M [23], and ASTM C566 [24], respectively. Furthermore, the standard test procedure depicted in ASTM C127 [25] was followed to determine the water absorption and specific gravity of BA. In addition, AIV and ACV, FI, and EI were determined according to IS 2386-IV [26], BS 812-105.1 [27], and BS 812-105.2 [28], respectively.

The properties of BA are shown in Table 1 and the gradation of BA is shown in Table 2. These tables show that the FM, FI, EI, relative density (SSD), water absorption, unit weight, moisture content, ACV, and AIV of BA were 7.09, 10.90%, 12.60%, 2.41, 12.80%, 1015 kg/m^3, 5.60%, 31.74%, and 30.43%, respectively. These results were consistent with the preceding studies [20,21] that successfully used BA to produce concrete. Noaman et al. [21] reported that the FM, relative density, water absorption, and unit weight of BA were 7.00, 2.56, 16.38%, and 925 kg/m^3, respectively, in their study. On the other hand, Rashid et al. [20] found the FM, relative density, water absorption, and unit weight of BA as 6.97, 2.10, 15.80%, and 1089 kg/m^3, respectively, in their study. Therefore, the BA selected for this study was considered acceptable for preparing concrete. Some of the BA used in this study is shown in Figure 2.

Figure 2. BA used in making concrete mixes.

3.1.3. Fine and Coarse Sands

In this study, locally available coarse and fine sands were used as fine aggregates. They were obtained from the riverbed. The physical properties such as the FM and moisture content of sands were determined following ASTM C136/C136M [22] and ASTM C566 [24], respectively. The test procedure given in ASTM C128 [31] was followed to determine the relative density (SSD) and water absorption of fine aggregate. Moreover, ASTM C29/C29M [23] was followed to evaluate the unit weight of fine aggregate.

The physical properties of sands are given in Table 1 and their gradations are shown in Table 2. These tables show that the FM, relative density, water absorption, unit weight, and moisture content of combined sand were 1.81, 2.66, 1.71%, 1420 kg/m^3, and 0.50%, respectively. Noaman et al. [21] reported that the FM, relative density, water absorption, and unit weight of sand were 2.10, 2.68, 1.04%, and 1386 kg/m^3, respectively, in their study. On the other hand, Rashid et al. [20] found the FM, relative density, and water absorption of sand as 1.86, 2.50, and 2.60%, respectively, in their study. Therefore, the properties of the combined sand used in this study were consistent with the preceding studies [20,21].

3.1.4. Normal Portland Cement

In this research, normal (ASTM Type-I) Portland cement (NPC), locally produced by Seven Circle (Bangladesh) Limited, was used as the binding material. The standard test methods given in ASTM C187 [32] and ASTM C191 [33] were followed to determine the normal consistency and setting times of cement, respectively. Furthermore, ASTM C109/C109M [34] was followed to determine the compressive strength of cement by testing the mortar cube specimens.

The properties of cement obtained from the above-mentioned tests are given in Table 3. This table shows that the normal consistency, initial setting time, and final setting time are 31%, 105 min, and 300 min, respectively. The compressive strength at 3 days, 7 days, and 28 days was 22.14 MPa, 25.24 MPa, and 31.77 MPa, respectively. For NPC, the minimum initial setting time and the maximum final setting time should be 45 min and 375 min, respectively, as specified in ASTM C150/C150M [35]. In addition, the minimum requirement for the compressive strength at 3 days, 7 days, and 28 days is 12.00 MPa, 19.00 MPa, and 28.00 MPa, respectively [35]. Therefore, from the test results shown in Table 3, it can be concluded that the properties of cement used in the present study fulfilled the ASTM requirements for NPC.

Table 3. Major physical and mechanical properties of normal Portland cement.

Cement Property		Value	ASTM Limits [35]
Normal consistency (wt.%)		31	26–33%
Initial setting time (min)		105	Not less than 45 min
Final setting time (min)		300	Not more than 375 min
Compressive strength (MPa)	3 days	22.14	Min. 12 MPa
	7 days	24.24	Min. 19 MPa
	28 days	31.77	Min. 28 MPa

3.1.5. Water

Water is the most important and least expensive ingredient of concrete. It is essential for cement hydration, which results in calcium silicate hydrate (C-S-H), the strength-contributing chemical compound to bind aggregates [36]. Moreover, the curing of concrete with water significantly enhances its strength development [37]. In this study, pure drinking water supplied from the laboratory was used in the mixing and curing processes of concrete.

3.2. Mix Design of Concretes

Various CSBACs containing 0%, 5%, 10%, and 15% CSA as a partial replacement of BA were produced in this study based on the water to cement (w/c) ratios of 0.45, 0.50 and 0.55, as recommended in IS 10262: 2019 [38] and IS 456: 2000 [39] for normal concrete mixes with a 28-day cylinder compressive strength of 15–25 MPa. The w/c ratios of 0.45–0.50 was selected because the CSA concretes are intended to be applied in structures that require a compressive strength below 25 MPa. Furthermore, the constant mix ratio of 1:1.5:3 (cement: fine aggregate: coarse aggregate) by bulk volume, as suggested in IS 456: 2000 [39], was used to produce the CSBAC mixes possessing the minimum compressive strength of M20 grade concrete (20 MPa cube compressive strength or 15 MPa cylinder compressive strength). IS 456: 2000 [39] allows designing a concrete based on the volumetric mix ratio of cement, fine aggregate, and coarse aggregate (by bulk volume including air voids, not by absolute volume).

In designing the concrete mixes for this study, the cement content was kept unchanged, but the water content was varied based on the selected w/c ratios. The replacement percentages (0−15%) of CSA were selected based on the published literature on the use of CS in concrete. Rajeevan and Shamjith [6] stated that the concrete made with 15% CSA as a partial replacement of NCA provided the optimum compressive strength. Mohapatra and Parhi [9] demonstrated that the concretes with 5−15% of CSA gave the targeted strength of M25 grade concrete. Such findings were the basis for selecting 0–15% CSA for this study. Furthermore, it should be mentioned that no air-entraining admixture was used in this study for air entrainment in the concrete mixes. In addition, the entrapped air content was not considered separately in the mix design, because it was already accounted for in the bulk volume of concrete.

The basics of the mix design for various CSBAC mixes are presented in Table 4. The concrete mixes were designated based on the w/c ratio and CSA content. For example, WC50CS5 designates a CSBAC mix whose w/c ratio and CS content is 0.50 and 5%, respectively.

Table 4. Basics of mix design for different CSBACs.

Concrete Mix	Volumetric Mix Ratio of Dry Concrete			Weight Based w/c Ratio	Relative Weight Ratio of BA and CSA		Relative Weight Ratio of Cement and Water	
	Cement	Sand	BA		BA	CSA	Cement	Water
WC45CS0	1	1.5	3	0.45	1	0	1	0.45
WC45CS5	1	1.5	3	0.45	0.95	0.05	1	0.45
WC45CS10	1	1.5	3	0.45	0.90	0.10	1	0.45
WC45CS15	1	1.5	3	0.45	0.85	0.15	1	0.45
WC50CS0	1	1.5	3	0.50	1.00	0	1	0.50
WC50CS5	1	1.5	3	0.50	0.95	0.05	1	0.50
WC50CS10	1	1.5	3	0.50	0.90	0.10	1	0.50
WC50CS15	1	1.5	3	0.50	0.85	0.15	1	0.50
WC55CS0	1	1.5	3	0.55	1.00	0	1	0.55
WC55CS5	1	1.5	3	0.55	0.95	0.05	1	0.55
WC55CS10	1	1.5	3	0.55	0.90	0.10	1	0.55
WC55CS15	1	1.5	3	0.55	0.85	0.15	1	0.55

3.3. Preparation of Fresh Concretes

The fresh CSBACs were prepared by mixing the concrete ingredient in a drum-type concrete mixer. During the mixing operation, firstly, CSA and BA were put into the mixer and thoroughly mixed for 30 s. This step was omitted in the cases of the control concretes (0% CSA). After the premixing of CSA and BA, cement and combined sand were added and mixed for 60 s with the addition of half of the mix water. In the cases of the control concretes, BA, combined sand, and cement were mixed concurrently for 90 s with half of the mix water. The mixer machine was stopped thereafter for 60 s and the drum opening was covered by a wet burlap. After the rest period, the remaining half of the mix water was added and the mixing was continued for another 90 s to obtain the fresh CSBACs.

3.4. Testing of Fresh Concretes

3.4.1. Slump Test

Immediately after the completion of mixing operation, the freshly mixed concrete was unloaded from the mixer and its slump as a measure of workability was determined according to ASTM C143/C143M [40]. The slump test was performed for all concretes prepared with 0–15% CSA at the w/c ratios of 0.45, 0.50, and 0.55.

3.4.2. Wet Density and Air Content Test

The wet density and air content of concrete were measured in accordance with ASTM C138/C138M [41]. These two properties were determined for the concretes made with 0–15% CSA at the w/c ratio of 0.50 only.

3.5. Casting of Test Specimens

Steel cylinder molds (Ø100 mm × 200 mm) were cleaned, oiled, and placed on a leveled surface. After measuring the slump, wet density, and air content, the fresh concrete was placed into the cylinder molds in three layers and each layer was compacted using the specified tamping rod to prepare the specimens in accordance with ASTM C31/C31M [42]. Then, the cylinder specimens were kept in the laboratory without any disturbance for 1 day. The specimens were covered with a plastic sheet and the room temperature of 25 °C at 95% relative humidity was maintained to reduce the loss of moisture through evaporation. At the age of 1 day, the concrete cylinder specimens were de-molded and identified with a permanent marker. Subsequently, the concrete cylinders were transferred to the curing tank, and they were kept immersed in water until the day of testing for dry density and compressive strength. At the ages of 7, 28, and 90 days, some of the molded cylinders were cut to prepare 20 mm cube specimens for the microstructural analysis of CSBACs.

3.6. Testing of Hardened Concretes

3.6.1. Dry Density Test

After 28 days of curing, the dry density of CSBAC was determined using the cylinder specimens of Ø100 mm × 200 mm dimensions. In this test, the CSBACs including different CSA contents (0%, 5%, 10%, and 15% CSA) at the w/c ratio of 0.50 were used. The CSBAC with 0% CSA was used as the control concrete. The dry density of the above concretes was performed in accordance with the procedure given in ASTM C642 [43]. Triplicate specimens were used for each concrete.

3.6.2. Compressive Strength Test

After the curing periods of 7, 28, and 90 days, the compressive strength was determined for all CSBACs (0%, 5%, 10%, and 15% CSA) made with the w/c ratios of 0.45, 0.50, and 0.55. The compression test was conducted on triplicate concrete cylinder specimens of Ø100 mm × 200 mm dimensions. This test was performed following the procedure depicted in ASTM C39/C39M [44]. The CSBAC with 0% CSA was used as the control concrete.

3.6.3. Microstructural Analysis

The microstructure of various CSBACs at the ages of 7, 28, and 90 days was observed using a scanning electron microscope (SEM) made by HITACHI (Model-SUI5I0). SEM has become one of the most widely utilized instruments for materials characterization. The secondary electron (SE) and the backscattered electron (BSE) modes are commonly used to obtain images from SEM. In this study, the SE mode was used to investigate the microstructure of CSBACs including 0–15% CSA.

For microstructural analysis, the cylindrical specimens of Ø100 mm × 200 mm dimensions were first cut into 20 mm thick slices. Then, the 20 mm thick slices were cut into 20 mm cubes to get four fresh faces by using a fine graded diamond blade. A diamond saw blade lubricated with propylene glycol is suitable for exposing a fresh surface. One of the four fresh faces was smoothened with the help of abrasive papers of 220, 320, 400, and 600 grits (silicon carbide paper). After smoothing, the cube specimens were washed in clean water. Then, the cubes were oven-dried for about 15 min followed by cooling to room temperature. Once the cooling was done, the test cubes were wrapped by aluminum foil paper to prevent them from getting uncontrolled moisture. The cube specimens were unwrapped one by one just before the SEM test.

The SEM images were produced using the smooth surface of 20 mm cube specimens. After getting the images, the fissure width (defined as the irregular gap between the cement paste and CSA) was determined through "ImageJ" software. For each such measurement, the scale shown in the respective SEM image was used as the reference.

4. Test Results and Discussion

4.1. Fresh Properties of Concretes

4.1.1. Workability

The workability of all CSBACs was measured with respect to slump. The slump of concrete varied in the range of 30–85 mm. The detailed results and a discussion on the slump of various CSBACs are beyond the scope of this study. However, they are available in Bari et al. [45]. The slump results of the concretes including 0–15% CSA at the w/c ratio of 0.50 are shown in Table 5. In general, the slump of concrete decreased in the presence of CSA. However, the decrease in slump was lower for higher percentage of CSA. Gunasekaran et al. [11], Kamal and Singh [7], and Ahlawat and Kalurkar [46] also observed similar effects. Furthermore, for the CSBACs prepared with the w/c ratio of 0.50, the slump values were 73 mm, 60 mm, 66 mm, and 72 mm for 0%, 5%, 10%, and 15% CSA, respectively. According to ACI 213R [14], a slump of about 75 mm is an indication of adequate workability for a concrete mix prepared with lightweight aggregate (LWA), with no upward segregation or floating of LWA. Hence, the CSBACs fabricated with the w/c ratio of 0.50 were selected for further study and tested for wet density, dry density, air content, and microstructural analysis. However, the compressive strength was determined for all CSBACs made with the w/c ratios of 0.45, 0.50, and 0.55.

Table 5. Fresh properties of different CSBACs (w/c: 0.50).

Concrete Mix	Slump (mm)	Wet Density (kg/m^3)	Air Content (%)
WC50CS0	73	2245	3.5
WC50CS5	60	2218	4.6
WC50CS10	66	2173	4.9
WC50CS15	72	2097	3.7

4.1.2. Wet Density and Air Content

The wet density results of the freshly mixed concretes with 0–15% CSA are given in Table 5, which shows that the density of fresh concrete decreased with the increase in CSA content. The density of the fresh concretes including 0%, 5%, 10%, and 15% CSA was 2245, 2218, 2173, and 2097 kg/m^3, respectively. The lower relative density and unit weight of CSA as compared with BA (refer to Table 1) decreased the wet density of CSBAC. Yerramala and Ramachandrudu [47] as well as Kukarni et al. [48] found similar results from their study.

The air content results of the concretes made with 0–15% CSA at the w/c ratio of 0.50 are given in Table 5. It is obvious from Table 5 that the CSBACs including 5% and 10% CSA had more air content than the control concrete (0% CSA). In contrast, the air content of the CSBAC made with 15% CSA was very close to that of the control concrete. These results are linked with the workability of concrete. A higher workability facilitates the expulsion of air voids from a concrete mix during compaction [49]. It implies that the entrapped air content of a concrete can be higher if it possesses a lower slump. The concretes with 5% and 10% CSA had a relatively less slump. Hence, they had higher air content than the control concrete. On the other hand, the concretes with 0% and 15% CSA had identical slumps and therefore their air content was not significantly different.

4.2. Hardened Properties of Concretes

4.2.1. Dry Density

The dry density (hardened density) was determined at the age of 28 days for various CSBACs fabricated with the w/c ratio of 0.50. Triplicate Ø100 mm × 200 mm cylinder specimens were used for each concrete. The average dry density of CSBAC was found as 2021, 1997, 1956, and 1888 kg/m^3 for 0%, 5%, 10%, and 15% CSA, respectively. The effect of CSA on the dry density of CSBAC is presented in Figure 3. It is evident from Figure 3 that the dry density decreased as the amount of CSA was increased in the concrete mix. The decreases in dry density were 1.18%, 3.21%, and 6.58% for 5%, 10%, and 15% CSA, respectively. These reductions are responsible for the lower relative density and unit weight of CSA than BA (refer to Table 1). Similar observations were made by previous researchers [6,47,50]. It was also found that SLWC with a dry density as given by commonly used LWAs [1,51–53] can be produced utilizing CSA as a partial replacement of BA.

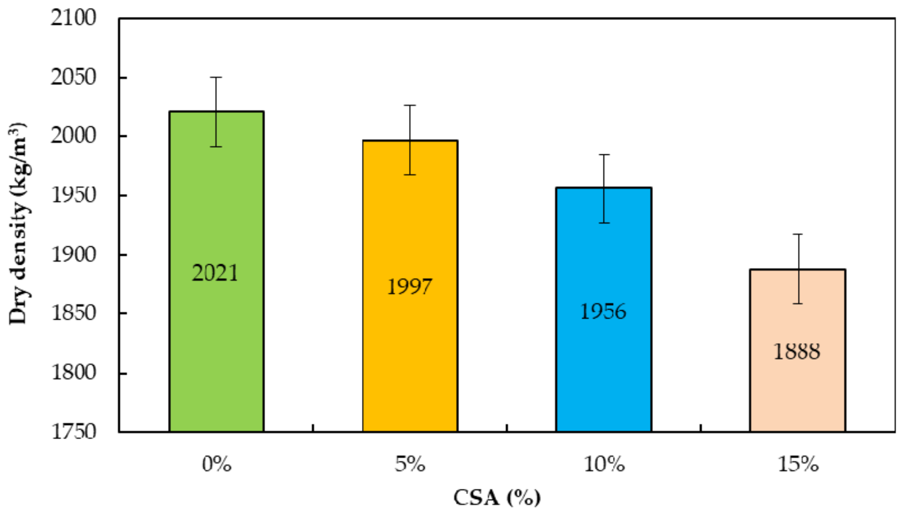

Figure 3. Dry density of CSBAC with different replacement levels of BA by CSA (w/c: 0.50).

4.2.2. Compressive Strength

The compressive strength was determined at the ages of 7, 28, and 90 days for all CSBACs prepared with the w/c ratios of 0.45, 0.50, and 0.55. Triplicate Ø100 mm × 200 mm cylinder specimens were used for each concrete at every testing age. The details of the compressive strength results are presented in Table 6. The compressive strength values of various CSBACs fulfilled the minimum requirement of SLWC at all CSA contents. In terms of structural design, the compressive strength of 21–35 MPa at the age of 28 days is common for concrete structures [14]. This range of compressive strength was achieved for all CSBACs, except WC50CS15, WC55CS10, and WC55CS15, as evident from Table 6. However, it should be mentioned that the minimum compressive strength of concrete at 28 days can be relaxed to 17 MPa for buildings up to four stories [54]. Furthermore, the minimum 28-day compressive strength requirement is 17 MPa for SLWC [14]. This minimum compressive strength was achieved for all CSBACs, except WC55CS15, as can be seen from Table 6.

Table 6. Compressive strength results of different CSBACs (w/c: 0.45, 0.50, and 0.55).

Concrete Mix	Compressive Strength (MPa)		
	7 Days	28 Days	90 Days
WC45CS0	19.7	30.4	33.4
WC45CS5	17.3	25.5	29.9
WC45CS10	15.8	23.6	27.6
WC45CS15	13.5	19.7	21.9
WC50CS0	19.2	30.0	33.0
WC50CS5	16.2	24.6	29.5
WC50CS10	15.2	22.4	26.5
WC50CS15	12.7	18.2	21.3
WC55CS0	18.6	28.3	30.9
WC55CS5	15.5	22.9	26.5
WC55CS10	11.5	17.2	18.9
WC55CS15	11.2	15.8	17.5

The compressive strength results of 7, 28, and 90 days old CSBACs made with the w/c ratio of 0.50 are selectively plotted in Figure 4 to show the effect of CSA. It is evident from Figure 4 that the compressive strength decreased as the CSA content was increased. Duna and Musa [13] had similar findings. Several factors such as the shape, water absorption, and orientation of CSA, the bond between CSA and cement paste, and the entrapped air content were involved in the reduction of compressive strength. Particularly, the CSA particles in concrete cylinder specimens were orientated parallel to the direction of compressive load, as observed by the authors of this paper and reported in Bari et al. [45]. Hence, the compressive load was not resisted effectively due to the thin segment of CSA.

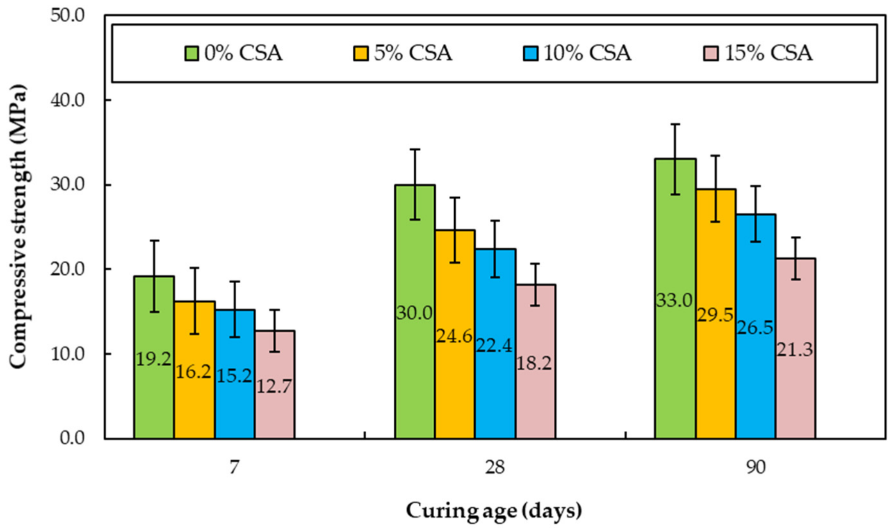

Figure 4. Compressive strength of CSBAC with different replacement levels of BA by CSA (w/c: 0.50).

The compressive strength of CSBACs was also linked with the quality of the ITZ between the cement paste (CP) and CSA in concrete, which is further explained in Section 4.3. The weaker interface of CSA particles with CP decreased the compressive strength of CSBAC. Nevertheless, despite the decrease in compressive strength due to the inclusion of CSA, all CSBACs provided acceptable compressive strength, except WC55CS15. In past research, Ealias et al. [55] observed that the concrete made with 10% CSA as a partial replacement of coarse aggregate provided 65–80% of the compressive strength of conventional M25 grade and M30 grade concretes. Patel et al. [8] also noticed that the concrete made by substituting 20% of NCA with CSA provided a reasonably good compressive strength as compared to conventional concrete. In the present study, the concretes including 5–15% CSA possessed 56–84% of the compressive strength of the control concrete.

The compressive strength of all CSBACs was improved with the extended curing age of concrete in water. Such improvement in compressive strength occurred through densification of the ITZ in concrete by more C-S-H gel generated from cement hydration. This is also related to the gel/space ratio in concrete. An increased amount of C-S-H gel increases the gel/space ratio of concrete. A higher gel/space ratio contributes to increasing the compressive strength [56], because it decreases the capillary porosity and thus improves the microstructure of concrete.

4.3. Microstructure of CSBAC

The microstructure of CSBAC was investigated at the ages of 7, 28, and 90 days by using an SEM. Figures 5–7 present the micrographs of various CSBACs including 0%, 5%, 10%, and 15% CSA contents.

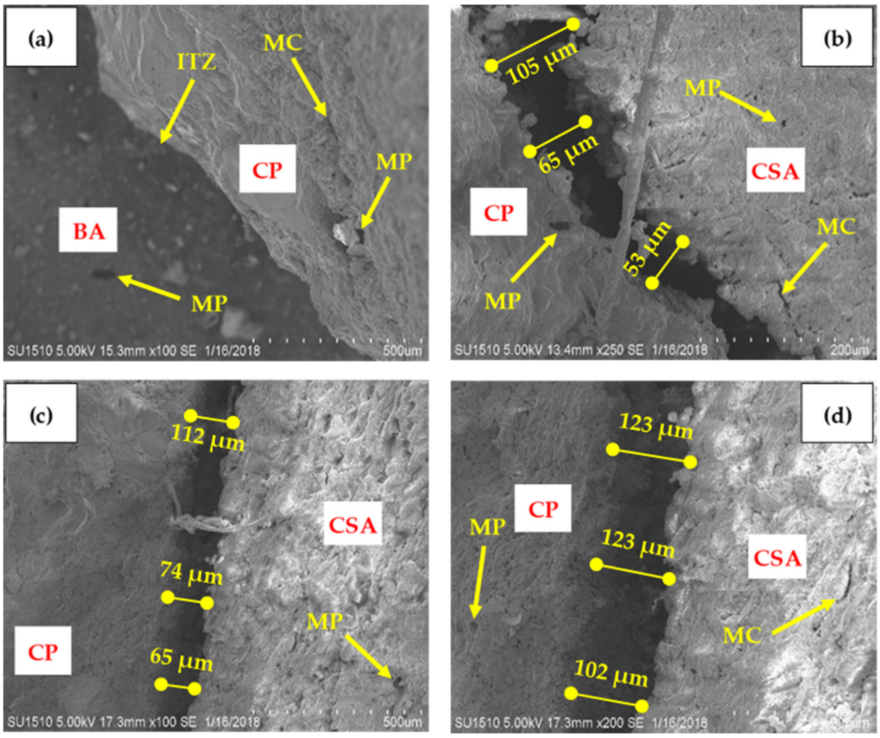

Figure 5. Microstructure of CSBAC (w/c: 0.50) after 7 days of curing: (**a**) 0% CSA, (**b**) 5% CSA, (**c**) 10% CSA, and (**d**) 15% CSA.

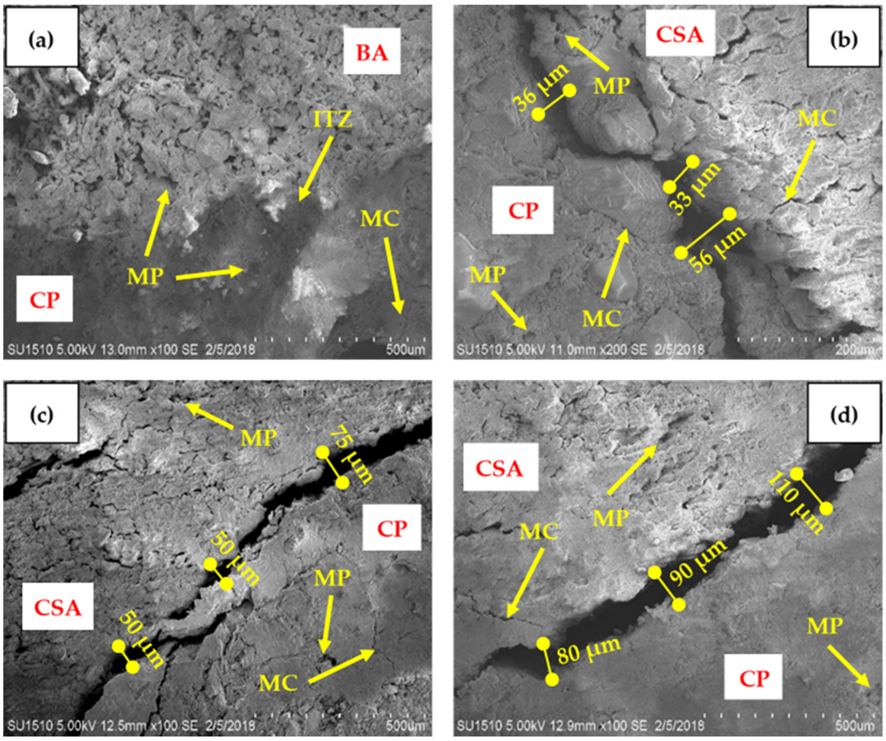

Figure 6. Microstructure of CSBAC (w/c: 0.50) after 28 days of curing: (**a**) 0% CSA, (**b**) 5% CSA, (**c**) 10% CSA, and (**d**) 15% CSA.

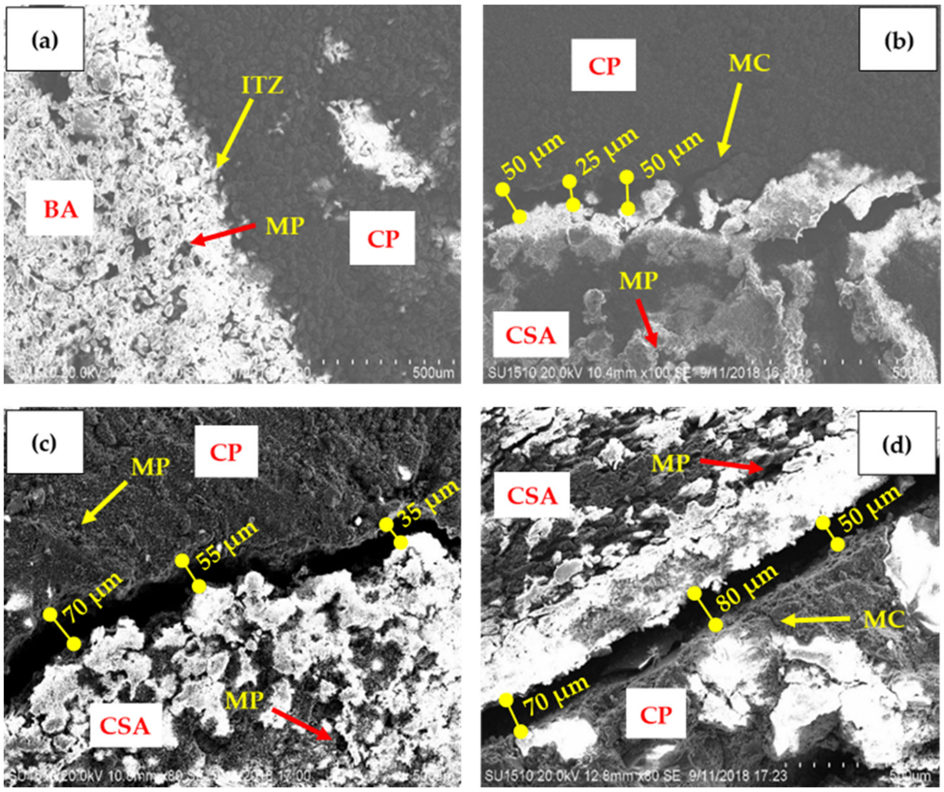

Figure 7. Microstructure of CSBAC (w/c: 0.50) after 90 days of curing: (**a**) 0% CSA, (**b**) 5% CSA, (**c**) 10% CSA, and (**d**) 15% CSA.

The presence of fissures (narrow spaces) between the cement paste (CP) and CSA in concrete was observed in the micrographs (Figures 5–7). Moreover, there were micropores (MPs) and microcracks (MCs) in the CP and CSA components of concrete. However, a relatively large number of MPs was observed in CSA. This is consistent with the water absorption result obtained for CSA. The absorption value of CSA was quite high (refer to Table 1) which indicates its more porous nature. The porous nature of CSA is obvious from the micrographs of CSBACs. However, more distinctive was the ITZ between the cement paste and CSA of CSBACs. Large fissures were noticed in the ITZ of CSBACs including 5–10% CSA. The presence of such fissures in the ITZ of CSA concrete was reported by Gunasekaran et al. [12]. ITZ plays an important role in modifying the compressive strength of concrete. The interfacial MPs can be interconnected resulting in macropores, which limit the strength of the paste-aggregate bond; in addition, cement particles cannot pack efficiently around an embedment (e.g., aggregate), which is well-known as "wall effect"—this raises the local w/c ratio in ITZ [57]. These effects are further intensified in the presence of CSA in concrete. The ITZ between CSA and CP becomes much porous and weaker due to the accumulation of water from the porous surface of CSA that generates supplementary capillary pores (interconnected pores) in this zone [12,15,58]. For these reasons, fissures can develop in the ITZ of CSBACs.

The ITZ of the BAC without any CSA was very dense at all ages, as is obvious from Figures 5a, 6a and 7a. It is evident from Figures 5a, 6a and 7a that there were no cracks or fissures at the ITZ of the CSBAC containing 0% CSA. In contrast, Figure 5b–d, Figures 6b–d and 7b–d show that there were fissures in the ITZ of the CSBACs incorporating 5–15% CSA. It was also noticed that the width of fissures varied for different CSBACs. The fissure width depends on many factors, such as the size, shape, and amount of coarse aggregate, the w/c ratio of concrete, and the mixing and placing techniques. In the present study, for the CSBACs prepared with a given w/c ratio (0.50) and by following the same mixing and placing procedures, the CSA content was the dominant factor in modifying the width of fissures, as perceived from the analysis of micrographs. In general, the fissure width increased with the increased CSA content in concrete.

The fissure width observed in the micrographs (Figures 5–7) of various CSBACs was determined in this study using "ImageJ" software. The fissure widths of different concretes are shown in Table 7 with their corresponding compressive strength results. At the age of 7 days, the fissure widths were 53–105 µm, 65–112 µm, and 102–123 µm for the CSBACs including 5%, 10%, and 15% CSA, respectively. Similarly, at the age of 28 days, the CSBACs incorporating 5%, 10%, and 15% CSA had the respective fissure width of 33–56 µm, 50–75 µm, and 80–110 µm. Furthermore, at the age of 90 days, the fissure widths were 25–50 µm, 35–70 µm, and 50–80 µm for the CSBACs with 5%, 10%, and 15% CSA, respectively. These results reveal that the increase in CSA content enlarged the fissure width, and thus decreased the compressive strength of CSBAC.

Table 7. Fissure width and corresponding compressive strength of different CSBACs (w/c: 0.50).

CSA Content (%) of Concrete	Age of Concrete					
	7 Days		28 Days		90 Days	
	Fissure Width (µm)	Compressive Strength (MPa)	Fissure Width (µm)	Compressive Strength (MPa)	Fissure Width (µm)	Compressive Strength (MPa)
0	0	19.2	0	30	0	33
5	53–105	16.2	33–56	24.6	25–50	29.5
10	65–112	15.23	50–75	22.4	35–70	26.5
15	102–123	12.74	80–110	18.2	50–80	21.3

The microstructure of CSBACs improved with the extended curing age of concrete in water. With the increased curing age, the fissure width in the ITZ of the CSBACs with 5−15% CSA decreased, as can be seen from Table 7 and Figures 5–7. A similar trend of narrowing of the fissure width with increasing ages was noticed by Gunasekaran et al. [12] who used SEM to investigate the microstructure of CSA concretes prepared with the w/c ratio of 0.42. In their study, the fissure width between the CSA and CP of 100% CSA concrete varied in the range of 52.31–88.27, 41.72–47.96, and 24.94–26.63 µm at the ages of 3, 7, and 28 days, respectively. This suggests that the fissures are constricted with the curing age of concrete and thus the bond between CP and CSA becomes better at later ages. For these reasons, the compressive strength of the CSBACs produced in this study increased significantly at the ages of 28 and 90 days, as evident from Table 7.

4.4. Correlation between the Fissure Width and Compressive Strength of CSBAC

The correlation between the fissure width and compressive strength of CSBAC was examined. The relationship is graphically presented in Figure 8. It is obvious from Figure 8 that the fissure width was strongly correlated with the compressive strength of CSBAC. The compressive strength and fissure width of CSBAC showed a linear relationship (Figure 8). The correlation coefficient (r) was 0.9418, which indicates a strong relationship. Moreover, the slope (–0.2115) of the linear relationship was negative, which means that the compressive strength decreased with an increase in the fissure width. Conversely, the compressive strength increased with a decrease in the fissure width. The fissure width in the ITZ of CSBAC was narrowing with the extended curing age of concrete, as observed from the micrographs. This is due to the continuous hydration process that formed more C-S-H gel, which contributed to decreasing the width of fissures in the concrete. As a result, there was a progressive increase in the compressive strength of CSBAC. Therefore, such a strong relationship between the compressive strength and fissure width of CSBAC was noticed.

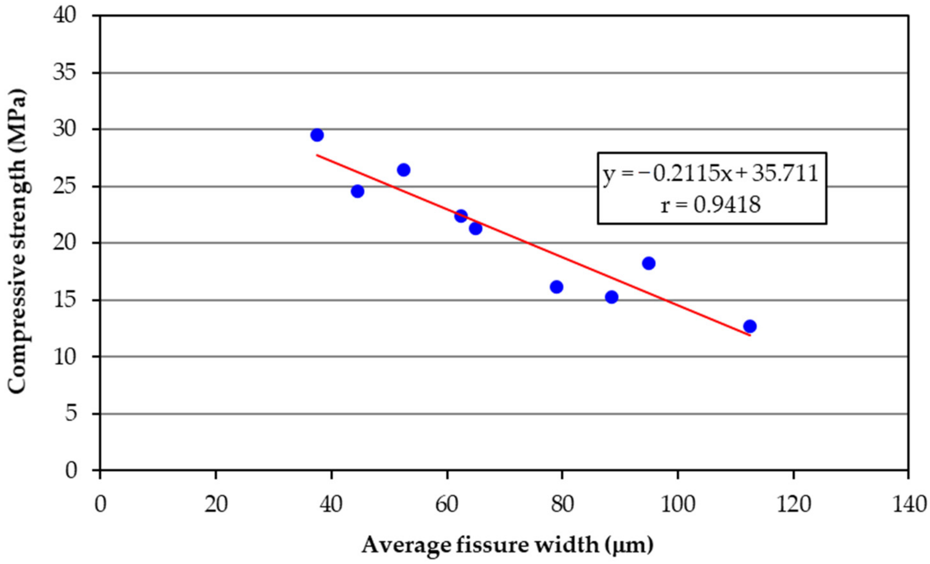

Figure 8. Correlation between the fissure width and compressive strength of CSBAC.

5. Sustainable Benefits of Using CSA in Concrete

Rapid industrialization in the world is increasing the quantity of waste materials day by day, thus creating environmental hazards due to uncontrolled disposal. Among the agricultural wastes, large quantities of CS solid waste from de-husked coconuts are generated in the tropical countries of the world. Each year, about 62 million tons of coconuts are produced and distributed throughout the world [1]. A huge amount of CS waste (about 9.7 million tons per year) is being generated from these coconuts. Particularly, CS waste is generated abundantly in coconut-producing countries, such as Bangladesh and Sri Lanka. After the coconut meat (pulp) is scraped out, the shell is typically discarded as waste in open fields. The vast amount of this discarded CS creates serious disposal and environmental problems due to its non-biodegradable nature. Such issues can be resolved if CS is utilized in construction industry.

Attempts have been made to utilize the CS waste as a replacement of aggregate material in the construction industry, especially to produce concrete, for the sake of sustainable development in developing countries. Furthermore, if CS is used in concrete as coarse aggregate, at least partially, it would compensate the scarcity of natural aggregates. It could be accomplished without significantly affecting the properties of concrete. Past research showed that the concretes made incorporating CS as a partial replacement of coarse aggregate can provide satisfactory workability and reasonably good compressive strength, bond strength, and impact and crushing resistance [11,12]. CSA concrete has already been used to some extent in rural areas and other places where CS is generated abundantly or NCAs are costly due to their scarcity [6,11,12,59].

In the construction industry, the use of coarse aggregates from natural sources should be reduced and alternative materials, such as CSA, need to be used as a substitute of natural aggregate for sustainable development. The increasing consumption of NCA creates an ecological imbalance, which can be alleviated by using alternative sources of coarse aggregate in the construction industry. Furthermore, in certain regions, such as Bangladesh and West Bengal (India), natural rock deposits are scarce. In these regions, burnt-clay bricks are crushed to produce BA, which is used as an alternative of NCA. In Bangladesh, BA is commonly used as coarse aggregate for the construction of rigid pavements, small- to medium-span bridges, culverts, and low-rise buildings [16,17,20]. However, the brickkilns are one of the sources of CO_2 emissions that cause air pollution. In addition, the huge quantity of bricks produced for use as masonry units and in making BA for construction work is causing the overexploitation of clay soils. These environmental problems can also be lightened if CSA is used to reduce the consumption of BA in concrete.

6. Conclusions

The following conclusions are drawn from this study:

- The incorporation of CSA decreased the workability of concrete. However, the adverse effect of CSA on the workability was insignificant at a higher CSA content.
- The wet density of concrete decreased in the presence of CSA due to its lower relative density and unit weight than BA. In addition, the incorporation of CSA tended to increase the entrapped air content of concrete when its workability was affected.
- The dry density of CSBAC at 28 days decreased with the increase in CSA content; however, all concretes satisfied the density requirement of SLWC.
- At all testing ages, the compressive strength of CSBAC gradually decreased with the increase in CSA content; however, the compressive strength of all CSBACs fulfilled the requirement of SLWC, except WC55CS15.
- Although the inclusion of CSA affected the compressive strength of concrete, the gain in the compressive strength of all CSBACs occurred at later ages due to further cement hydration resulting in more C-S-H gel.
- The microstructural study of CSBACs revealed that the incorporation of CSA created fissures in the ITZ of concrete that were formed due to the accumulation of water migrated from the saturated CSA particles.
- The width of the fissures in the ITZ of CSBACs increased with the increase in CSA content; however, the analysis of the micrographs revealed that the fissure width was narrowing at later ages with an extended period of water curing that produced more C-S-H gel.
- The compressive strength of CSBAC was progressively improved as the width of the fissures in the ITZ of CSA and cement paste decreased. Therefore, a strong correlation was observed between the compressive strength and fissure width of CSBAC.
- The use of CSA in concrete shall bring forth many sustainable benefits by reducing the environmental impact of CS waste, compensating the scarcity of natural aggregates, decreasing the depletion of natural sources of aggregates, alleviating ecological imbalance, lessening the overexploitation of clay soils in brickfields, and declineing the emission of CO_2 from brickkilns.

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Abbreviations

ACI	American Concrete Institute
ACV	Aggregate crushing value
AIV	Aggregate impact value
ASTM	American Society for Testing and Materials
BAC	Brick aggregate concrete
BA	Brick aggregate
BS	British Standard
BSE	Backscattered electron
CS	Coconut shell
CSA	Coconut shell aggregate
CSBACs	Coconut shell brick aggregate concretes (BACs containing CSA)
CP	Cement paste
C-S-H	Calcium silicate hydrate
EI	Elongation index
FI	Flakiness index
FM	Fineness modulus
IS	Indian Standard
ITZ	Interfacial transition zone
LAAV	Los Angeles abrasion value
LWA	Lightweight aggregate
MC	Microcrack
MP	Micropore
NCA	Natural coarse aggregate
NPC	Normal Portland cement
SE	Secondary electron
SEM	Scanning electron microscope
SLWC	Structural lightweight concrete
SSD	Saturated surface-dry
w/c	Water to cement ratio
wt.	Weight

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