Journal of Sustainable Construction Materials and Technologies
Web page info: https://jscmt.yildiz.edu.tr
DOI: 10.47481/jscmt.1666237

JSCMT
Journal of Sustainable Construction Materials and Technologies

Research Article

Investigation of coconut shell biochar as an eco-friendly additive to mitigate the alkali-silica reaction in recycled aggregate concrete

A. K. P. ARANDARA*[1], G. N. PARANAVITHANA[1], S. T. PRIYADARSHANA[1], H. M. T. G. A. PITAWALA[2], R. DISSANAYAKE[3]

[1]Department of Civil Engineering, Open University of Sri Lanka, Colombo, Sri Lanka
[2]University of Peradeniya, Postgraduate Institute of Science, Galaha, Sri Lanka
[3]Department of Civil Engineering, University of Peradeniya, Galaha, Sri Lanka

ARTICLE INFO

Article history
Received: 02 November 2024
Revised: 03 January 2025
Accepted: 07 January 2025

Key words:
Alkali-silica reaction (ASR), cement mortar bar test (CMBT), coconut shell biochar (CSB), recycled aggregate concrete (RAC), recycled concrete aggregate

ABSTRACT

Alkali-Silica Reaction (ASR) in Recycled Aggregate Concrete (RAC) is one of the main challenges in using demolished concrete in construction. Several methods are available to mitigate the impact of ASR, and they have less circular economic potential. This study aims - to investigate the possibility of coconut shell biochar (CSB) as an eco-friendly additive to mitigate ASR in RAC. In this investigation, the authors have conducted cement mortar bar test experiments according to the American Society for Testing and Materials (ASTM 1260) standard, Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS). Studies have found a higher rate of ASR in recycled concrete aggregate (RCA) compared with natural concrete aggregate (NCA). More importantly, it is found that CSB can adsorb cations (Na+ and K+) that cause ASR in RAC, thereby reducing ASR while not compromising concrete strength. Hence, the authors concluded that CSB can effectively mitigate ASR in RAC while sequestrating carbon into concrete structures.

Cite this article as: Arandara, A. K. P., Paranavithana, G. N., Priyadarshana, S. T., Pitawala, H. M. T. G. A., & Dissanayake, R. (2025). Investigation of coconut shell biochar as an eco-friendly additive to mitigate the alkali-silica reaction in recycled aggregate concrete. *J Sustain Const Mater Technol*, 10(1), 52–63.

1. INTRODUCTION

The demand for construction is growing around the globe due to the steadily increasing human population, which is expected to reach 8.5 billion by 2030 and 9.7 billion by 2050 [1]. In accordance, the global construction sector, responsible for building structures, bridges, and pavements, consumes approximately 50% of the world's annual projected materials and generates an equal share of its waste [1]. The rapid expansion of the construction industry has led to a surge in waste generation, known as Construction and Demolition waste or CDW [2], which constitutes at least 30% of global solid waste generation [3]. There are various categories of CDW [4], in which the CDW concrete accounts for a significant portion, ranging from 20% to 40% of total CDW. Consequently, it necessitates using sustainable materials to ensure a consistent supply chain and, more importantly, to reduce environmental stress and the depletion of natural resources like rocks, sand, and soil. From this perspective, recycled concrete aggregate emerges as a sustainable construction material derived from CDW concrete, comprising 55–73% of recycled aggregate concrete [5].

***Corresponding author.**
*E-mail address: kokila@leanandgreensolutions.com

Published by Yıldız Technical University Press, İstanbul, Türkiye

Table 1. Cost comparison of additives used to mitigate ASR

No	Mitigation method	Additive used	Price of 1 kg of additive in Sri Lanka (USD)	Dosage	The effective cost of additive for 1 kg of cement (USD)
1		Silica fume	0.75	Replacement of cement with 5%–15% silica fume [28]	0.038-0.114
2		Metakaolin	0.21	Replacement of cement with 10–20% of calcined kaolin in weight [29]	0.032
3	Addition of SCM	Low-calcium fly ash	0.04	Replacement of cement with 20%–40% of fly ash in weight [11]	0.008-0.016
4		Ground granulated blast furnace slags.	Not available in Sri Lanka, and cement manufacturers import as bulk for cement manufacturing	N/A	N/A
5	Additions Lithium-based chemical	Lithium Nitrate (lithium salt)	111.11	20%-30% [30]	22.2-33.3
6	Addition of Biochar	Coconut Shell Biochar	0.762	2.5% of cement [31]	0.019

SCM: Supplementary cementitious materials.

Utilizing RCA in various proportions together with natural concrete aggregates (NCA) to produce recycled aggregate concrete (RAC) is being broadly experimented as an alternative way to reduce excessive quantities of CDW [6]. RAC is widely acknowledged as an environmentally friendly product, suitable for both mass and structural concrete applications, with ongoing research and development efforts worldwide [7–9]. However, there are several challenges and drawbacks associated with RAC, followed by the complexity of RCA due to its diverse sources, the presence of residual mortar, and significant differences in mechanical, physical, and durability properties compared to traditional concrete [10]. Mainly, RAC is more susceptible to alkali-silica reaction (ASR), a chemical reaction that can significantly impact its durability [11].

ASR is a slow chemical reaction due to the reactive silica on natural and recycled concrete aggregates and the alkalis in cement. It expands like a gel when exposed to residual water [12, 13]. The pressure generated by the expansive ASR gel can lead to cracking in the aggregates and the surrounding cement matrix of concrete [12]. Factors such as the age of concrete, environmental conditions, crushing processes, and the heterogeneity of the source of RCA can encourage the formation of ASR in RAC [10, 11].

There are some limited methods of controlling ASR in new concrete, and the best method to mitigate ASR is to refrain from using aggregates susceptible to reactive silica. However, as that is not always practical, researchers have declared a few different ways applicable to mitigate or control ASR impact in concrete [12, 14]. For example, minimizing exposure conditions such as contact with residual water, limiting alkali loading in concrete, adding mineral or supplementary cementitious materials (SCM) such as silica fume, metakaolin, low-calcify ash, and ground granulated blast furnace slags, and including lithium compounds in concrete. However, these are not sustainable means, and there is a lack of evidence for research to find such alternatives. It is realized that investigating a sustainable alternative way to control and mitigate ASR in concrete, specifically in RAC, is very significant.

Biochar is an organic, carbon-rich substance that enhances soil productivity [15]. Coconut shell biochar (CSB), derived from the inner shells of coconut nuts, has demonstrated superior properties. It has been used to develop more weather-resistant composites due to its high lignin content [16]. Comparatively, CSB has a higher carbon sequestration rate; for example, it is about ten times more capable than fly ash. Ajien et al. [17] predict that 4.9 million tons of CSB can store 9.9 million tons of atmospheric CO_2. It reveals that around 2020 kg of CO_2 is sequestrated by 1 ton of CSB, compared to 212.57 kg per 1 ton of fly ash [18]. Suppose CSB can be utilized as an alternative supplementary cementitious material (SCM). In that case, it can reduce the carbon footprint of building construction, which currently contributes 11% of global carbon dioxide emissions [19]. Furthermore, the last row of Table 1 indicates that the cost of utilizing CSB as an RAC additive is minimal compared to other additives. Researchers have recently tested CSB as an additive in cementitious composites and concrete containing NCA and RCA [20, 21]. Recent research has shown several benefits that can be gained by mixing biochar in concrete, which include reducing bleeding, improving workability, decreasing plastic and drying shrinkage, and enhancing flexural strength [22, 23]. CSB has also shown positive effects on concrete properties such as initial and final setting time, average density, compressive strength, and silica fume-cement mortar [16, 24, 25]. Further, biochar in concrete is described as a beneficial ad-

Table 2. Physical properties of RCA and NCA samples

No	Physical properties	Experiment Results (Reference)		Minimum from Literature (Reference)		Maximum from Literature (Reference)	
		RCA	NCA	RCA	NCA	RCA	NCA
1	Bulk Specific Gravity (specific gravity of oven-dried basis)-kg/m^3	1.66	2.25	2.10 (f)	1.95 (g)	2.49 (d)	2.90 (f)
2	Bulk Specific Gravity (specific gravity of SSD basis)-kg/m^3	1.74	2.26	2.39 (h)	2.58 (b)	2.69 (c)	2.88 (d)
3	Apparent Specific Gravity (based on oven-dried sample)-kg/m^3	1.81	2.27	2.62 (h)	2.70 (h)	2.71 (d)	2.90 (d)
4	Bulk Density-kg/m^3	1192	1510	1200 (f)	1658 (d)	2394 (e)	2890 (e)
5	Water Absorption -%	5.25	0.28	3.00 (a)	0.20 (g)	5.93 (b)	4.20 (e)

References: (a) [33], (b) [34], (c) [35]; (d) [36], (e) [37], (f) [38]; (g) [39], (h) [40]. RCA: Recycled concrete aggregate; NCA: Natural concrete aggregate.

ditive [21], and biochar contributes positively to the mechanical and permeability properties of concrete exposed to elevated temperature [26]. Particularly, researchers identify biochar as a green additive in concrete while enabling carbon sequestration [27].

Table 1 Rows 1 to 5 indicate different global mitigation methods to prevent ASR. Further, it shows the effective cost for each additive based on the literature. According to Table 1, various types of SCM, such as silica fume, metakaolin, low-calcium fly ash, and ground granulated blast furnace slag, are applied. It can also be mentioned that adding lithium compounds is comparatively expensive. However, using coconut shell biochar to control ASR in concrete is a moderately new and economical option compared to the methods described in Table 1.

Notably, biochar can adsorb cations such as sodium (Na^+) and potassium (K^+), which can interact with the alkali-silica reaction [32]. In line with this potential, the authors of this paper have conducted a petrographic analysis of coconut shell biochar (CSB) as an absorbent to mitigate Alkali-Silica Reaction (ASR) in Recycled Aggregate Concrete (RAC). In their investigation, it was found that certain precipitates are absorbed into CSB particles. Despite these promising properties of CSB, its potential as an additive to mitigate ASR in RAC has yet to be thoroughly examined [31]. Furthermore, the exact cause of ASR reduction in RAC by CSB remains unclear. Therefore, this study aims to assess the impact of CSB as an additive in addressing ASR in RAC and to determine its effects on the mechanical properties of RAC.

In this study, the investigations were initiated by analyzing the mechanical properties of concrete samples with added CSB. An assessment of the impact of CSB on ASR in RAC in compliance with ASTM1260 followed this. Subsequently, the mortar bars were sectioned into thin slices and optically examined using petrographic methods. For the final experiment, Scanning Electron Microscopy with Energy Dispersive X-ray Spectrometry (SEM-EDS) analysis was conducted on selected sites of the thin sections to determine the cause of ASR reduction, which concludes that the adsorption of Na^+ and K^+ cations by CSB additives in the concrete, leads to a decrease of ASR in RAC

2. MATERIALS AND METHODS

2.1. Materials

The aggregate samples and biochar particles were mainly concerned, and all were arranged from Sri Lanka.

2.1.1. RCA and NCA

Specifically, the coarse fraction RCA samples were obtained from the Construction Waste Management (COWM) Center in Galle, located in southern Sri Lanka. NCA samples were collected from a quarry plant in the western part of the country. The RCA and NCA aggregate samples were thoroughly washed and dried to ensure they were impurities-free. They were then graded according to the BS 882-1992 standard and obtained in the size range of 20 mm.

Furthermore, before commencing the research, the physical properties of both RCA and NCA samples, including bulk density, specific gravity (on an oven-dry basis, saturated surface dry basis, and apparent specific gravity), and water absorption, were evaluated. Table 2 compares the physical properties obtained through these procedures and findings from the literature. Specific gravity and water absorption tests were conducted following the ASTM C 127-88 standard, while the bulk density of the samples was evaluated according to the ASTM C 29/C 29M-97 standard. According to Table 2, the physical properties of the tested RCA and NCA samples are within the range of minimum and maximum values found in the literature.

2.1.2. Coconut Shell Biochar (CSB)

Biochar is a carbon-rich product produced through pyrolysis [41] or gasification processes [22] using organic waste materials. In the agricultural sector, it serves as a soil enhancer. Various types of biochar can be produced from different organic waste sources, such as agricultural waste, rice husks, bagasse, paper products, animal manures, and even urban green waste [23]. Specifically, CSB is a solid product obtained by heating coconut shell biomass to temperatures typically between 300°C and 700°C under oxygen-deprived conditions. Biochar possesses various capabilities, including adsorption, sequestration, functionality, and synergy [19]. Its adsorption capability can manifest in different forms, such as physical adsorption, electronic attraction, and cation exchange.

Table 3. Physical properties of biochar [42]

Measured property	Measured value	Measured property	Measured value
Carbon (%)	86.6	Total pore volume (mL/g)	0.21
Hydrogen (%)	3.03	Total basic groups (μmol/g)	3048
Nitrogen (%)	0.08	Total acidic groups (μmol/g)	272
Oxygen (%)	10.3	Carboxylic groups (μmol/g)	156
Ash content (%)	5.53	Lactone groups (μmol/g)	72
pH	8.8	Phenol groups (μmol/g)	44
EC (μS/cm)	139	Maximum Cd+ adsorption capacity (mol/kg)	30.8
(BET) surface area (m^2/g)	212	Maximum Pb+ adsorption capacity (mol/kg)	64.9

EC: Electrical conductivity; BET: Brunauer, Emmett and Teller.

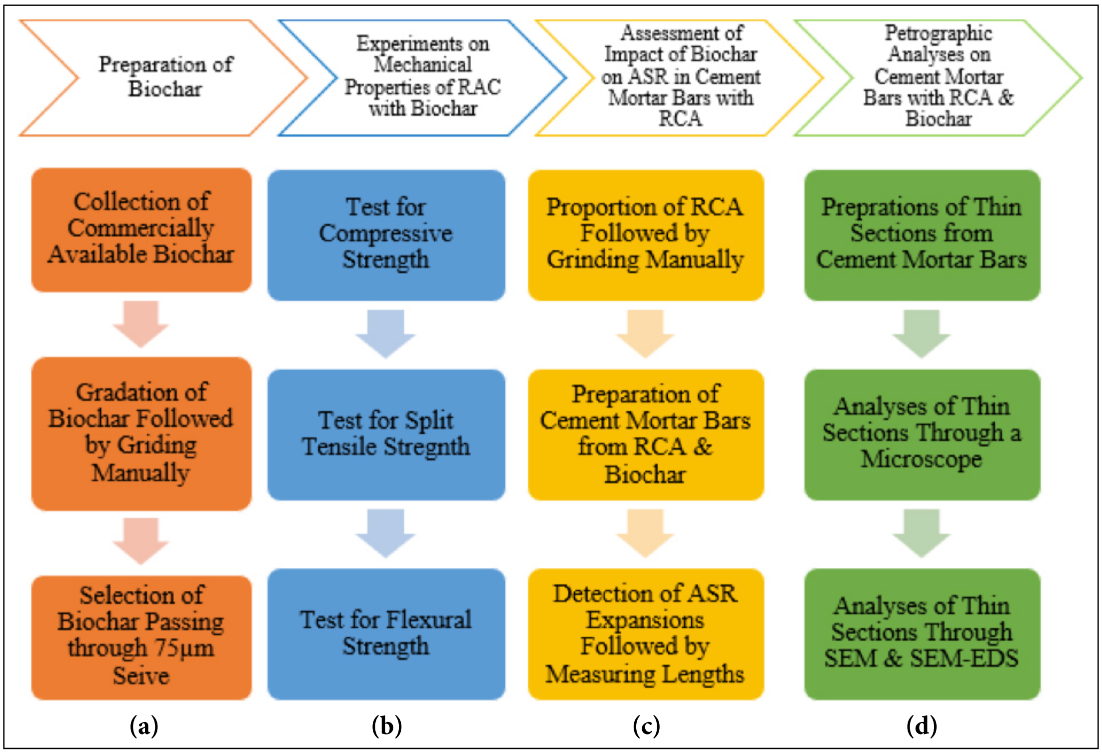

Figure 1. Methodology adopted in the research.

Table 3 describes prominent properties of coconut shell biochar, such as elemental percentages of Carbon, Hydrogen, Nitrogen, Oxygen, ash content, potentials of hydrogen (pH), electric conductivity (EC), Brunauer-Emmett Teller (BET), and including the ability to adsorb cations [24]. Based on these findings, coconut shell biochar was selected as an additive for testing in this research.

Coconut shell biochar, readily available in the western part of the Sri Lankan market, was obtained in bulk for the experiments. The coarse fraction of the biochar was separated from the lot, and biochar particles that had not undergone adequate pyrolysis were discarded upon physical observation. Specific biochar samples were then further assessed to confirm their potential as adsorbents for Na^+ and K^+ cations. Two particular tests, kinetic adsorption, and isotherm tests, which were not presented in this paper, were conducted to evaluate this potential.

2.2. Methods

The methodology adopted to investigate the effect of CSB on the alkali-silica reaction on RAC consists of several steps. The flow chart shown in Figure 1 illustrates a methodology composed of experiments and analytical steps. Accordingly, the key steps of the method are the preparation of biochar, experiments on mechanical properties of RCA with biochar, assessment of the impact of biochar in ASR within the cement mortar bars of RCA, and petrographic analysis on the cement mortar bars of RCA & biochar.

2.2.1. Preparation of Biochar

Commercially available coarse fractions of coconut shell biochar were ground manually. Then, the finer-size biochar particles that passed through a 75μm sieve were collected, as explained in Figure 1a. The selected biochar particles were mixed to ensure a uniformly distributed mix was available for the experiments.

Table 4. Material Compositions of test samples and nomenclature [31]

No	Sample Category	Sample ID	Biochar (%)	RCA % WRT to NCA	Material Compositions				Remarks
					Cement (kg/m³)	Biochar (kg/m³)	Sand (kg/m³)	Coarse Aggregate (kg/m³)	
1	NCA	NCA-C	0.0%	0%	320	0	847	1249	Control Sample
2		NCA-B	2.5%	100%	320	8	847	1249	Test Sample
3	RCA	RCA-C	0.0%	100%	320	0	847	1118	Control Sample
4		RCA-B	2.5%	100%	320	8	847	1118	Test Sample

RCA: Recycled concrete aggregate; NCA: Natural concrete aggregate.

Table 5. Material Compositions and the Nomenclature of Cement Mortar Bar Test Samples [31]

No	Sample Name	Aggregate Type	No Test Samples	Weight in grams			Coconut Shell Biochar (% out of cement)
				Aggregates	Cement	Water (Cement: Water=1:0.47)	
1	RCA-C	RCA	3	669	440	206.8	0.0%
2	RCA-B		3	669	440	206.8	2.5%
3	NCA-C	NCA	3	990	440	206.8	0.0%
4	NCA-B		3	990	440	206.8	2.5%

RCA: Recycled concrete aggregate; NCA: Natural concrete aggregate.

2.2.2. Experiments on the Mechanical Properties of RAC with Biochar

The mechanical properties of Grade 25 Recycled Aggregate Concrete (RAC), which consists of CSB and RCA, were examined (Fig. 1b). The mixed designs included replacing 2.5% of the binder with CSB and completely substituting the coarse aggregate with RCA. The samples were tested for compressive strength (cubes measuring 150x150x150 mm) according to the BS 1881, Part 116:1983 standard, split tensile strength (cylinders with a diameter of 150 mm and a height of 300 mm) based on the BS 1881, Part 117:1983 standard, and 3-point flexural strength (beams with dimensions of 100 mm in height, 100 mm in width, and 400 mm in length) by the BS 1881, Part 118:1983 standard after curing for 28 days. The materials' compositions applicable for each mix design of each concrete batch used for preparing the samples are presented in Table 4, along with the nomenclature used in this research. According to Table 4, RCA-C and NCA-C represent control samples of RCA and NCA, respectively. Similarly, RCA-B and NCA-B explain CSB test samples. The compositions of the materials of cement, biochar, sand, and aggregate used in each sample are given in weight per unit volume (kg/m³). All tests were conducted using a universal testing machine (HLY 600KN/1000KN).

2.2.3. Assessment of the Impact of Biochar on ASR (Cement Mortar Bar Test)

In this research, ASTM C 1260 was employed to quantify the Alkali Silica Reaction (ASR). The cement mortar bar test (or prism test) specified by ASTM C 1260 is used to measure the percentage of expansion caused by ASR in aggregates within the prisms, as elaborated in Figure 1c. If the average expansion of triplicate samples exceeds 0.10% on the 16th day after casting, the corresponding aggregate is suspected of alkali-silica reactivity and requires further investigation for conclusive findings. Accordingly, the expansion percentages of test specimens in Table 5 were reviewed to assess the impact of biochar as an additive. Table 5 indicates the proportions of aggregate, cement, water, and biochar in each sample.

Figure 1c shows that cement mortar prisms were prepared using graded finer-size recycled concrete aggregate and natural coarse aggregate as described in the ASTM C 1260 standard. The steps in the standard are shown in the Figure 2. A triplicate of prism samples was prepared for each mix design. During the experiment, special attention was given to maintaining certain experimental conditions, including the dimensions of prism samples, the temperature of the water in the bath, and the concentration of NaOH solution.

As explained in the ASTM C 1260 standard, the following equation, denoted as equation (1), is used to calculate the expansion percentage of the specimen (Sn) after measuring the final length on the 16th day of the experiment.

$$\text{Expansion percentage of specimen } (S_n) = \frac{(L_f - L_0)\ x\ 100\%}{L_e} \quad (1)$$

Lf: final measurement of the length of the prism after 16 days
Lo: Initial measurement of the length of the prism after two days
Le: The gap between the heads of screws embedded in prisms

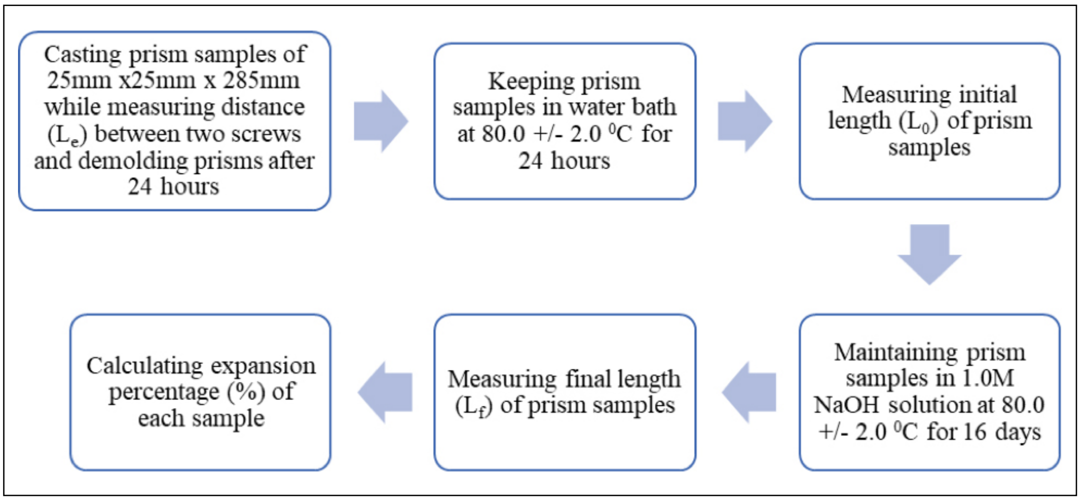

Figure 2. Key steps in the cement mortar bar test.

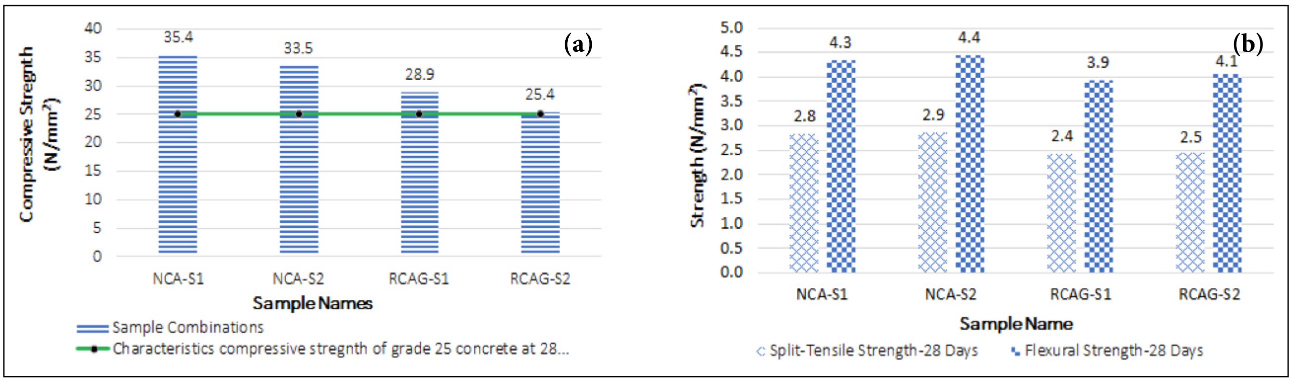

Figure 3. Test Results **(a)** Compressive Strength in 28 Days; **(b)** Split Tensile Strength in 28 Days; and Flexural Strength in 28 Days [31].

2.3. Petrographic Analysis and SEM Analysis on RAC Mix Designs

Three types of petrographic analysis (Fig. 1d) were conducted to examine the thin sections prepared from the respective cement mortar bars. The petrographic observations aimed to gain insights into the microscale structural features, textural characteristics, mineralogical compositions, and alterations (secondary reactions) of the cement matrices in RCA and NCA mixes with both 0.0% and 2.5% of Coconut Shell Biochar (CSB).

Firstly, optical microscopic assessments were performed using a ZEISS Primotech microscope from Oberkochen, Germany, equipped with Crossed Polarized Light (CPL) and Plane Polarized Light (PPL) on the designated samples. Secondly, to deduce the textural features and physicochemical processes at the micro and nanoscale levels of the samples, Scanning Electron Microscopy (SEM) analysis was carried out using a ZEISS-EVO LS15 microscope from Oberkochen, Germany.

Furthermore, additional SEM studies were conducted with energy-dispersive X-ray Spectrometry (SEM-EDS) using a ZEISS-EVO 18 microscope from Oberkochen, Germany. These SEM-EDS studies were utilized to identify the precipitates adsorbed onto biochar in the cement matrices of RAC for prisms cast from RCA and NCA.

3. RESULTS AND DISCUSSION

3.1. Mechanical Properties of RAC with Biochar as an Additive

The compressive strengths of RCA-B and NCA-B show a 12.1% and 5.4% decrease, respectively, compared to RCA-C and NCA-C, as illustrated in Figure 3. However, the compressive strength values obtained (Fig. 3a) are still within the specified target strengths for Grade 25 concrete [31].

Figure 3b displays the readings of split tensile strength and flexural strength tests performed on the samples from all four mix designs (Table 4). Notably, there is a noticeable increase in strength for RCA-B and NCA-B compared to their control samples (RCA-C and NCA-C) in both split tensile and flexural strength. RCA-B exhibits a gain of 4% in split tensile strength and 13% in flexural strength, while NCA-B demonstrates gains of 3% in split tensile strength and 10% in flexural strength. These results are aligned with the previous research findings on biochar-mixed concrete [21, 25, 43].

Overall, it can be concluded that coconut shell biochar, as an additive, enhances the mechanical properties of recycled aggregate concrete, namely split tensile strength and flexural strength, while achieving the targeted compressive strength at 28 days [31].

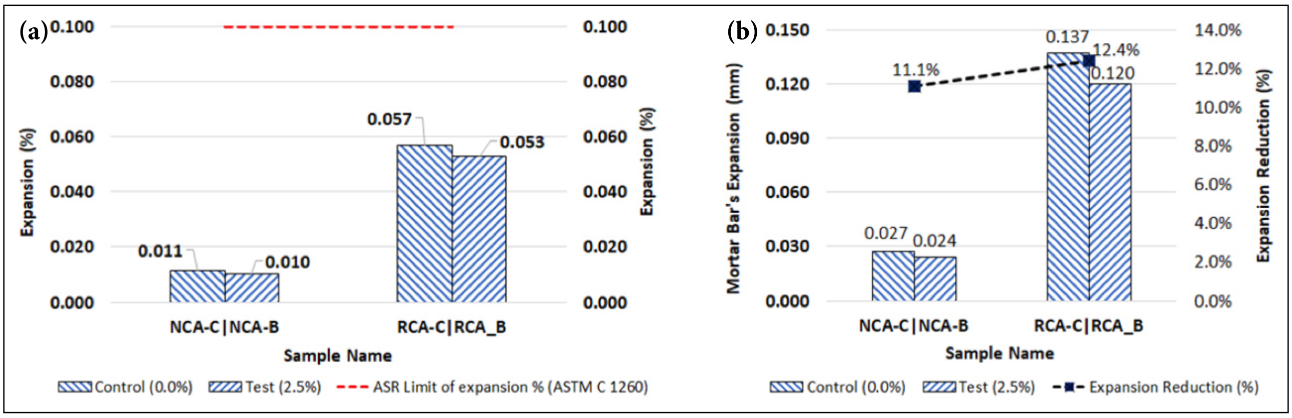

Figure 4. **(a)** Expansion percentages (%); **(b)** Expansion reduction percentages (%) in the cement mortar bar samples of RCA and NCA with 0.0% and 2.5% of CSB.

3.2. Assessment of the Impact of Biochar on ASR

Figure 4a presents the expansion percentages (%) of RCA-B and NCA-B compared to RCA-C and NCA-C. In contrast, Figure 4b indicates expansions in millimeters and reduction percentages for specific samples. The RCA-C and RCA-B samples exhibited expansions of 0.057% and 0.053%, respectively, while the NCA-C and NCA-B samples showed expansions of 0.011% and 0.010%, respectively. Since both RCA-B and NCA-B samples with biochar demonstrate a reduction in expansion, it can be concluded that Coconut Shell Biochar (CSB) has positively impacted the expansion of cement mortar bars caused by the alkali-silica reaction.

Accordingly, the ASR reduction percentage of RCA-B samples compared to the RCA-C samples is 7.0%. This reduction of ASR is caused by 2.5% (11.0 g) of CSB against 440 g of cement. Consequently, the ASR reduction percentage per gram of CSB and per gram of cement can be estimated as 0.0014%. A study conducted by Karalis et al. [18] reports ASR reduction when adding fly ash in percentages of 15% and 25% against cement (637.5 g), resulting in ASR reductions of 0.009% and 0.0011% per gram of CSB and per gram of cement, respectively. This suggests that adding 2.5% of CSB is more effective in reducing ASR than adding 15% or 25% of fly ash to concrete.

It can be stated that coconut shell biochar in each mortar bar with RCA and NCA has contributed to reducing the expansion of mortar bar samples by 12.4% and 11.1%, respectively, as illustrated in Figure 4b. The results of the experiments conducted with petrographic analysis and SEM analysis are further validated below.

Previous researchers have documented that Recycled Concrete Aggregate (RCA) has a higher potential for Alkali-Silica Reaction (ASR) compared to Natural Coarse Aggregate (NCA) [11, 44]. This is corroborated by the results presented in Figure 4a. In this research, RCA exhibited an ASR expansion (0.057%), five times higher than NCA's (0.011%).

The petrographic analysis allowed researchers to examine the microstructure (Fig. 5) of the cement matrices in mortar bars made from RCA and NCA, which were influenced by the presence of biochar. Therefore, the authors argue that the increased expansion observed in the samples with RCA is due to residual alkalis released by the adhered mortar present in RCAs, as visible in Figure 5. Furthermore, a higher density of cracks was observed on the surfaces of RCAs (Fig. 5) compared to NCA. These cracks' development (initiation and propagation) could create a favorable environment for forming ASR gel [10], leading to additional expansions. Simultaneously, ferrous compounds (FC) were observed at several locations (Fig. 5) within the cement matrices of RCA samples compared to NCA.

Reactive silica could exist in aggregates that are used to produce concrete. In the presence of alkali solution in the pores of concrete, particular reactive silica tends to react, producing leisurely but harmful cracks in the concrete structure [12]. Natural aggregates, generally in quartz, are composed of silica (SiO_2) and are recognized as chemically inactive [45]. Also, it is found that Ichikawa and Minura (2007) describe that silica (SiO_2) in aggregates is primarily structured as siloxane groups (≡Si – O – Si≡) or siloxane networks [12]. The same researchers argue that reacting reactive silica with an alkali solution would result in the disarrangement of crystalline silica at the surface of the arrangement. Further, they explain that when there is water, these structurally disordered crystalline silica inclines to absorb water and produce hydrous silica, which is amorphous and can be identified as a silanol group (≡Si – OH) in the pore solution [12, 45]. When highly concerted hydroxyl ions exist, the silica neutralizes the silanol and siloxane groups in two stages, as illustrated in equations (2) and (3), respectively [45].

$$\equiv Si{-}OH + OH^- = SiO^- + H_2O \quad (2)$$
$$\equiv Si{-}O{-}Si + 2OH^- = 2SiO^- + H_2O \quad (3)$$

The hydroxyl ions shown in both equations (1) and (2) are present in the concrete pore solution as NaOH or KOH [45, 46]. Equation (4) illustrates the products of alkali-silicate solution and gel that result from the reaction between siloxane groups and hydroxyl ions. The literature has used the notation R^+ to denote Na^+ or K^+ [12, 45].

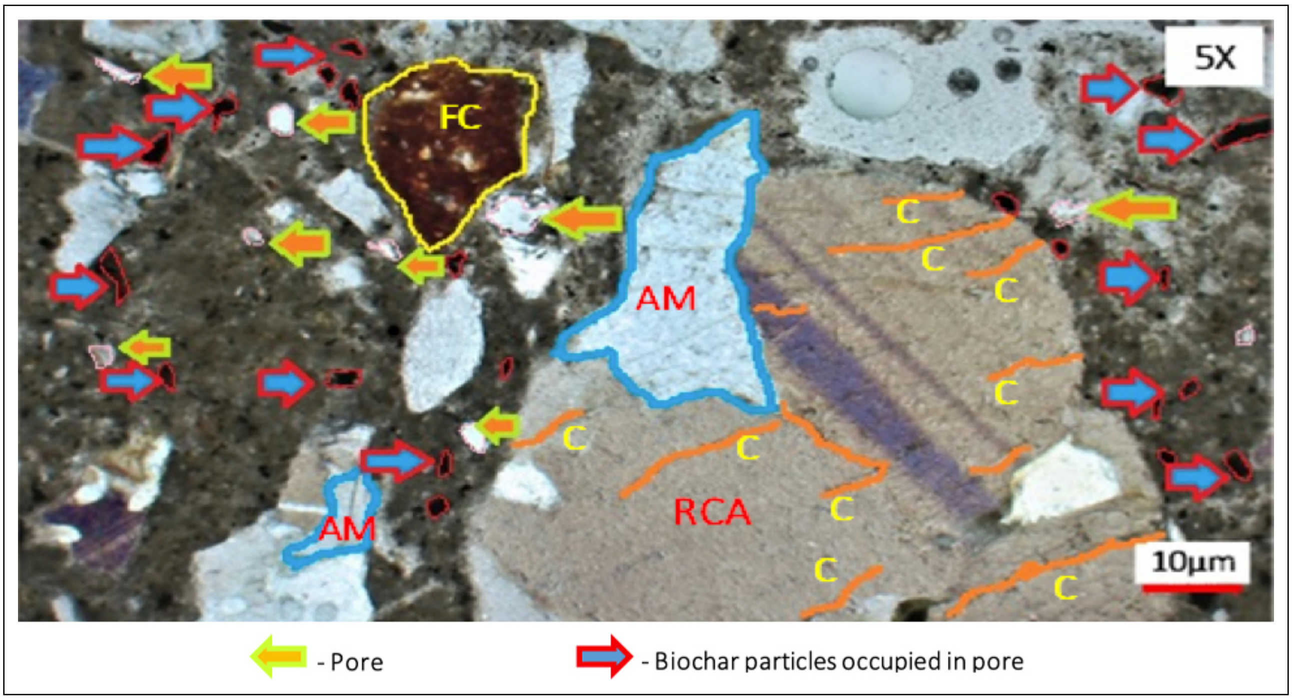

Figure 5. Microscopic view of a cement matrix comprised of RCA and biochar particles.

RCA: Recycled Concrete Aggregate Particle; AM: Adhered Morta; C: Cracks; FC: Ferrous Compound.

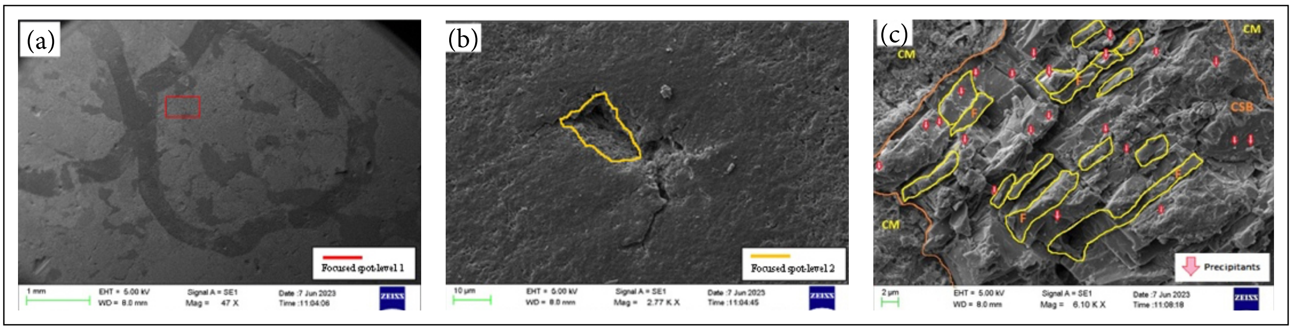

Figure 6. SEM images of precipitants adsorbed onto biochar in the cement matrix of RCA-B: **(a)** Focused level 1; **(b)** Focused level 2; (c) Focused level 3.

CM: Cement Matrix; CSB: Coconut Shell Biochar Particle; F: Flakes of CSB.

$$\equiv Si\text{-}O\text{-}Si\equiv + OH^- + R^+(Na^+ \text{ or } K^+) = \equiv Si\text{-}O\text{-}R + H\text{-}O\text{-}Si= \quad (4)$$

When there are higher contents of OH^- and alkali metals around the hydrous silica (Si-OH), the reactions designated by equations (5) and (6) would be further performed in the concrete pore solution. Finally, alkali-silica hydrate and water are identified as the ultimate products of the alkali-silica reaction.

$$\equiv Si\text{-}OH + OH^- + R^+ (Na^+ \text{ or } K^+) = \equiv Si\text{-}O\text{-}R + H_2O \quad (5)$$

$$\equiv Si\text{-}O\text{-}R + nH_2O = Si\text{-}O^- + (H_2O)_n + R^+ (Na^+ \text{ or } K^+) \quad (6)$$

Accordingly, the researchers primarily suspect that intervention in Alkali-Silica Reaction (ASR) has occurred due to biochar mixing, as there is a noticeable reduction in ASR expansions in biochar-mixed prisms. Consequently, SEM-EDS analysis was performed on the thin sections produced for petrographic analysis to identify the reactions caused by adding biochar. Figure 6 indicates some precipitation spots on flakes of biochar particles observed in the RCA samples through SEM-EDS analyses. Figure 6a highlights a spot (Focused level 1) observed on a thin section at the millimeter (mm) scale. Figure 6b shows the same place (Focused level 2) at the micrometer (μm) scale. Specifically, Figure 6c presents an enlarged version of the same spot (Focused level 3), with labels indicating the Cement Matrix (CM), Coconut Shell Biochar Particle (CSB), and Flakes of CSB (F). Figure 7a indicates the focused area of the precipitations, and Figure 7b illustrates specific precipitation spots of a biochar particle through the SEM-EDS study. The precipitation spots were identified as draw point no.1 FD 1) out of the 12 free draw points, and spectra were captured to one graph while having individual spectra for some points of the same lot. For clarity, only the spectra in Figures 7c and Figure 7d display the respective elements recognized from FD 1 and 2 points, respectively, based on their energy (keV) and intensity (counts) values. Several

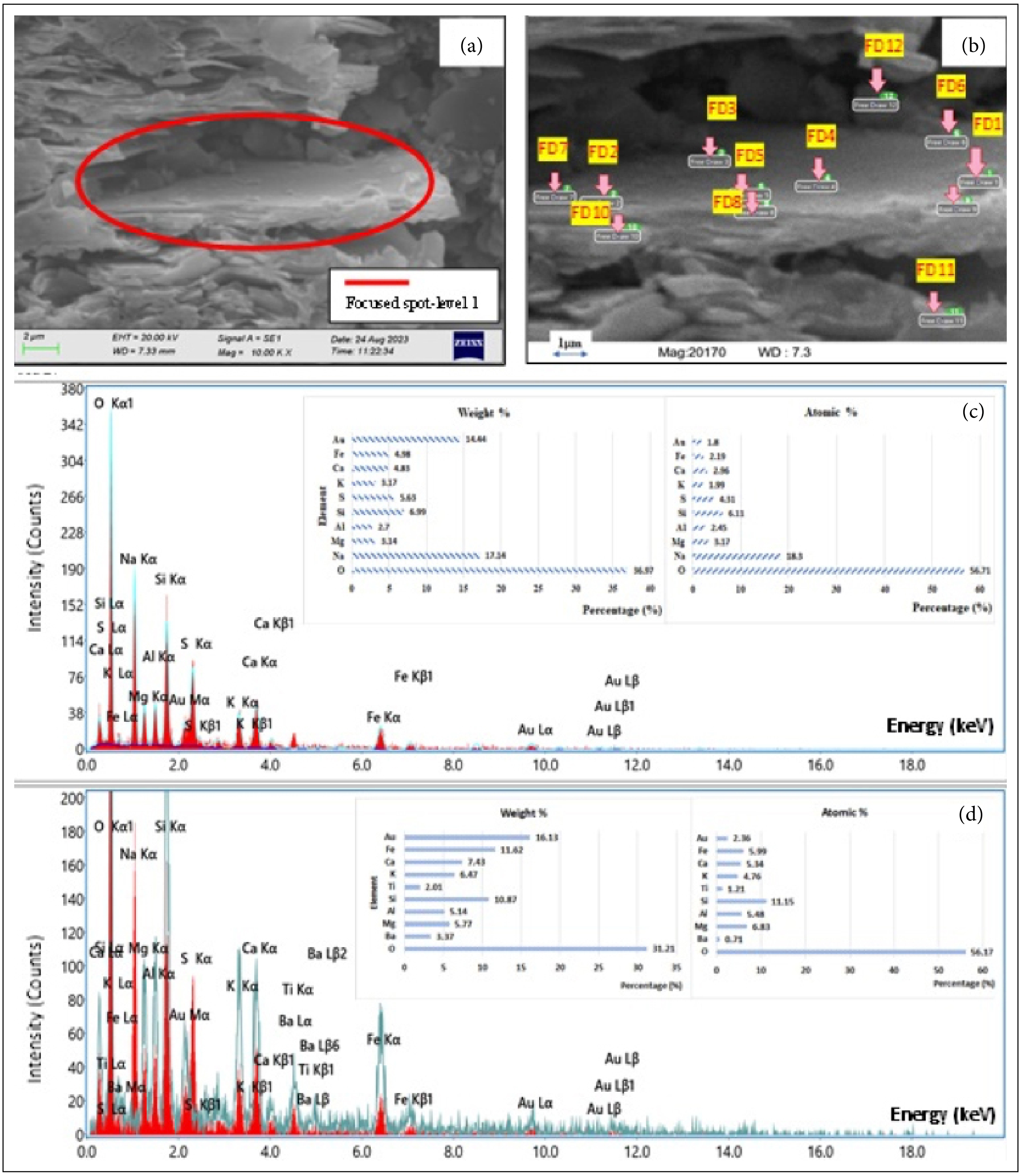

Figure 7. SEM-EDS images; **(a)** Focused-biochar particle; **(b)** Assessed free draw points (FD1–FD12); **(c)** and **(d)** SEM-EDS (Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy) spectra, weight (%), and atomic (%) of FD1 and FD2, respectively, in the sample of RCA-B.

chemical elements, including Na^+ and K^+, were found in FD 1 and 2. Similarly, the other free draw points (FD 3-12) were studied, and the availability of each element was reported as a percentage of weight relative to the total weight of elements counted at each spot. The minimum and maximum weight (%) values of each component for the 12 spots captured from the RCA-B sample are tabulated in Table 6.

Table 6 reveals the presence of Na^+ and K^+ elements in the precipitants adsorbed onto biochar particles. It was observed that the weight percentages (%) of Na^+ varied from 0.0% to 20.04%, while K^+ ranged from 0.0% to 18.33%. In contrast, biochar particles in the NCA-B samples showed zero weight percentages (%) for the element Na^+, with K^+ ranging from 3.61% to 7.07%. Consequently, biochar has

Table 6. SEM-EDS results: Presence of elements (minimum and maximum) in the precipitants found on biochar within the cement matrix of RCA-B and NCA-B [47]

No	Element	Weight (%)			
		RCA-B		NCA-B	
		Minimum	Maximum	Minimum	Maximum
1	C	–	13.54	4.40	51.17
2	O	–	43.21	19.89	44.16
3	Na	–	20.04	–	–
4	Mg	–	8.54	1.73	4.91
5	Al	–	7.86	2.28	8.45
6	Si	3.95	15.92	5.12	15.03
7	S	–	6.58	–	–
8	K	–	18.33	3.61	7.07
9	Ca	2.86	59.18	0.96	4.50
10	Ba	–	5.54	–	1.60
11	Ti	–	13.35	1.06	3.36
12	Fe	5.82	44.53	7.99	16.03
13	Co	–	1.30	–	–
14	Pd	–	–	–	1.20

RCA: Recycled concrete aggregate; NCA: Natural concrete aggregate; SEM-EDS: Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy.

adsorbed Na^+ and K^+ from the cement matrix of RCA-B and NCA-B samples. Therefore, it is factual to assert that coconut shell biochar is an additive that can be utilized to mitigate the alkali-silica reaction in Recycled Aggregate Concrete (RAC) when controlling the presence of cations such as Na^+ and K^+ (R^+ in above Eq. (6)).

According to Figure 4b, although there are relatively similar reduction percentages in expansion for RCA-B and NCA-B, Table 6 indicates that biochar particles in the RCA-B samples have absorbed more cations than those in the NCA-B samples. Several factors may have contributed to this difference. For instance, in addition to Na^+ and K^+ elements, biochar in the RCA-B and NCA-B samples has adsorbed Fe (Ferrous) elements in the range of 5.82% to 44.53% and 7.99% to 16.03%, respectively. Comparatively, a higher weight (%) of Fe elements is observed in RCA than in NCA [47].

4. CONCLUSIONS AND RECOMMENDATIONS

The authors draw the following conclusions based on their investigation into the utilization of Coconut Shell Biochar (CSB) as an additive to mitigate the Alkali-Silica Reaction (ASR) in Recycled Aggregate Concrete (RAC):

I. It was found that incorporating 2.5% of CSB into RAC resulted in a 4% increase in split tensile strength and a 13% increase in flexural strength. Although a marginal decline of 12.1% in compressive strength compared to the 0.0% CSB mix remained within acceptable limits of target strength for grade 25 concrete. Thus, as an additive, coconut shell biochar enhances the mechanical properties of recycled aggregate concrete.

II. Notably, including coconut shell biochar in cement matrices with RCA and NCA has reduced the expansion by 12.4% and 11.1%, respectively. This suggests coconut shell biochar can mitigate ASR in recycled aggregate and conventional concrete.

III. It has been estimated that the reduction in ASR due to the addition of CSB is 0.0014% per gram of CSB and gram of cement. A smaller amount of CSB could outperform a higher amount of fly ash regarding ASR reduction.

IV. There was a tendency for the development (initiation and propagation) of micro cracks in RCA compared to NCA, which is identified as a reason for additional expansions in RAC due to ASR in RCA. Additionally, residual ferrous compounds leached from reinforcements in the parent concrete were observed in several locations of the cement matrices of RCA, more so than in NCA.

V. Finer biochar particles act as fillers and occupy a significant amount of pore space in the cement matrices. This fineness allows for a uniform distribution of biochar particles throughout the cement matrix, ensuring consistent performance.

VI. The authors assert that CSB mitigates ASR by leveraging biochar's ability to adsorb cations such as Na^+ and K^+. Furthermore, CSB in RAC exhibited higher stress and workload than NCA in cation adsorption onto respective biochar particles, likely due to additional cations resulting from residual ferrous compounds in RCA.

VII. Finally, the authors recommend further investigations into using coconut shell biochar as an additive in RAC to control residual ferrous compounds in RCA.

The above conclusions are based on the Sri Lankan RCA and CSB; therefore, further studies are recommended to generalize these results to other world regions.

ACKNOWLEDGMENTS

The authors wish to convey their appreciation to the individuals and organizations who extended supportive contributions to the success of this research. The researchers would like to sincerely thank the COWAM Centre in Galle, Sri Lanka, and its management for kindly providing the RCA samples essential for this study. The technical officer and research assistants of the Department of Civil Engineering at the Open University of Sri Lanka, who made available timely assistance during the research, are acknowledged. Also, the staff of the thin-section preparation, SEM laboratories at the Department of Geology, University of Peradeniya, Sri Lanka, and SEM-EDS laboratories at the Faculty of Technology, University of Colombo, Sri Lanka, are appreciated.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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

USE OF AI FOR WRITING ASSISTANCE

Not declared.

PEER-REVIEW

Externally peer-reviewed.

REFERENCES

[1] Renne, N., Maeijer, P. K. D., Craeye, B., Buyle, M., & Audenaert, A. (2022). Sustainable assessment of concrete repairs through life cycle assessment (LCA) and life cycle cost analysis (LCCA). *Infrastructures, 7*, 128. [CrossRef]

[2] Oyenuga, O. A., & Bhamidimarri, R. (2015). Economic viability of construction and demolition waste management in terms of cost savings - A case of UK construction industry. *Sci Eng Invest, 4*(43), 16-23.

[3] Ginga, C. P., Ongpeng, J. M. C., & Daly, M. K. M. (2020). Circular economy on construction and demolition waste: A literature review on material recovery and production. *Materials, 13*, 2970. [CrossRef]

[4] Arandara, A. K. P., Priyadarshana, S. T., Paranavithana, G. N., & Dissanayake, R. (2022). A review on utilization of C & D waste for road and pavement construction in the international context and applicability of the findings to Sri Lanka. *Road and Airfield Pavement Technology Lecture Notes in Civil Engineering*, (p. 757-770). Springer. [CrossRef]

[5] Wijayasundara, M. (2019). *Recycled concrete*. Elsevier. [CrossRef]

[6] Junak, J., & Sicakova, A. (2017). Concrete containing recycled concrete aggregate with modified surface. *Proc Eng, 180*, 1284-1291. [CrossRef]

[7] Naik, T. R., & Moriconi, G. (2005). Environmentally friendly durable concrete made with recycled materials for sustainable concrete construction. *J Struct Eng, 61*(1), 237-244.

[8] Wagih, A. M., Karmoty, H. Z. E., Ebid, M., & Okba, S. H. (2012). Recycled construction and demolition concrete waste as aggregate for structural concrete. *J Housing Building Nat Res Center, 9*, 193-200. [CrossRef]

[9] Silva, S. R. D., & Andrade, J. J. O. (2022). A review of mechanical properties and durability of concrete with construction and demolition waste (CDW) and fly ash in the production of new concrete. *Sustainability, 14*, 6740. [CrossRef]

[10] Trottier, C., Ziapour, R., Zahedi, A., Sanchez, L., & Locati, F. (2021). Microscopic characterization of alkali-silica reaction (ASR) affected recycled concrete mixtures induced by reactive coarse and fine aggregates. *Cement Concr Res, 144*, 106426. [CrossRef]

[11] Santos, M. B., Brito, J. D., & Silva, A. S. (2020). A review on alkali-silica reaction evolution in recycled aggregate concrete. *Materials, 13*, 2625. [CrossRef]

[12] Ichikawa, S., & Miura, M. (2007). Modified model of alkali-silica reaction. *Cement Concr Res, 37*, 1291-1297. [CrossRef]

[13] Bavasso, I., Costa, U., Mangialadi, T., & Paolini, A. E. (2020). Assessment of alkali-silica reactivity of aggregates by concrete expansion test in alkaline solutions at 38°C. *Materials, 13*, 288. [CrossRef]

[14] Sutter, L. L. (2020). *Overview of alkali-silica reactivity in concrete pavements*. https://www.intrans.iastate.edu/wp-content/uploads/2020/12/MAP-briefWinter2020.pdf (Accessed Mar 19, 2025)

[15] Lehmann, J., & Joseph, S. (2009). *Biochar for Environmental Management*. Earthscan.

[16] Nagarajan, V. K., Devi, A., Manohari, S. P., & Santha, M. M. (2014). Experimental study on partial replacement of cement with coconut shell ash. *Int J Sci Res, 3*(3), 651-661.

[17] Ajien, A., Idris, J., Sofwan, N. M., Husen, R., & Seli, H. (2023). Coconut shell and husk biochar: A review of production and activation technology, economic, financial aspects, and application. *Waste Manag Res, 41*(1), 37-51. [CrossRef]

[18] Karalis, K., Kollias, K., Bartzas, G., Mystrioti, C., & Xenidis, A. (2021). CO_2 sequestration using fly ash from lignite power plants. *Mater Proc, 5*, 131. [CrossRef]

[19] Adams, M., Burrows, V., Richardson, S., Drinkwater, J., & Gamboa, C. (2019). *Bringing embodied carbon upfront*. World Green Building Council.

[20] Jeyakaran, T., Dilushran, C., Nivoshan, S., & Thamboo, J. A. (2017). *An investigation of engineering properties of high-strength concrete containing rice hush ash and recycled aggregates*. 8th International

Conference on Structural Engineering and Construction Management, Kandy, Sri Lanka.

[21] Barissov, T. (2021). *Application of biochar as a beneficial additive in concrete* [Master's Thesis], University of Nebraska.

[22] Khitab, A., Ahmad, S., Khan, R. A., Arshad, M. T., Anwar, W., Tariq, J., Khan, A. S. R., Khan, R. B. N., Jalil, A., & Tariq, Z. (2021). Production of biochar and its potential application in cementitious composites. *Crystals, 11*, 527. [CrossRef]

[23] Maljaee, H., Madadi, R., Paiva, H., Tarelho, L., & Ferreira, V. M. (2021). Incorporation of biochar in cementitious materials: A roadmap of biochar selection. *Constr Build Mater, 283*, 122757. [CrossRef]

[24] Gupta, S., & Kua, H. W. (2019). Combination of biochar and silica fume as partial cement replacement in mortar: Performance evaluation under normal and elevated temperature. *Waste Biomass Valor, 11*, 2807-2824. [CrossRef]

[25] Akhtar, A., & Sarmah, A. K. (2018). Strength improvement of recycled aggregate concrete through silicon-rich char derived from organic waste. *J Clean Prod, 196*, 411-423. [CrossRef]

[26] Gupta, S., Wei, K. H., & Dai, P. S. (2019). Effect of biochar on mechanical and permeability properties of concrete exposed to elevated temperature. *Constr Build Mater, 234*, 117338. [CrossRef]

[27] Lei, W., Liang, C., Daniel, T. C., Binglin, G., Jian, Y., Zhengtao, S., Deyi, H., Sik, O. Y., & Sun, P. C. (2020). Biochar as green additives in cement-based composites with carbon dioxide curing. *J Clean Prod, 258*, 120678. [CrossRef]

[28] Silica Fume Association. (2022). *Silica fume user's manual - Second edition*. https://www.silicafume.org/pdf/silicafume-users-manual.pdf (Accessed Mar 20, 2025).

[29] Thomas, M. D., Fournier, B., & Folliard, K. J. (2013). *Alkali-aggregate reactivity (AAR) facts book*. Federal Highway Administration.

[30] Agarwal, R., Vidyarthi, U. S., Gupta, U. C., & Sivakumar, N. (2017). Alkali-silica reaction (ASR) mitigation in concrete by using lithium nitrate. *Int J Eng Appl Sci, 4*(3), 5-7.

[31] Arandara, A. K. P., Paranavithana, G. N., Priyadarshana, S. T., Pitawala, H. M. T. G. A., & Dissanayake, R. (2024). Evaluation of coconut shell biochar on recycled aggregate concrete through petrographic studies. *Constr Build Mater, 428*, 136342. [CrossRef]

[32] Zhang, Y., Wang, S., Feng, D., Gao, J., Dong, L., Sun, S., Huang, Y., & Qin, Y. (2022). Functional biochar synergistic solid/liquid-phase CO_2 capture: A review. *Energy Fuel, 36*(6), 2945-2970. [CrossRef]

[33] Deiyagala, D. A. T. H., Priyadarshani, P. G. N., Perera, M. A. N., Pallewatte, T. M., Samarawickrama, M. N. C., & Tibbatuwawa, D. P. M. B. (2017). Engineering and economic viability of using crushed construction waste in production of concrete and mortar. *Engineer, 3*, 41-53. [CrossRef]

[34] Nili, M., Hoseinian, M., & Ahmadi, S. (2012). *Mechanical properties of concrete containing high volume of recycled concrete aggregates and waste glass*. 10th International Congress on Advances in Civil Engineering, Ankara, Turkiye.

[35] Poongodi, K., Moorthi, P., Gobinath, R., Srinivas, A., & Sangeetha, G. (2019). Mechanical properties of pavement quality concrete using recycled aggregate. *Int J Innov Technol Explor Eng, 9*(1), 33-38. [CrossRef]

[36] Ansary, M. A., & Iyengar, S. R. (2013). Physiochemical characterization of coarse aggregates in Qatar for construction industry. *Int J Sustain Built Environ, 2*, 27-30. [CrossRef]

[37] Neil, K. M., & Kang, T. H. K. (2013). Recycled concrete aggregates: A review. *Int J Concr Struct Mater, 7*, 61-69. [CrossRef]

[38] Safiuddin, M., Alengaram, U. J., Rahaman, M. M., Salam, M. A., & Jumaat, M. Z. (2013). Use of recycled concrete aggregate in concrete: A review. *J Civ Eng Manag, 19*(6), 796-810. [CrossRef]

[39] Savitha, R., & Ranatunge, N. B. M. (n.d.). *A study on types and quality of aggregates used in building construction*. https://www.nbro.gov.lk/images/content_image/publications/symposia/2010/a_study_on_types_and_quality.pdf (Accessed Mar 20, 2025).

[40] Gayani, J. K. U. (2010). *Rigid pavement design with recycled concrete aggregate for low volume roads*. http://dl.lib.uom.lk/items/7665fe88-7ace-4991-a973-baffdffc4112 (Accessed Mar 20, 2025).

[41] Echeverri, J. L. M., Martinsen, V., Strand, L. T., Zivanovic, V., Cornelissen, G., & Mulder, J. (2018). Cation exchange capacity of biochar: An urgent method modification. *Sci Total Environ, 642*, 190-197. [CrossRef]

[42] Paranavithana, G. N., Kawamoto, K., Inoue, Y., Saito, T., Vithanage, M., Kalpage, C. S., & Herath, G. B. B. (2016). Adsorption of Cd^{2+} and Pb^{2+} onto coconut shell biochar and biochar-mixed soil. *J Environ Earth Sci, 75*, 484. [CrossRef]

[43] Gupta, S., Krishan, P., Kashani, A., & Kua, H. W. (2020). Construction and building materials. *Constr Build Mater, 262*, 120688. [CrossRef]

[44] Boehme, L., & Joseph, M. (2016). *Assessment of the ASR expansion of concrete made with recycled concrete aggregates*. CESB16, Prague.

[45] Fanijo, E. O., Kolawole, J. T., & Almakrab, A. (2021). Alkali-silica reaction (ASR) in concrete structures: Mechanisms, effects, and evolution test methods adopted in the United States. *Case Stud Constr Mater, 15*, e00563. [CrossRef]

[46] Godart, B., Rooij, M. R., & Wood, J. M. C. (2013). *Guide to diagnosis and appraisal of AAR damage to concrete structures*. Springer. [CrossRef]

[47] Arandara, A. K. P., Paranavithana, G. N., Priyadarshana, S. T., Pitawala, H. M. T. G. A., & Dissanayake, R. (2024). Investigating coconut shell biochar as a sustainable solution for removing iron residues in recycled concrete aggregates. *Clean Technol Environ Pol, 2024*, s10098-024-03029-0. [CrossRef]