Research Article

Contribution of Surface Treatment on Physical and Mechanical Properties of Recycled Concrete Aggregates

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The demand for virgin aggregates for concrete production worldwide has been increasing. At the same time, there is an increase in the production of rubbles from construction-related activities. The residues are produced either due to leftovers or from the demolished structures. However, worldwide, the utilization of recycled concrete aggregate (RCA) material for structural concrete has been limited, often considered inferior due to distorted surfaces. The problems with RCA arise because it is a composite aggregate made of natural aggregate and cement, and adhered surface mortar is the discontinuities on the surface that arise from the production technique or the strength of the original concrete. The development of hydrated calcium silicate binder in the concrete matrix has been the critical desire of researchers to make better concrete material. This research focuses on the treatment of RCA from locally available rice husk ash with minimum pozzolanic cement. The objective was achieved by conducting tests on the properties of aggregates that include specific gravity and water absorption, aggregate crushing value (ACV), and aggregate impact value (AIV). The effectiveness of the treatment technique is assessed by the analysis of SEM imagery and XRD analysis of the microstructure cement paste around the RCA. At 20% pozzolan concentration, RCA treatment yields comparable specific gravities, water absorption, ACV, and AIV. Furthermore, the replacement of 5% rice husk ash (in 20% concentration) provided the optimal proportion of treatment for RCA, resulting in a reduction of ACV by 31.4%, AIV by 30.0%, and water absorption by 12.7% compared to the untreated RCA. XRD showed that calcite ($CaCO_3$), quartz, and portlandite phases were the majority in the untreated RCA. The study indicates that pozzolanic cement with 15% can be used with 5% RHA to produce RCA with characteristics almost similar to virgin aggregates. This research presents a consistent methodology to achieve modified RCA for application in construction.

1. Introduction

Around the world, infrastructural development has been measured by physical facilities such as good roads and structural buildings. These facilities consume a lot of aggregate and cement, which is the main binder of aggregates. About 40 billion tons of natural coarse aggregates (NCA) are used to make concrete worldwide, leading to the scarcity of these resources [1]. The consumption of natural aggregate for the production of concrete has been very high; in fact, in the year 2020, the Kenya National Bureau of Statistics

(KNBS) estimated that 20 billion metric tons were used [2, 3], an increase of 20% from the year 2015. With over-consumption and reliance on natural aggregates comes the associated environmental degradation and depletion of the resource [4–8].

The construction industry is also considered the major contributor of concrete waste, which comes from old, demolished concrete structures [9, 10]. To constructively utilize these wastes in construction, RCA is obtained by manual or mechanical crushing of parent concretes [11]. However, RCA as a material is known to have compromised

mechanical qualities than virgin aggregates. It is characterized by high porosity and preexisting interior fractures (due to crushing procedures). This is likely to present a significant variation of residual mortar and original virgin aggregate amount, which therefore determines the key properties of RCA [12]. According to Malešev et al. [13], the amount of old cement mortar ranges from 25% to 65% by volume of RCA. The proportion also differs in certain fractions where the smaller the fraction, the greater the amount of cement mortar, as well as the level of water absorption. Therefore, the amount of adhered mortar depends mainly on the crushing method during the recycling process [13].

Engineers and stakeholders have always shied away from reusing RCA given its fragile nature being of low quality due to the adhered surface mortar resulting in low performance in concrete [12, 14, 15]. Indeed, according to Krezel et al. [16], the aggregate consists of 24% cement paste residue and fines content of approximately 2%, which can significantly influence the characteristics of new concrete with RCA. This study seeks to modify the structure of RCA using a targeted pozzolanic treatment of surface mortar for better performance compared to NCA.

The quality and source of RCA greatly influence its performance in terms of compressive strength regardless of the replacement ratio [17]. Shahbazpanahi et al. [1] suggested that some of the critical aspects that affect the properties of coarse RCA include water-to-cement ratio, age, source of parent concrete and moisture content, amount of adhered mortar within RCA, and the crushing method adopted to retrieve the coarse RCA [18]. The inherent features of RCA, such as attached mortar, microcracks, and old ITZ, adversely affect its quality compared to virgin aggregate [19]. Various attempts of RCA are normally used with the view that it will perform the same function and contribute the same contribution as natural aggregates in concrete production for structural performance. However, the physical properties of RCA depend on the quality of adhered mortar.

Nedeljković et al. [20] noted that the key limiting properties of RCA are identified as high water absorption, particle agglomeration, and surface-adhered mortar. The high absorption rate of water is a common phenomenon mainly due to defects and fissures caused by the crushing process during production [18]. Therefore, the continuous quality of RCA is challenging to obtain, although they may be more consistent in terms of chemical composition. Furthermore, the recycling of mixed parent concretes causes inconsistent quality, physical and compositional variations in RCA concrete, the use of different recycling techniques, and the storage of recycled material. However, some of the key challenges in using recycled concrete aggregates have been the source's determination and the fractured surface, which is composed of natural aggregate and attached porous hydrated cement mortar.

To a large extent, the mortar on the attached surface defines the properties and characteristics of the new aggregate, which is high in water absorption, low density, low impact, and crushing value, often resulting in reduced

performance of the new concrete. The weak properties of RCA could be due to the low quality and strength of the original concrete or the attached mortar. A study by Lu et al. [7] indicates that the old ITZ of RCA makes the new concrete microstructure more fragile due to higher porosity and cracks, which could have resulted from fractures at the processing stage or low grade of parent concrete, thus acting as the weak link.

Ostrowski et al. [21] suggested that aggregate-specific parameters are crucial in defining the properties of the concrete mix and the physical and mechanical properties of hardened concrete. These crucial aggregate parameters are not only limited to their type and particle size distribution but also their surface morphology. This is the case for normal strength concrete (NSC), high-performance concrete (HPC), self-compacting concrete (SCC), lightweight concrete (LWC), and concrete made from RCA [21]. In addition, aggregate shape morphology and properties are influenced by the crushing method adopted [1, 13, 18] and thus affected the compressive strength of the resulting concrete [21].

An investigation of the effect of the aggregate types, source, and origin on properties of concrete by Beshr et al. [22] found that the quality of coarse aggregate has a significant effect on the compressive strength, split tensile, and modulus of elasticity of high strength concrete. Therefore, in the author's opinion, based on the study by Beshr et al. [22], the condition of the aggregate surface will contribute significantly to the physical and hardened properties of the resulting concrete.

Prajapati and Karanjit [17] suggested that given that approximately three-quarters (3/4) of the quantity of concrete is occupied by aggregate, its quality is of great importance in concrete. Aggregate not only influences the strength of concrete, but its quality also affects the durability and structural performance of concrete. The coarse aggregate quality is controlled by its source, size, shape, unit weight, and texture. Kalra and Mehmood [23] emphasized that the quality of the mortar mix for better concrete performance and the strength of the coarse aggregate are also vital, as they dictate the strength of the resulting concrete. Ahmad and Alghamdi [24] noted that the effect of the coarse aggregate type is very low when the strength of the mortar controls the compressive strength of the concrete mixture. Indeed, this is the case for normal concrete, but in the case of RCA, there is an additional interfacial transitional zone (ITZ) created due to the attached mortar [7, 19, 20, 25–28].

According to Tang et al. [9], the hardened properties of concrete utilizing coarse RCA depend on parameters that include the percentage by the proportion of RCA used, RCA sources, crushing method, and size and quality of RCA. In addition, Shaban et al. [29] pointed out that the main issue of RCA hindering its adoption as a construction material is weak surface-adhered mortar, which is highly porous and thus allows ingress of water within the concrete matrix. For this reason, the aggregate produces a strength comparatively lower than virgin aggregate due to weak ITZ, a key influencer of mechanical properties. Therefore, in order to make RCA more effective as structural concrete material, the

quality and property of the weakly attached mortar must be improved.

Various combinations of mixing approaches and surface pretreatment methods with different pretreatment materials (cement slurry and cement slurry plus silica solution) have been developed and optimized to improve the compressive strength of RCA [30]. According to Liang et al. [30], coating RCA with a suitable pretreatment material can fill the pores of the residual cement paste on the aggregate because the pores of the residual cement paste can absorb large amounts of water, leading to poor workability and low strength of RCA. Therefore, the study by Liang et al. [30] adopted various pretreatment materials and mix methods, namely mortar mixing approach (MMA), sand enveloped mixing approach (SEMA), and two-staged mixing approach (TSMA), to improve the compressive strength of concrete containing RCA. As a result, the study used water-to-cement (w/c) ratios between 0.49 and 0.43 and achieved a compressive strength of 27.6–43.3 MPa, sufficient for structural application.

Shaban [31] studied the properties of RCA soaked in pozzolan slurries containing varied proportions of fly ash, silica fume, and nano-silica fume. The study concluded that the aggregate water absorption was reduced by 50–55%, while particle densities increased by 10-11%. The improved performance of the basic properties was attributed to the fact that the pozzolan slurry soaking methods generally helped to strengthen the weak adhered mortar around the RCA surface. This is achieved when pozzolanic materials react with the hydrous compounds (C–H) in the adhered mortar [5], leading to the formation of new hydrated compounds, C–S–H (gel) [31].

Wang et al. [18] suggested that the mechanical and durable properties of recycled concrete aggregate (RCA) must be improved to make it effective for use in structural concrete. They noted ways to improve RCA by strengthening or improving the mortar matrix and the interfacial zone (ITZ). One of the methods that prove to be cost-effective and environmentally friendly is the chemical approach that uses the pozzolanic treatment of the mortar matrix and the ITZ of RCA to reduce the defects in the structure of the RCA.

Indeed, Givi et al. [32] stated that pozzolanic reactive material could be used to improve the surface area of the interfacial transition zone (ITZ) between the microstructure of cement paste and aggregate. The production of calcium silicate hydrates from the pozzolanic reaction contributes to the densification of the concrete microstructure to decrease porosity and increase the strength of ITZ. Golewski [33] suggested that an improvement in ITZ is positively influenced by mineral additives such as fly ash (FA) which is rich in silica, and can change the morphology of ITZ of RCA. RHA has high silica in the amorphous phase [32], so it will only be effective to perform the pozzolanic activity by reacting with a cementitious binder. RHA is a hydrophilic material (maximizes the physical contact with water) with a reducing affinity for water compared to an equivalent quantity of cement beyond 25% [32].

To improve quality and durability, it was observed that the use of supplementary cementitious materials (SCM)

delays the ingress of water and gasses into concrete with RCA [20]. In this research, the treatment method is proposed using pozzolanic cement (CEM II) and rice husk ash (RHA) through a pozzolanic reaction on the surface of RCA. Treatment with pozzolanic slurry changes mainly the microstructure of the old cement mortar around the original natural aggregate. Surface properties were determined by SEM and XRD analysis of the treated and untreated mortar around the surface of the RCA to determine the presence and proportions of compounds of calcium hydroxide and silicates through the hydration process induced by the treatment slurry. This was done to determine the chemical activities that contribute to its physical and mechanical performance.

1.1. Research Significance and Objectives.

Research, to date, on the use of RCA has been more geared to the usage of the aggregate in concrete. Existing research has reported and evaluated the viability of the aggregate in concrete. However, reduced performance has been observed, citing drawbacks related to surface characteristics that consist of adhered mortar loosely held on virgin aggregate and fractures resulting from the aggregate production process. In addition, the mechanical properties of RCA are generally lower than those of conventional concrete due to the higher porosity, lower density, and higher water absorption of the recycled concrete aggregate. Therefore, prior treatment of RCA is essential before the aggregate is used for structural performance. This study focuses on the modification of the RCA surface through an induced chemical reaction process to improve the microstructure properties around the aggregate.

This research proposes a method for producing hydrated calcium silicate using a pozzolanic slurry containing cement and RHA to treat the surface of RCA. The RHA contains amorphous silica, and hence it contributed to the enhancement of various concrete properties [34, 35]. Furthermore, the induced reaction (hydration of cementitious elements) results in increased quantities of hydrated calcium silicate (C–S–H) gel production that fills the gaps and strengthens the fractures within and around RCA. Finally, an optimum content of cement and RHA is established in the treatment slurry that results in an aggregate with adequate physical properties to guide the usage of treated aggregate in the construction industry.

2. Materials and Methods

2.1. Coarse Aggregate Sourcing and Preparation.

In this research, RCAs were obtained from laboratory concrete lumps of normal strength concrete samples in the form of flexure beams, cubes, and cylinders. One of the challenges with RCAs is ascertaining consistent quality from sources. Therefore, the virgin coarse aggregates for normal strength concrete samples were prepared and are of sizes ranging between 5 and 20 mm, sourced from a local supplier, Warren Concrete Limited (K), in Kiambu County, Kenya. The parent RCA laboratory-based concrete was class C30 with a mix

proportion, as shown in Table 1. The strength of the parent concrete used was determined using Universal Testing Machine (UTM) with a capacity of 1500 kN, and other crucial details of virgin aggregates (denoted as NCA) and RCA are shown in Table 1. The laboratory-tested concrete samples were manually crushed using a small claw hammer crusher into RCAs in the size range of 5–20 mm. The particle sizes passing through a 5-mm standard sieve were discarded as were composed fine particles.

To ensure all the coarse aggregates in this research meet the required sizes, sieve analysis for particle gradation was done according to BS 882 [36], as shown in Figure 1. The coarse aggregates (NCA and RCA) were classified as well graded as the particle distributions were within the grading envelop as provided in ASTM: C33/C33M−13 [37]. This meant that the coarse aggregates used in concrete for this investigation met the necessary criteria and could thus be utilized to produce concrete for the research without the need for blending. The particle size distribution of RCA is similar to the sieve curve of NCA, with little variation.

Apart from the aggregate size distribution, the preliminary physical and mechanical properties of the aggregates were determined. Table 2 presents the results of coarse aggregates' physical and mechanical properties. The aggregates used were confirmed to comply with BS 882 [36], which details necessary tests before being used (see Table 2). Comparatively, there is a clear distinction between the general properties of NCA and RCA. These differences can be explained by the weaknesses within the additional mass of adhered cement paste on the original natural aggregate.

Figure 2 displays the physical feature of the natural and recycled concrete aggregates used in this study. Natural coarse aggregate is composed of the pure status of virgin aggregate, while the RCA is composed of original natural aggregate and attached mass of hydrated cement paste clinging on the surface of natural aggregate. From visual inspection of the RCA, the adhered mortar has voids and ducts within its matrix. The presence of adhered cement paste is responsible for most of the distinctive features (given in Figure 2) of the two types of aggregates.

2.2. Properties of Pozzolanic Cement and Rice Husk Ash.
Pozzolanic cement (PC) and rice husk ash (RHA) were used to treat the surface of RCA in a liquid slurry form. The cement class C32.5 was procured from the local distributor of Bamburi Cement Company Ltd in Kenya. Figure 3(a) shows that RHA is more brownish with loosely held grains, while cement is dark grey coloration in Figure 3(b). The rice husk ash was obtained from Mwea, Kirinyaga County, Kenya and was prepared by burning rice husks for 2 hr at 450°C. The material was allowed to cool before RHA powder was sieved through a 300-μm sieve.

The RHA and cement were taken for chemical analysis to ascertain their crucial mineral compositions, which are given in Table 3. Table 3 shows that RHA has a high content of amorphous silicon, SiO_2 (at 88.18%), while the pozzolanic cement (CEM II) has a high calcium oxide (CaO, at 54.95%). The RHA used in this research was classified as class N

Table 1: Mix proportion and compressive strength of the parent concrete used to produce RCA.

Specifications	Values
Water-to-cement ratio	0.54
Cement (kg/m^3)	389
Water (kg/m^3)	210
Fine aggregates (kg/m^3)	645
Coarse aggregates (kg/m^3)	1052
Average compressive strength (MPa)	34 ± 4.49

pozzolan, because of silica, SiO_2, the proportion is greater than 70% [39]. These components are essential in the hydration process during the surface treatment of RCA. The hydration process is enhanced because the surface of the RCA also contains $Ca(OH)_2$ in addition to those produced by the hydration of the pozzolanic cement, which would fill the gaps in the RCA [40]. Therefore, RHA cannot be used alone but together with pozzolanic cement (PC) facilitates the binding effect in a proportion of cement through the hydration process.

Figure 4 illustrates the microstructure analysis of RHA and cement used to prepare the slurry solution for the treatment of RCA. The ground RHA and cement images were captured using a scanning electron microscope (SEM) at a 1000x magnification scale. Figure 4(a) for RHA shows a highly porous and honeycombed structure composed of numerous residual pores distributed within the ash samples indicating that the silica is active. Figure 4(b) shows a more compact structure of closely held particles within the cement matrix. The interparticle voids are seen to be smaller in cement than in RHA. Images suggest that the particles are more loosely bound, making them highly amorphous and reactive.

2.3. Surface Treatment Method of RCA.
To strengthen the surface of RCA, the adhered mortar, and the improved properties of RCA using cement slurry and RHA, the treatment process was achieved in two phases. First, cement slurry was used to treat in five (5) different treatment concentrations at an interval of 20% by weight of RCA (see Table 4). This was to determine the optimum cement slurry to treat the aggregates (RCA) effectively. Second, RHA proportions were used to replace content cement at an interval of 5%, as shown in Table 4.

Figure 5 demonstrates the treatment of RCA where cement slurry was prepared by first applying 20% of the mixing water to RCA to achieve SSD condition and then applying the remaining 80% to the pozzolanic slurry. RCA was introduced to the slurry, stirred for 5 minutes, and then the mix was soaked for 15 minutes. The aggregates were then removed from the treatment bath in a moist state. The coated aggregates were further air-dried at room temperature of 20°C for 3 days. Finally, the hardened RCA was sieved to remove the fine particles before carrying out the material tests. This process was adopted for both phases of the treatment process: for pure cement slurry and that containing cement and RHA slurry.
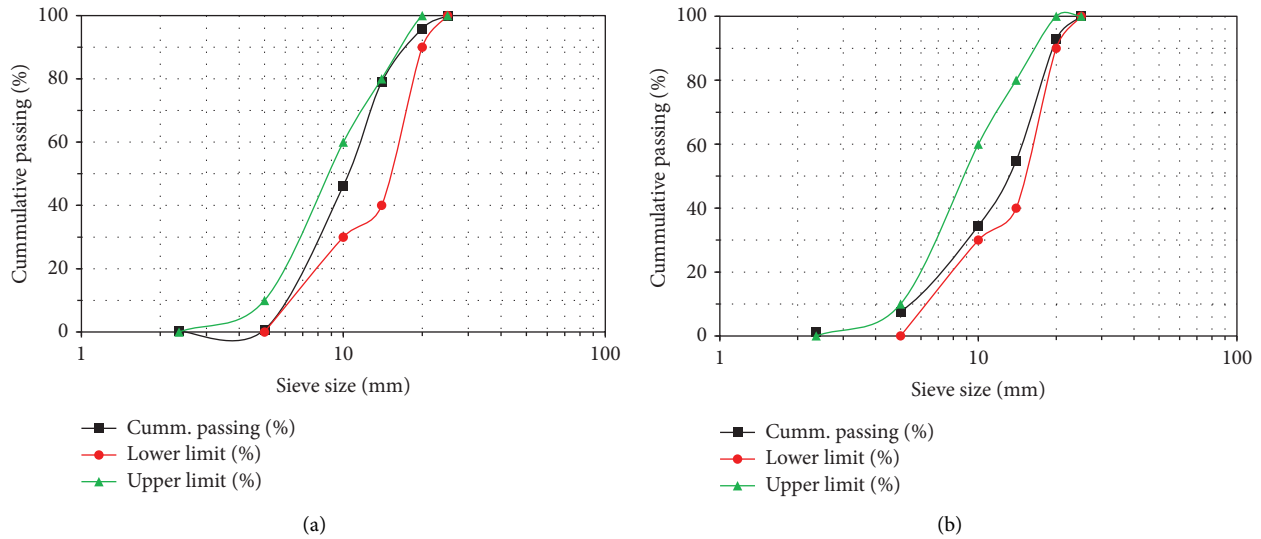
(a)

(b)

Figure 1: Sieve analysis for coarse aggregates: (a) particle distribution for NCA and (b) particle distribution for RCA.

Table 2: Physical and mechanical properties of coarse aggregates.

Properties	NCA	RCA
Specific gravity (SSD condition)	2.54 ± 0.07	2.4 ± 0.06
Specific gravity (ovendry condition)	2.45 ± 0.12	2.25 ± 0.08
Bulk density (g/cm^3)	1.6 ± 0.08	1.42 ± 0.09
Voids (%)	40.1 ± 3.12	44.2 ± 6.35
Water absorption (%)	3.36 ± 0.17	6.44 ± 0.36
Fineness modulus	2.78 ± 0.08	3.33 ± 0.18
Water content (%)	2.82 ± 0.03	3.3 ± 0.10
Aggregate impact value (%)	8 ± 1.20	19.2 ± 2.07
Aggregate crushing value (%)	14.8 ± 1.37	24.4 ± 2.19

(a)   (b)
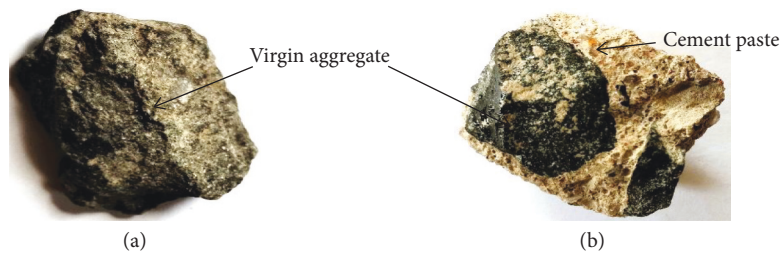
Figure 2: Coarse aggregates: (a) NCA and (b) RCA.

2.4. Scanning Electron Microscope Analysis. The surface-adhered cement paste has been identified as the main drawback of RCA [20, 28, 41]. The surface modification using cement and RHA slurry was done to strengthen the adhered mortar and, by extension, the properties of RCA. Microstructural analysis using SEM was employed to analyze the surface structure of RCA. SEM produces images by probing the samples with a focused beam of electrons, which interacts with atoms on the surface to produce various signals that contain information about a material. This study used JCM-7000 NEOSCOPE, the fourth generation, which can allow navigation through optical images at an increased maximum magnification of 100,000x. For the microstructure analysis of the mortar matrix, backscattered electron

images (BSE) were performed to detect with a low acceleration voltage at 15.0 kV and display images captured at magnifications of 2500x (2.5 μm) and 5000x (5 μm). Samples of approximately 10 grams of mortar were extracted from the surface of the original parent aggregate for SEM analysis. Using carbon tape, the powder mortar was mounted on a 15-mm thick metallic disk.

SEM was performed on the treated and untreated RCA aggregates to capture the effectiveness of the treatments of adhered mortar around the original natural aggregates. The microstructural development process was captured by visual observation of digital images to study the surface morphological and textual changes of RCA by SEM image analysis of the aggregate surfaces. Noticeable pores can be
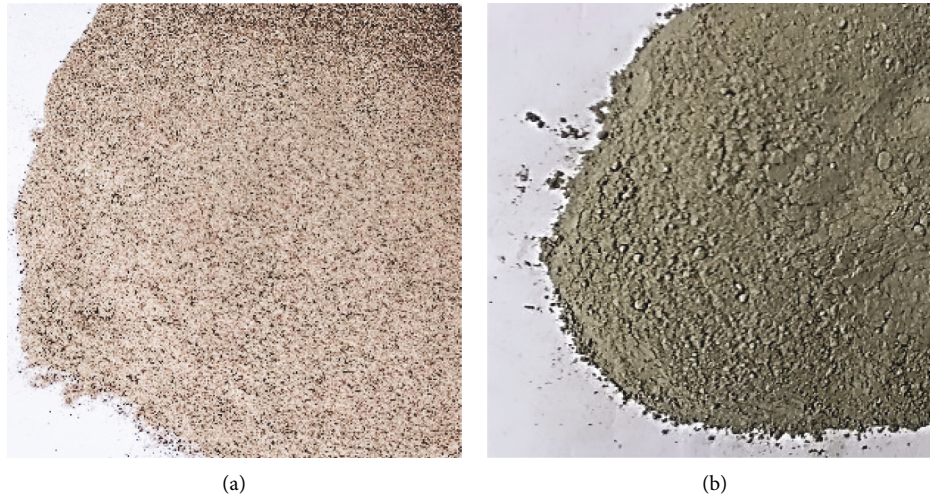
(a)   (b)

FIGURE 3: Pictorial photograph of rice husk ash and cement powder used.

TABLE 3: Chemical analysis of RHA pozzolan and pozzolanic cement.

Content	PC (%)	RHA (%)
Silicon dioxide, SiO_2	29.36 ± 0.01	88.18 ± 0.09
Potassium oxide, K_2O	2.62 ± 0.01	3.85 ± 0.01
Calcium oxide, CaO	54.95 ± 0.03	2.94 ± 0.02
Aluminium oxide, Al_2O_3	4.62 ± 0.01	—
Iron oxide, Fe_2O_3	4.74 ± 0.02	0.92 ± 0.01
Others	3.71 ± 0.01	4.11 ± 0.01
*LOI (%)	4.19 ± 0.02	4.59 ± 0.01

*LOI = Loss of ignition according to BS EN 196-2 [38].

identified from the grayscale contrast. Since the images are black and white, in terms of grayscale, the darkest areas of the image are recognized as porous areas.

2.5. X-Ray Diffraction (XRD) Analysis. The chemical mineralogy was examined by XRD, a technique in which the scattering of X-rays by atoms of a crystal produces an interference effect so that the diffraction pattern gives unique information about the structure and identity of the crystal. Various minerals diffract X-rays at their preferred orientations of the specified atoms but at varying intensity peaks. The intensity signifies the orderliness and quantity of the particles available, producing more light at the preferred orientation.

The X-ray diffraction (XRD) technique was recommended to provide information on the phase composition that forms during the hydration activities around the surface of RCA. In this research, the analysis was performed based on an Empyrean Diffractometer System with CuKα radiation ($\lambda = 1.5406$ Å). The electric current was 40 mA, and the working voltage was 45 kV. The specimens were scanned from $5°$ to $75°$ (2θ) with a $0.026°$ (2θ) step size and an accumulated time per step of 23.97 sec.

Similar to SEM analysis, sample proportions of about 10 grams of hydrated cement paste covering the original natural aggregate were retrieved for XRD analysis. The paste was then milled and then placed in a vacuum drying oven for 2 hours to allow possible moisture to evaporate before being sealed off.

3. Results and Discussion

3.1. Apparent Specific Gravity and Aggregate Water Absorption. Aggregate-specific gravity and water absorption properties are key aspects to suggest the structural formation of aggregate matrix. High specific gravity and low water absorption could mean a more compact structure of aggregate, an indication of a stronger comparatively. However, low specific gravity and high water absorption could indicate a more heterogenic material mass with many weak points. Therefore, the specific gravities and water absorption test for coarse aggregates were carried out according to EN 1097-6 [42].

Figure 6 shows that the specific gravity range is between 2.56 and 2.71, where untreated RCA gave the lowest value of 2.56. On a contrary trend, the water absorption fluctuates depending on the type of aggregate but the values are within the limits 5–15% for lightweight aggregates, according to Zulkarnain and Ramli [43]. Among the RCA category, R-20 and R-40 show the lowest water absorption of 6.95 and 6.83%, respectively, which are still lower than the untreated RCA by 29.4% and 30.7%, respectively. The comparatively low values can be explained by a reduction in the network of voids and cracks within the paste by the hydration product C–S–H.

The presence of water from the treatment slurry initiates a pozzolanic reaction on the surfaces, pores, and microcracks of RCA involving the utilization of $Ca(OH)_2$ to insoluble C–S–H gel. This improves the aggregate structure of the aggregate matrix by reducing the network and the size of pores and cracks within the recycled concrete aggregate. In addition, this increases the packing of elements by bonding loosely held particles together, reducing water absorption within the aggregate.
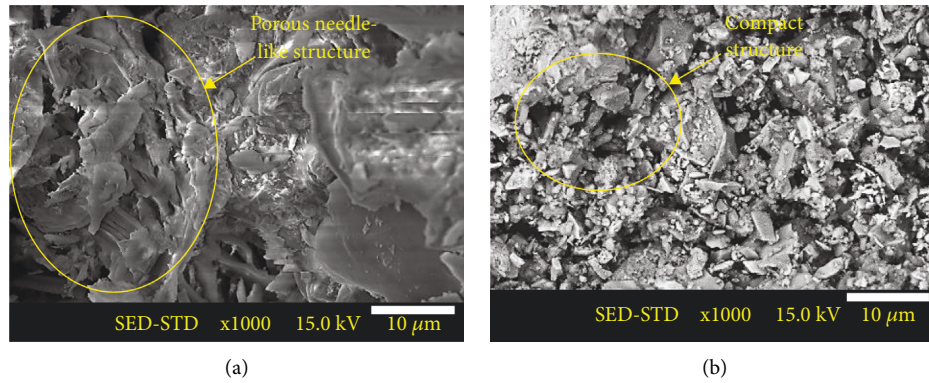
Figure 4: SEM imagery of rice husk ash and cement: (a) RHA and (b) PC 32.5.

Table 4: Proportion of treatment slurries.

Notation	Treatment slurries	Pozzolan concentration (%)	Binder (kg/m^3)		RCA (kg/m^3)	Water (kg/m^3)	Binder to water ratio
			PC	RHA			
RCA	—	0	—	—	—	—	—
R-20	20% PC	20	20	—	100	100	2 : 10
R-40	40% PC	40	40	—	100	100	4 : 10
R-60	60% PC	60	60	—	100	100	6 : 10
R-80	80% PC	80	80	—	100	100	8 : 10
R-100	100% PC	100	100	—	100	100	10 : 10
R-40|0	40% PC + 0% RHA	40	40	0	100	100	4 : 10
R-35|5	35% PC + 5% RHA	40	35	5	100	100	4 : 10
R-30|10	30% PC + 10% RHA	40	30	10	100	100	4 : 10
R-25|15	25% PC + 15% RHA	40	25	15	100	100	4 : 10
R-20|0	20% PC + 0% RHA	20	20	0	100	100	2 : 10
R-15|5	15% PC + 5% RHA	20	15	5	100	100	2 : 10
R-10|10	10% PC + 10% RHA	20	10	10	100	100	2 : 10
R-5|15	5% PC + 15% RHA	20	5	15	100	100	2 : 10
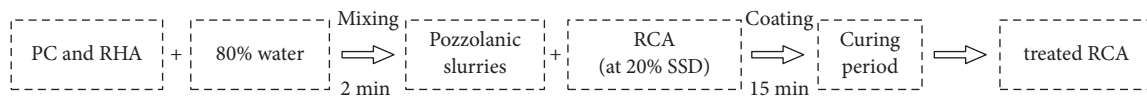
Figure 5: Schematic treatment process for RCA with pozzolanic cement and RHA slurry.

For samples treated with 20% pozzolanic concentration, Figure 7, the specific gravity ranged between 2.66 and 2.71, while water absorption showed a steady increasing trend up to 10% replacement, then drops at 15%. The drop of water absorption at 15% replacement can be attributed to increased unhydrated pastes and precipitates of $CaCO_3$, which serves no strength gain but rather filler substance within the pores of cement paste. The increased water absorption within the aggregate structure could be explained by the reduction in pH beyond the equilibrium concentration acidic condition. This leads to the dissolution of C–S–H and C–A–S–H by the actions of $Ca(OH)_2$ in the pore solution of the hydrated cementitious face of the matrix. This condition facilitates deterioration within the concrete, creating more pores that accumulate water in the aggregate matrix [44].

Works in literature have agreed that the main hydration products that occur on the surface of RCA are C–S–H and $Ca(OH)_2$ [45, 46], which are nanoscale materials with the highest proportion, 60% having a density of 2.604 mg/m^3 [47]. This explains the insignificant difference in apparent specific gravity of the samples treated at 20% and 40% concentrations using the pozzolanic cement and rice husk ask slurry. The apparent specific gravity ranged from 2.60 to 2.71. Similarly, low specific gravity and high water absorption compared to NCA have also been reported by Padhi et al. [15]. The attached mortar contains a large amount of $Ca(OH)_2$ [31]. The silica content in RHA facilitates the reaction with $Ca(OH)_2$ to form more C–S–H that increases the density of RCA [31] and fills the voids in the adhered mortar in RCA.

3.2. Aggregate Impact and Crushing Value.
The impact and crushing resistance test of coarse aggregates represent the toughness and fracture resistance of aggregate against the applied forces on the aggregate. Since coarse aggregate
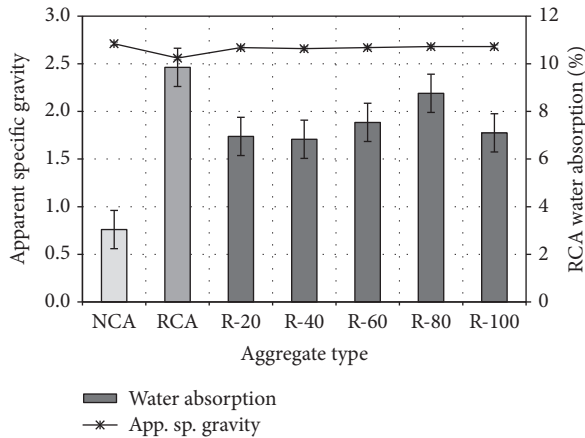
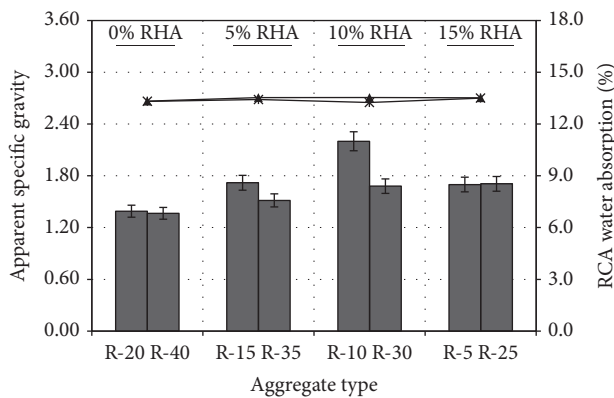FIGURE 6: Cement slurry on the treatment of RCA.

FIGURE 7: Effect of cement and RHA slurry on specific gravity and water absorption of aggregate.

constitutes more than 50% of the volume of concrete [48], it plays a role in determining the strength of concrete. Normal and high strength concrete is defined by the ability of the aggregate and cement paste to coalesce the resulting crack within the concrete matrix. In the case of RCA, the crack path may go through the mixing mortar or the attached mortar on the natural aggregate; hence the impact and crushing resistance are key to determining the strength of RCA.

The test for aggregate impact value (AIV) and aggregate crushing value (ACV) was carried out according to BS 812-112 [49] and BS 812-110 [50], respectively. Figures 8(a) and 8(b) give the experimental results of aggregate impact and crushing values for the RCA treated with varying concentrations of cement slurry. For the aggregate samples tested for impact resistance (Figure 8(a)), the results show that the impact was 8% for NCA, clearly lower than the untreated RCA, 27.4%. As expected, the natural aggregate falls under the category of exceptionally strong aggregates, as stated in IS 2386 (Part IV) cited by Das et al. [51]. RCA is known to be retrieved from used concrete, and the mechanical production process initiates tiny weaknesses within the ITZ zone. This explains the reduced resistance to impact and crushing effect.

However, the modification of RCA using cement slurry resulted in an approximate decrease in impact value by 21.9%, 22.6%, 24.5%, 31.8%, and 24.1% for R-20, R-40, R-60, R-80, and R-100, respectively. These outcomes were also depicted by the aggregate crushing value test, although with a slight variation in the trends across all types of aggregates (Figure 8(b)). Here, the ACV values for treated aggregates decreased to 21.9%, 22.6%, 24.5%, 31.8%, and 24.1% for R-20, R-40, R-60, R-80, and R-100, respectively, was observed for ACV. Aggregates treated with 20% and 40% gave the lowest values among the categories of recycled concrete aggregates.

This decrease is certainly due to surface treatment that improves the structure and surface of the RCA by filling the pores and voids with new hydrated products such as the C–S–H gel, which can reduce the stress singularity caused by them and thus increase the strength. Among the treatment concentration of the cement slurry, the results of the treated aggregates did not show significant change from the 95% confidence level, especially for impact values. However, for aggregates crushing value, samples treated with 20% and 40% concentration comparatively resulted in a significant reduction in the crushing value of 24.7% and 23.7% (see Figure 8), categorized as satisfactory [51].

The introduction and replacement of cement content in treatment slurry with proportions of rice husk ash were done to increase the quantity of silicon oxide (SiO_2) that facilitates the production of C–S–H gel. The reduction in impact resistance was 11.7%, 31.4%, 24.1%, and 19.0% for R-20|0, R-15|5, R-10|10, and R-5|15, respectively. Interestingly, there was a reduction in performance on further increase in concentration to 40%, the decrease in impact resistance was generally less than 20%. In Figure 9, it is observed that the impact value was reduced by 15.3%, 10.9%, 20.4%, and 24.8% for R-40|0, R-35|5, R-30|10, and R-25|15, respectively. This decline is particularly surprising considering the increase in cement within the slurry. This decrease is explained due to the reduced SiO_2, within which there is less C–S–H formation.

The treatment of RCA with 15% PC and 5% RHA produced the best impact resistance. This, therefore, suggested that the treatment methods and material had increased the strength and quantity of RCA. This is consistent with the findings by Wang et al. [27]. Furthermore, almost similar research by Saran and Magudeswaran [52] showed that silica fume and RA mixed with $Ca(OH)_2$ led to the production of more C–S–H, which fairly improves the strength of concrete.

Again in Figure 9(b), the test results for crushing value for the treatment decrease by 28.0%, 30.0%, 26.6%, and 25.7% for R-20|0, R-15|5, R-10|10, and R-5|15, respectively. Increasing concentration to 40%, the decrease in impact resistance was generally lower than 20%. From Figure 9, it is observed that the impact value was reduced by 20.9%, 23.6%, 18.1%, and 17.1% for R-40|0, R-35|5, R-30|10, and R-25|15, respectively.

These results demonstrate that treatment with pozzolanic material is effective in improving surface strength. Pozzolanic materials can react with $Ca(OH)_2$, the main
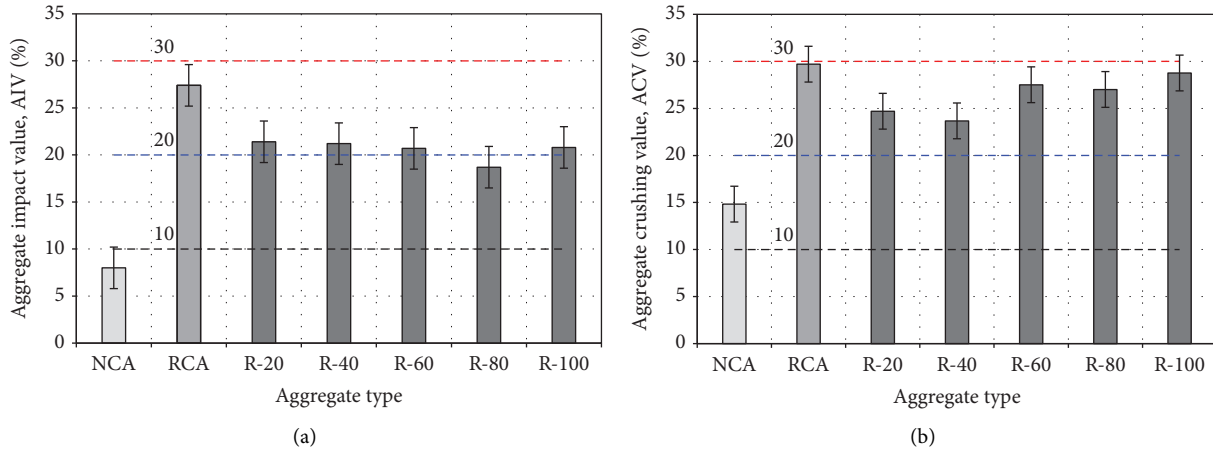
Figure 8: Effect of cement slurry on aggregate strength: (a) aggregate impact value and (b) aggregate crushing value.
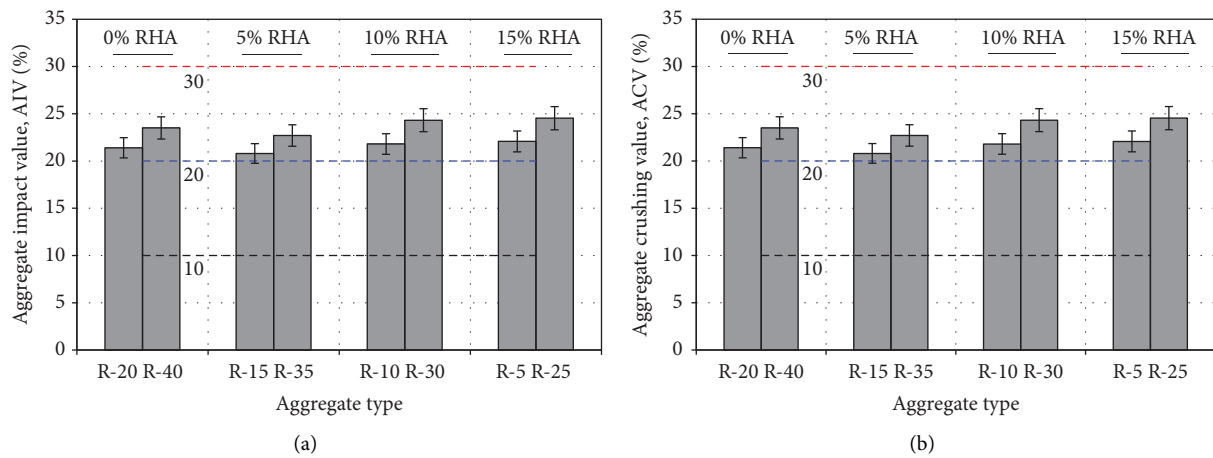

Figure 9: Effect of cement and RHA slurry on aggregate strength: (a) aggregate impact value and (b) aggregate crushing value.

component of the adhered mortar, forming new hydrated components, especially $Ca(OH)_2$, that solidify and occupy cracks and fractures within the mortar and enhance strength and the anti-crushing capability of RCA [31]. This could be explained by the fact that replacement of the cement proportion with an RHA with a high siliceous content that reacts with $Ca(OH)_2$, one of the by-products of initial cement hydration, results in an additional C–S–H gel, which results in increased strength [53]. Surprisingly, from both Figures 9(a) and 9(b), even though there was a slight decrease in 5% replacement of RHA with cement content in treatment slurry, a further increase beyond 5% resulted in increasing values of AIV and ACV accordingly.

3.3. Scanning Electron Microscope Analysis. Figure 10 illustrates the SEM imagery of cement paste drawn from untreated RCA. The image is marked with a large pore network within the paste matrix. Numerous pores are observed between the hydrated mass of elongated elements of C–S–H. This is likely an indication of pores that would be occupied by water, and other solutions are likely to be detrimental to concrete. RCA is characterized by high water absorption, which would eventually be stored within the pores.

The low density of the gel-like hydrated calcium silicates mass is observed on the pastes. In the same instance, numerous small particles of $Ca(OH)_2$ and calcium carbonate ($CaCO_3$) precipitates are sporadically observed on the surface of hydrated calcium silicate gel (C–S–H). As expected, the formation of $Ca(OH)_2$ is preceded by the hydration of cement to form C–S–H and $Ca(OH)_2$, which is transferred into a crystalline-like phase. Calcium hydroxide is an efflorescence in nature that escapes and diffuses to the exposed surfaces and pores within the cement paste. However, given the volatility of $Ca(OH)_2$ in the presence of CO_2, it is transformed to a whitish precipitate of $CaCO_3$ observed on the surface of C–S–H, as shown in Figure 10.

Figure 11 shows the imagery of cement paste from RCA treated with 20% cement slurry. The paste is characterized by the formation of C–S–H lamps ranging from small to big size. The lamped shapes of the gel could be seen throughout the mix. However, the surface of the hydrated paste looks like a marginal whitish formation, signifying the possibility
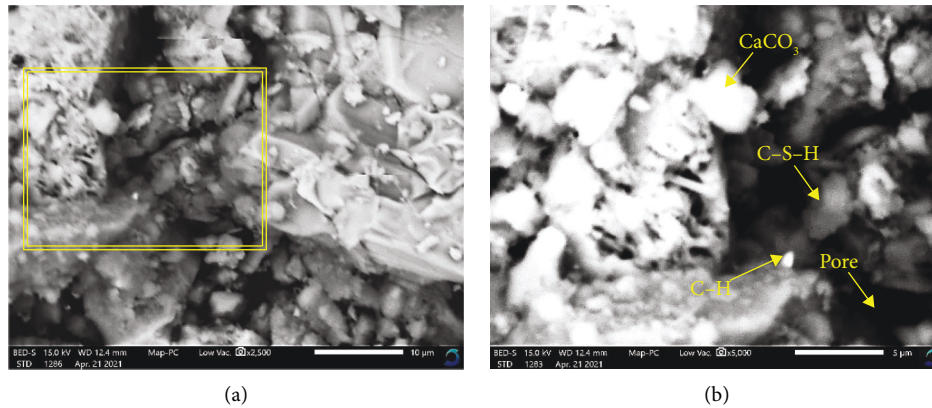
(a)   (b)
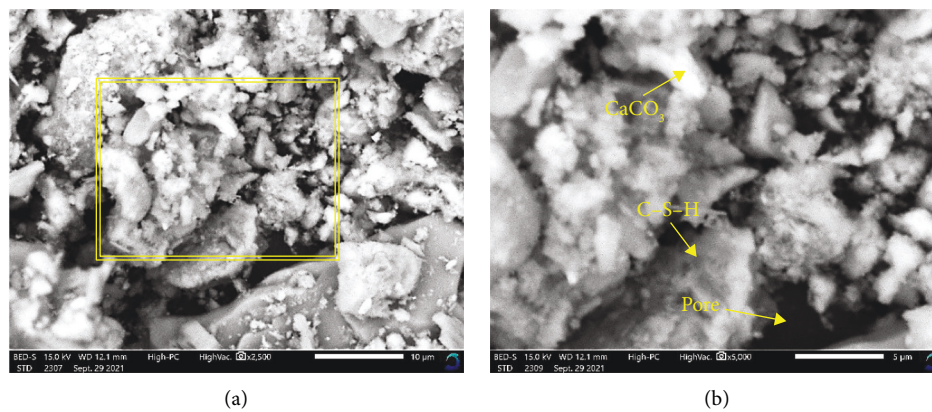
Figure 10: SEM analysis for RCA (untreated).

(a)   (b)

Figure 11: SEM analysis for R-20|0: (a) Mag. 2500 and (b) Mag. 5000.

of diffusion of portions of $Ca(OH)_2$ and $CaCO_3$ on the surface of the hydrated paste.

The formation of $CaCO_3$ could result from the carbonation process due to exposure to CO_2 from the air. The mix resulted in a more compact and homogeneous paste with lamps of hydrated gel, C–S–H, observed distributed throughout the paste. In addition, the number of pores is reduced compared to the untreated RCA. This could be explained by the better formation of C–S–H from the pozzolanic reaction of 20% cement slurry and excess $Ca(OH)_2$ from RCA. Thus, the paste was more homogeneous, and the strips of C–S–H were overly observed within the paste matrix. This indicates the formation of hydrated calcium silicates for the paste mix on the surface of aggregates. As a result, the surface looks more compact than untreated RCA, with fewer gaps or pores being observed.

In Figure 12, a homogeneous surface texture was observed with a series of grey elements of C–S–H. The mixture was more compact than R-20|0 and untreated RCA. This shows more conversion of the $Ca(OH)_2$ to form more hydrated pastes that fill the pores of the untreated RCA. The addition of 5% rice husk ash contributed more SiO_2 (silicon oxide) in silicic acid form, H_2SiO_3, reacted with $Ca(OH)_2$, leading to the formation of C–S–H. In this mix, more $Ca(OH)_2$ was contributed from the reaction of cement and

water together with excess $Ca(OH)_2$ present on the surface of RCA. The hydrated paste of C–S–H acts like a gel that fills the surface gaps and fractures on the aggregate surface. The SEM imagery showed that replacing the cement portion in the treatment slurry of 20% concentration with 5% of RHA improved the microstructure, attributed to the equilibrium pozzolanic reaction of the reacting components of hydration.

Figure 13 reveals the effect of replacing the proportion of cement with 15% RHA in the 20% slurry concentration for the treatment of RCA. It is observed that a large amount of unhydrated (UH) paste particles was formed. UH and hydrated paste particles are overly distributed, showing that at 15% RHA as pozzolan hindered the hydration process at the time of examination. As a result, few C–S–H lamps were formed, accompanied by a high proportion of unhydrated paste and $CaCO_3$. This phenomenon could result from incomplete hydration of $Ca(OH)_2$, given that the treatment slurry contains a high proportion of hydrophilic RHA, which absorbed water meant for the hydration process. Eventually, excess CaO from the cementitious treatment slurry instead reacts with CO_2 leading to the formation of calcite ($CaCO_3$). This, therefore, implies that the quantities and the volume of $Ca(OH)_2$ are tremendously reduced within the cement paste and treatment slurry because of the

(a)

(b)

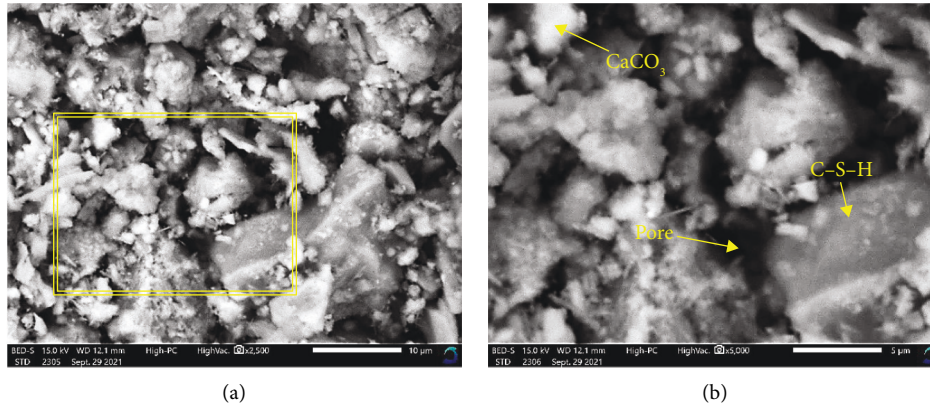Figure 12: SEM analysis for R-15|5: (a) Mag. 2500 and (b) Mag. 5000.
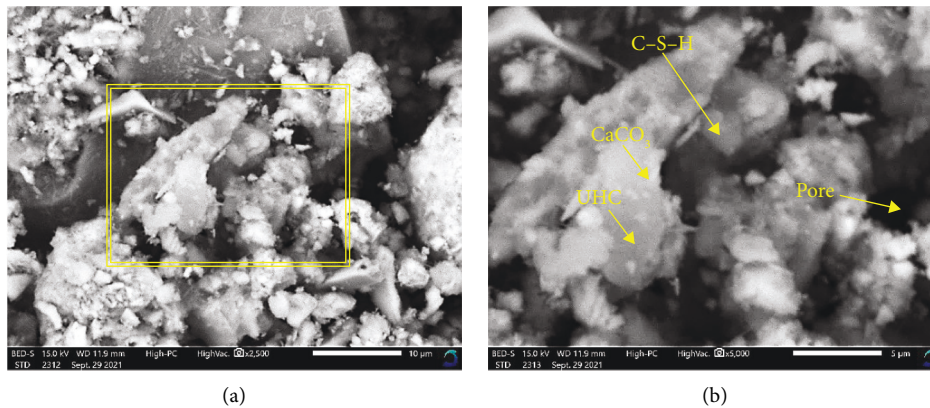

(a)

(b)

Figure 13: SEM analysis for R-5|15: (a) Mag. 2500 and (b) Mag. 5000.

consumption to form more C–S–H. A similar observation was made by Wang et al. [18].

From the SEM imagery shown in Figure 14, a complete hydration is observed with a high formation of C–S–H on the surface of the paste. The mix was characterized by layers of C–S–H shapes observed well distributed in the formation of lamps within the paste. This is a clear indication of maximum hydration achieved around the aggregate matrix. Increased formation of $CaCO_3$ because of increased cementitious elements and fewer C_3S, and less water contributing more CaO that could quickly be converted to a more stable compound, $CaCO_3$. However, there was a high formation of paste C–S–H lamps.

Figure 15 represents SEM imagery after replacing 5% RHA with proportions of the cement slurry at 40% pozzolanic treatment concentrations of RCA. The sample showed a more hydrated C–S–H mass even though pores were observed. This could indicate the hydration of $Ca(OH)_2$ forming C–S–H, but due to the presence of RHA, there were spots of reactions that occurred, leaving voids between hydrated mass.

Figure 16 displays the SEM image of cement paste for RCA treated with 25% cement and 15% RHA slurry. To a large extent, C–S–H formation reduces compared to the previous mixes with less RHA content. The additional 15%

of RHA can absorb water from paste, thus hindering the formation of $Ca(OH)_2$. Fapohunda et al. [54] reported that the lime-consuming agent is indeed composed of a high amount of SiO_2 that will react with amorphous $Ca(OH)_2$ to produce the C–S–H gel, and this has the effect of lowering the amount of $Ca(OH)_2$ in cement paste.

Reduction of $Ca(OH)_2$ formation facilitates the increase in the acidic condition by lowering pH within the matrix. This effect leads to two critical scenarios occurring within concrete. First, the existing $Ca(OH)_2$ on the surface of RCA are quickly converted to CaO and, finally, stable compound, $CaCO_3$. As a result, the precipitate of $CaCO_3$ deposits and accumulates in the pores of cement pastes. Second, more unhydrated cement paste and ettringite (C–A–S–H) formation increases.

3.4. X-Ray Diffraction (XRD) Analysis.

X-ray diffraction (XRD) was used to study the mineral composition and difference of the cement paste around the RCA. The samples in Figures 17–19 show that the samples were predominated by calcite and the portlandite mineral content of the paste was quartz, calcite, and portlandite as the primary minerals. The minerals have peaks at $2\theta \sim 26.5°$, $2\theta \sim 29.5°$, and $2\theta \sim 31°$ for quartz, calcite, and portlandite, respectively. However,
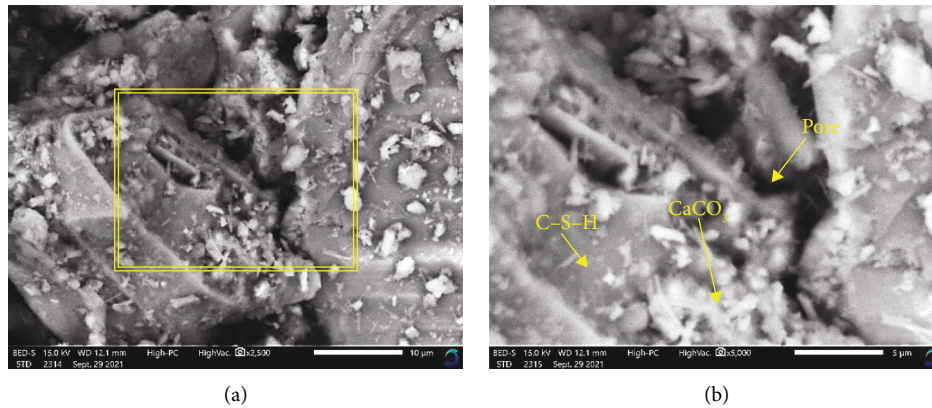
Figure 14: SEM analysis for R-40|0: (a) Mag. 2500 and (b) Mag. 5000.
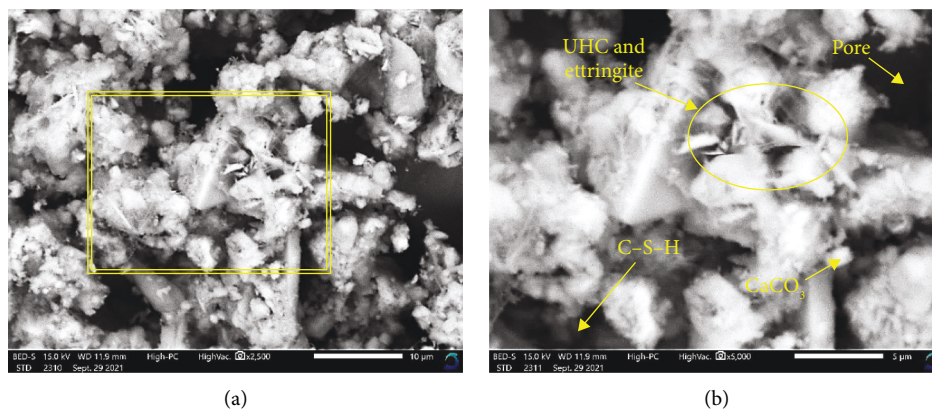

Figure 15: SEM analysis for R-35|5: (a) Mag. 2500 and (b) Mag. 5000.
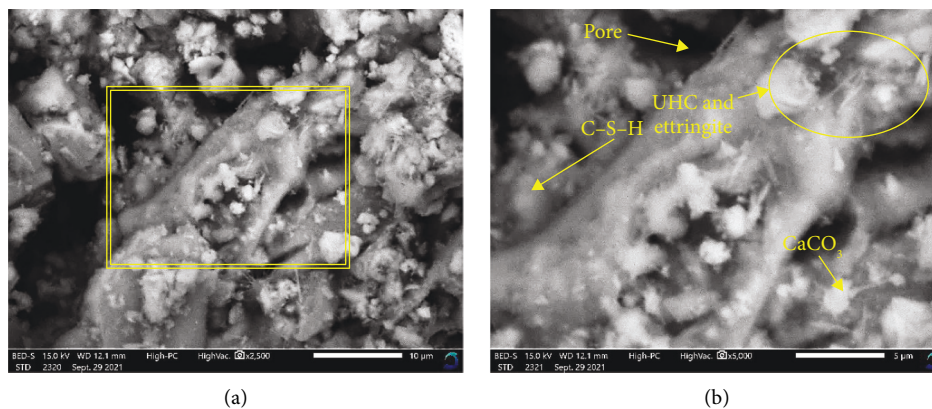

Figure 16: SEM analysis for R-25|15: (a) Mag. 2500 and (b) Mag. 5000.

the number of peak intensities for the samples differs depending on the content and concentration of the treatment slurry. The treatment slurry for the sample taken for XRD analysis contained cement and RHA in concentrations of 0%, 20%, and 40%. The XRD results show that all paste samples contain residual calcite. This is due to carbonization during the handling and preparation of the samples. The degradation leading to high intensity of calcite is probably due to the age factor that initiates the decomposition process of $Ca(OH)_2$ formed during hydration, as shown in the following equation [55].

$$Ca(OH)_2(s) \longrightarrow CaO(s) + H_2O(g) \qquad (1)$$
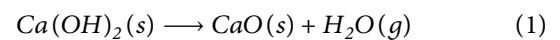
Calcite is a stable phase that contributes to a better filling effect [56] in the cementitious matrix around RCA, and the following equation (2) sows the carbonation process [55].
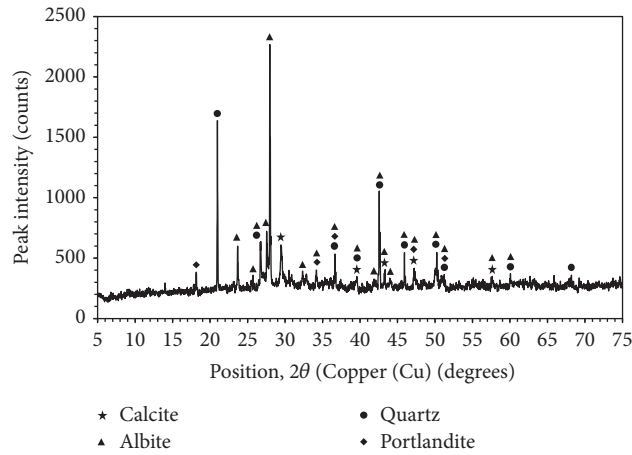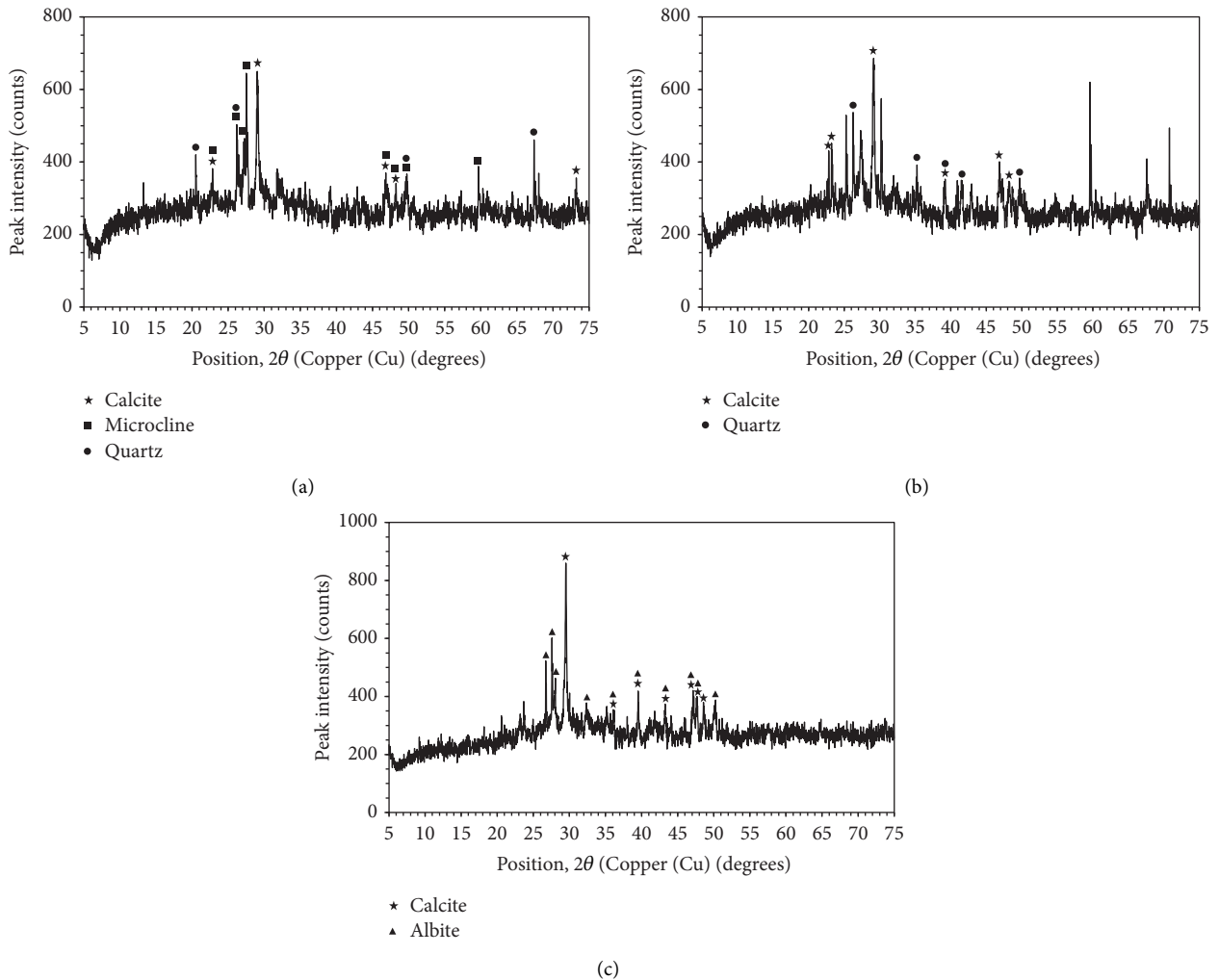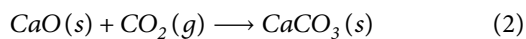
FIGURE 17: X-ray diffraction pattern for untreated RCA.

(a)

(b)

(c)

FIGURE 18: X-ray diffraction pattern for treated RCA with 20% slurry concentration: (a) XRD analysis for R-20|0, (b) XRD analysis for R-15|5, and (c) XRD analysis R-5|15.

$$CaO(s) + CO_2(g) \longrightarrow CaCO_3(s) \qquad (2)$$

The XRD pattern of the untreated RCA samples from laboratory waste is shown in Figure 17. In Figure 17, the laboratory-generated RCA samples, paste shows that the mineral crystal only constitutes calcite and portlandite. The analysis indicates the predominance of calcite peaks, and the proportion of portlandite, Ca(OH)₂, was the highest in the
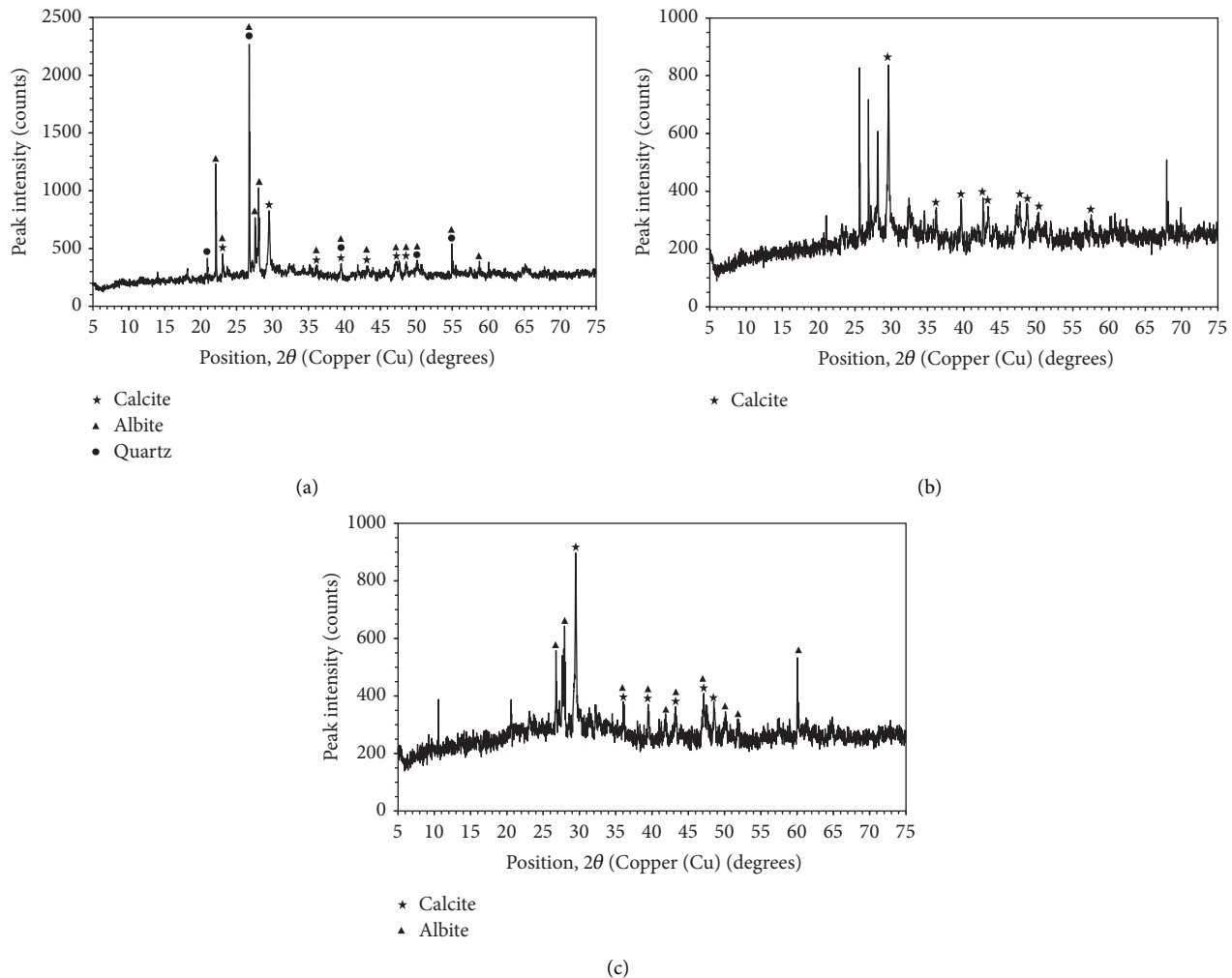
(a)

(b)

(c)

FIGURE 19: X-ray diffraction pattern for treated RCA with 40% slurry concentration: (a) XRD analysis for R-40|0, (b) XRD analysis for R-35| 5, and (c) XRD analysis for R-25|15.

untreated RCA (at more than 500 counts). Figure 17 shows that the paste could be initially be dominated by $Ca(OH)_2$. However, upon exposure to atmospheric conditions, CO_2 diffuses through the paste and reacts with portlandite, forming more calcite [56]. This could be explained by the time factor in which recycled concrete aggregate waste has not been exposed to a long-term period or exposure to CO_2 from the environment. This observation is supported by the Scanning Electron Microscope (Figure 10), which revealed overbearing whitish calcite pigments on the surface of the hydrated paste.

Figure 18 shows the XRD for the 20% concentration of pozzolans in the treatment of RCA. For samples treated with higher proportions of RHA in a 20% slurry concentration, beyond 5%, the intensity of calcite increases with an increase in RHA in the cement slurry; this is due to unhydrated products as water is drawn from the paste with the introduction of RHA. This is because the SiO_2 contributed by RHA reacts with $Ca(OH)_2$, but the activity reduces, allowing $Ca(OH)_2$ to react with CO_2 producing more $CaCO_3$.

The sample shows a high formation of calcium carbonate and albite, a likely indication of an incomplete hydration

process by the content of the treatment slurry. In addition, the high proportion of these compounds could be attributed to incomplete hydration since excess rice husk ash proportion draws more water meant for hydration from the mix. Consequently, this has the overall effect of facilitating the conversion of $Ca(OH)_2$ to quicklime (CaO) and eventually carbonates precipitate, $CaCO_3$.

For further increase of the pozzolanic slurry concentration to 40%, the results for the chemical analysis on the mortar paste are as shown in Figure 19. The increased treatment concentration of 40% resulted in a higher proportion of $CaCO_3$. This formation can be explained by a higher proportion of CaO from the cement within the treatment slurry. In addition, just like in the treatment of RCA with 20% concentration, the existing $Ca(OH)_2$ and additional $Ca(OH)_2$ contributed by the pozzolanic reaction of cement were consumed. However, CaO production was high, resulting in their conversion to carbonate precipitates, as depicted in the XRD histogram (Figure 19).

Although SEM analysis seems to indicate the increased formation of C–S–H, the intensity of calcite increased for RCA treated with a 40% concentration of cement slurry. This

could be due to an increase in the unhydrated compound. This phenomenon facilitates the reaction of CaO with CO_2 to form $CaCO_3$, given the increased demand for water due to an increase in the RHA content. A similar trend was observed for the inclusion of rice husk ash in the pozzolanic slurry, as seen from a 20% concentration of pozzolans. This means that the maximum consumption of RHA in the substitution of cement should not go beyond 5% in the concentration.

3.5. *Consideration for Practical Application.* The experimental results have shown that coarse RCA can be treated by pozzolanic slurry containing 15% cement and adding rice husk ash in proportion not exceeding 5% to produce aggregate of comparable characteristic to virgin aggregates. This study points out insights into the potential applications and utilization of RCA and RHA wastes as raw, renewable, and sustainable building materials for producing eco-friendly concretes. In addition, the concrete containing treated RCA can be used in areas that experience less extreme loads, such as low-rise structures. However, it is important to note that the water demand, volume stability, and durability of treated RCA remain a critical issue of concern that may negatively influence the full aggregate adoption in engineering practice.

Based on the findings, the aggregates have shown a slight increase in water absorption. Therefore, RCA needs to be effectively presoaked before applying pozzolanic slurry treatment to ensure the efficient formation of C–S–H that seals the voids and cracks around the RCA surface. For this to be realized, the quality control to achieve treatment of RCA as done in the laboratory may be more demanding and rigorous compared to the actual field applications. Some of the primary concerns include the unknown origin of RCA, upscaling, and lack of guidelines to achieve systematic methodology, as highlighted in this research. This can be best achieved with the participation of construction experts and engineers to establish the source of the RCA to ensure consistency and uniformity of the aggregates.

4. Conclusion

The results obtained from this study explain the prospects of the proposed surface treatment technique to strengthen the structure of the adhered fractured mortar in RCA and improve RCA's physical and mechanical characteristics. Based on the results and discussion, significant conclusions have been drawn as follows:

(i) Surface treatment using proportions of cement and RHA materials in slurry significantly strengthened weak adhered mortar in RCA and thereby effectively improved RCA's micro and macro properties. This is attributed to resulting hydration products (C–S–H) from reaction with $Ca(OH)_2$, thus filing pores and voids in the fractured adhered mortar

(ii) Generally, using a 20% concentration of the cement slurries and 5% replacement of RHA (containing 15% PC and 5% RHA) was considered optimal in all

surface treatment conditions. This was considered the best, given the low cost and environmentally sustainable advantage.

(iii) Mechanical properties of RCA treated with 15% and 5% RHA slurry resulted in a 31.4% and 30.0% reduction of AIV and ACV, respectively, compared to RCA (untreated).

(iv) Generally, aggregate treated using 15% cement and 5% RHA showed insignificant change in apparent specific gravity. The findings for apparent specific were within the 2.5–2.7 standard requirement, while aggregate water absorption was reduced by 12.7% over the untreated RCA.

(v) SEM tests observed that the surface texture of untreated RCA was rough, irregular, nonhomogeneous, and porous. While the treated RCA surface using 15% cement and 5% RHA was more homogeneous and had fewer pores and voids.

(vi) XRD showed that the calcite, quartz, and portlandite phases were the majority in the untreated RCA. In these samples, the XRD results showed quantities of calcite ($CaCO_3$) and complete leach of portlandite ($Ca(OH)_2$).

4.1. *Future Research Needs.* In this research, treated RCA samples' microstructure and physical and mechanical properties were investigated and cured at a uniform room temperature of $20 \pm 2°C$. However, under practical civil engineering, treated aggregates need to be subjected to the long-term duration of exposure to varied environmental conditions and analyzed the consequences of such on concrete structures. Aggregates must be inert and have sound volumetric stability despite the change in exposure conditions. In this regard, to better understand and use RCA in concrete structures, the following investigation needs to be conducted as follows: (i) effects of aggregate surface conditions, angularity, and interfacial transition zone; (ii) curing, environmental, and age effects (e.g., strength gain of concrete).

Data Availability

Data for this research article are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

References

[1] S. Shahbazpanahi, M. K. Tajara, and R. H. Faraj, "Studying the C–H crystals and mechanical properties of sustainable concrete containing recycled coarse aggregate with used nano-silica," *Crystals*, vol. 11, no. 122, 2021.

[2] K. C. Kibowen, *Sustainable Excavation Waste Management on Construction Sites*, Case of Nairobi County, Nairobi, Kenya, 2018.

[3] Economic Survey 2020, "Economic Survey 2020," 2020, https://www.indiabudget.gov.in/budget2021-22/economicsurvey/doc/echapter_vol2.pdf.

[4] M. Arezoumandi, J. Drury, J. S. Volz, and K. H. Khayat, "Effect of recycled concrete aggregate replacement level on shear strength of reinforced concrete beams," *ACI Materials Journal*, vol. 112, no. 4, pp. 559–568, 2015.

[5] M. Guo, S. Y. Alam, A. Z. Bendimerad, F. Grondin, E. Rozière, and A. Loukili, "Fracture process zone characteristics and identification of the micro-fracture phases in recycled concrete," *Engineering Fracture Mechanics*, vol. 181, pp. 101–115, 2017.

[6] M. Setkit, S. Leelatanon, T. Imjai, R. Garcia, and S. Limkatanyu, "Prediction of shear strength of reinforced recycled aggregate concrete beams without stirrups," *Buildings*, vol. 11, no. 9, pp. 14–18, 2021.

[7] B. Lu, C. Shi, J. Zheng, and T. C. Ling, "Carbon dioxide sequestration on recycled aggregates," in *Carbon Dioxide Sequestration in Cementitious Construction Materials,* Elsevier, Amsterdam, Netherland, 2018.

[8] N. Bheel, S. L. Meghwar, S. Sohu, A. R. Khoso, A. Kumar, and Z. H. Shaikh, "Experimental study on recycled concrete aggregates with rice husk ash as partial cement replacement," *Civil Engineering Journal*, vol. 4, no. 10, p. 2305, 2018.

[9] W. Tang, M. Khavarian, A. Yousefi, R. W. K. Chan, and H. Cui, "Influence of surface treatment of recycled aggregates on mechanical properties and bond strength of self-compacting concrete," *Sustainable Times*, vol. 11, no. 15, Aug. 2019.

[10] H.-D. Yun, Y.-C. You, and D.-H. Lee, "Effects of replacement ratio of recycled coarse aggregate on the shear performance of reinforced concrete beams without shear reinforcement," *LHI Journal of Land, Housing, and Urban Affairs*, vol. 2, no. 4, pp. 471–477, 2011.

[11] M. Malešev, V. Radonjanin, and S. Marinković, "Recycled concrete as aggregate for structural concrete production," *Sustainability*, vol. 2, no. 5, pp. 1204–1225, 2010.

[12] F. Ahimoghadam, "Effect of Recycled Concrete Aggregate Properties on the Behaviour of New Concrete," 2018, http://hdl.handle.net/10393/37588.

[13] M. Malešev, V. Radonjanin, and G. Broćeta, "Properties of recycled aggregate concrete," *Contemp. Mater*, vol. 2, pp. 239–249, 2014.

[14] Z. Chen, Y. Zhang, J. Chen, and J. Fan, "Sensitivity factors analysis on the compressive strength and flexural strength of recycled aggregate infill wall materials," *Appl. Sci. MDPI*, vol. 8, p. 1090, 2018.

[15] R. S. Padhi, R. K. Patra, B. B. Mukharjee, and T. Dey, "Influence of incorporation of rice husk ash and coarse recycled concrete aggregates on properties of concrete," *Construction and Building Materials*, vol. 173, pp. 289–297, 2018.

[16] Z. A. Krezel, K. J. McManus, N. Cumbo, H. Karlie, and C. Cox, "There is more to recycled concrete aggregate than just aggregate," *WIT Transactions on Ecology and the Environment*, vol. 102, pp. 981–989, 2007.

[17] J. Prajapati and S. Karanjit, "Effect of coarse aggregate sources on the compressive strength of various grade of nominal mixed concrete," *Journal of Science and Engineering*, vol. 7, pp. 52–60, 2019.

[18] H. L. Wang, J. J. Wang, X. Y. Sun, and W. L. Jin, "Improving performance of recycled aggregate concrete with superfine pozzolanic powders," *J. Cent. South Univ*, vol. 20, no. 12, pp. 3715–3722, 2013.

[19] S. Pradhan, S. Kumar, and S. V. Barai, "Impact of particle packing mix design method on fracture properties of natural and recycled aggregate concrete," *Fatigue and Fracture of Engineering Materials and Structures*, vol. 42, no. 4, pp. 943–958, 2019.

[20] M. Nedeljković, J. Visser, B. Šavija, S. Valcke, and E. Schlangen, "Use of fine recycled concrete aggregates in concrete: a critical review," *Journal of Building Engineering*, vol. 38, p. 2021, 2020.

[21] K. Ostrowski, D. Stefaniuk, L. Sadowski, K. Krzywiński, M. Gicala, and M. Różańska, "Potential use of granite waste sourced from rock processing for the application as coarse aggregate in high-performance self-compacting concrete," *Construction and Building Materials*, vol. 238, pp. 1–14, 2020.

[22] H. Beshr, A. A. Almusallam, and M. Maslehuddin, "Effect of Coarse Aggregate Quality on the Mechanical Properties of High Strength concrete," *Construction and Building Materials*, vol. 17, 2003.

[23] M. Kalra and G. Mehmood, "A Review paper on the Effect of different types of coarse aggregate on Concrete," *IOP Conference Series: Materials Science and Engineering*, vol. 431, no. 8, 2018.

[24] S. Ahmad and S. A. Alghamdi, "A study on effect of coarse aggregate type on concrete performance," *Arabian Journal for Science and Engineering*, vol. 37, no. 7, pp. 1777–1786, 2012.

[25] H. Zhang, K. Kuder, D. Lehman, P. Calvi, and C. Roeder, "Effect of recycled concrete aggregate on the shear behavior of reinforced concrete panels," in *Proceedings of the Fifth International Conference on Sustainable Construction Materials and Technologies*, vol. 2, no. 6, London, UK, January 2019.

[26] Z. Liu, P. Zhang, J. Bao, and Y. Hu, "Numerical simulation of water transport in unsaturated recycled aggregate concrete," *Front. Mater*, vol. 7, pp. 1–14, 2020.

[27] X. Wang, X. Yang, J. Ren, N. Han, and F. Xing, "A novel treatment method for recycled aggregate and the mechanical properties of recycled aggregate concrete," *Journal of Materials Research and Technology*, vol. 10, pp. 1389–1401, 2021.

[28] C. Shi, Y. Li, J. Zhang, W. Li, L. Chong, and Z. Xie, "Performance enhancement of recycled concrete aggregate - a review," *Journal of Cleaner Production*, vol. 112, pp. 466–472, 2016.

[29] W. M. Shaban, J. Yang, H. Su, K. H. Mo, L. Li, and J. Xie, "Quality improvement techniques for recycled concrete aggregate: a review," *Journal of Advanced Concrete Technology*, vol. 17, no. 4, pp. 151–167, 2019.

[30] Y. Liang, Z. Ye, F. Vernerey, and Y. Xi, "Development of processing methods to improve strength of concrete with 100% recycled coarse aggregate," *Journal of Materials in Civil Engineering*, vol. 27, no. 5, Article ID 04014163, 2015.

[31] W. M. Shaban, "Properties of recycled concrete aggregates strengthened by different types of pozzolan slurry," *Construction and Building Materials*, vol. 216, pp. 632–647, 2019.

[32] A. N. Givi, S. Abdul Rashid, F. A. Nora Aziz, and M. Amran Mohd Salleh, "Contribution of rice husk ash to the properties of mortar and concrete: a review," *J. Am. Sci*, vol. 6, no. 3, pp. 157–165, 2010.

[33] G. L. Golewski, "Evaluation of morphology and size of cracks of the Interfacial Transition Zone (ITZ) in concrete containing fly ash (FA)," *Journal of Hazardous Materials*, vol. 357, pp. 298–304, 2018.

[34] S. A. Saad, M. F. Nuruddin, N. Shafiq, and M. Ali, "Pozzolanic reaction mechanism of rice husk ash in concrete – a review," *Applied Mechanics and Materials*, vol. 773, no. 774, pp. 1143–1147, 2015.

[35] K. B. Park, S. J. Kwon, and X. Y. Wang, "Analysis of the effects of rice husk ash on the hydration of cementitious materials," *Construction and Building Materials*, vol. 105, pp. 196–205, 2016.

[36] BS 882, "Specification for aggregates from natural sources for concrete," pp. 1–14, British Standards Institution, London, UK, 1992, BS 882:1992.

[37] ASTM, "Standard Specification for Concrete Aggregates," pp. 1–11, ASTM Int, Ann Arbor, Michigan, USA, 2010, C33/C33M−13.

[38] BS EN 196-2, "Method of Testing Cement Part 2: Chemical Analysis of Cement," British Standards Institution, London, UK, En 196-2, 2013.

[39] ASTM Standard: C 618-12a, "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete," ASTM Int, Ann Arbor, Michigan, USA, C 618-12a, 2014.

[40] H. H. Bache, G. M. Idorn, P. Nepper-Christensen, and J. Nielsen, "Morphology of calcium hydroxide in cement paste," *Symposium on structure of Portland cement paste and concrete*, vol. 90, pp. 154–174, 1966.

[41] S. Yehia, K. Helal, A. Abusharkh, A. Zaher, and H. Istaitiyeh, "Strength and durability evaluation of recycled aggregate concrete," *Int. J. Concr. Struct. Mater*, vol. 9, no. 2, pp. 219–239, Jun. 2015.

[42] BS EN 1097-6, "Tests for Mechanical and Physical Properties of Aggregates Part 6: Determination of Particle Density and Water Absorption," British Standards Institution, London, UK, En 1097-6, 2013.

[43] F. Zulkarnain and M. Ramli, "Durability Performance of Lightweight Aggregate Concrete for Housing Construction," in *procceddings of the 2nd International Conference on Built Environment in Developing Countries (ICBEDC 2008)*, pp. 541–551, Penang, Malaysia, 2008.

[44] H. Yang, Y. Che, and F. Leng, "Calcium leaching behavior of cementitious materials in hydrochloric acid solution," *Scientific Reports*, vol. 8, no. 1, pp. 1–9, 2018.

[45] H. K. A. Al-Bayati, S. L. Tighe, and H. Baaj, "Effect of different treatment methods on the interfacial transition zone microstructure to coarse recycled concrete aggregate," *Green Technology in Geotechnical and Materials Engineering*, 2016.

[46] G. Yue, P. Zhang, Q. Li, and Q. Li, "Performance analysis of a recycled concrete interfacial transition zone in a rapid carbonization environment," *Advances in Materials Science and Engineering*, vol. 2018, pp. 1–8, 2018.

[47] A. J. Allen, J. J. Thomas, and H. M. Jennings, "Composition and density of nanoscale calcium-silicate-hydrate in cement," *Nature Materials*, vol. 6, no. 4, pp. 311–316, 2007.

[48] A. P. N. Siregar, E. L. Pasaribu, and W. Suarnita, "The effect of coarse aggregate hardness on the fracture toughness and compressive strength of concrete," *MATEC Web of Conferences, SCESCM*, vol. 258, p. 258, 2019.

[49] BS 812-112, "Testing aggregates — Part 112: methods for determination of aggregate impact value (AIV)," vol. 1, no. 14, BS 812-112, London, UK, 1990.

[50] BS 812-110, "Testing aggregates — Part 110: methods for determination of aggregate crushing value (ACV)," vol. 1, British Standards Institution, London, UK, 1990, BS 812-110.

[51] J. K. Das, S. Deb, and B. Bharali, "Prediction of aggregate impact values and aggregate crushing values using light compaction test," *Journal of Applied Engineering Sciences*, vol. 11, no. 2, pp. 93–100, 2021.

[52] A. S. A. Saran and P. Magudeswaran, "SEM analysis on sustainable high performance concrete," *Int. J. Innov. Res. Sci. Eng. Technol*, vol. 6, no. 6, 2017.

[53] Q. Kareem, N. Hilal, A. A. Ibrahim S Al-Jumaily, N. Naji, and Q. Kareem, "An overview on the influence of pozzolanic materials on properties of concrete," *Science Technology and Engineering*, vol. 4, no. 3, pp. 81–92, 2015.

[54] C. Fapohunda, B. Akinbile, and A. Shittu, "Structure and properties of mortar and concrete with rice husk ash as partial replacement of ordinary Portland cement – a review," *Int. J. Sustain. Built Environ*, vol. 6, no. 2, pp. 675–692, 2017.

[55] N. Ukrainczyk, M. Ukrainczyk, J. Sipusic, and T. Matusinovic, "XRD and TGA investigation of hardened cement paste," in *Proceedings of the 11. Conference Materials, Processes, Friction. Wear MATRIB'06*, pp. 22–24, Vela Luka, Croatia, June 2006.

[56] L. A. Silva, B. O. Nahime, E. C. Lima, J. L. Akasaki, and I. C. Reis, "XRD investigation of cement pastes incorporating concrete floor polishing waste," *Cerâmica*, vol. 66, no. 380, pp. 373–378, 2020.