Research Article

Strength and Durability Parameters of Brick Aggregate Concrete Incorporating Rice Husk Ash as a Partial Replacement of Cement

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This study assessed the strength and durability parameters of brick aggregate concrete (BAC) incorporating rice husk ash (RHA) as a partial replacement of cement. For this, concrete cylinders (100 mm × 200 mm) were made with 0% (control) to 25% RHA as a partial replacement of ordinary Portland cement (OPC) at a mix proportion of 1 : 1.5 : 3 and a water-to-binder (w/b) ratio of 0.50. Specimens were immersed separately in normal water, 3% sodium chloride (NaCl), 5% sodium sulfate (Na\textsubscript{2}SO\textsubscript{4}), 5% magnesium sulfate (MgSO\textsubscript{4}), 1% hydrochloric acid (HCl), and 1% sulfuric acid (H\textsubscript{2}SO\textsubscript{4}) solutions for several immersion periods. The slump test results indicated that the workability of BAC containing RHA (RBAC) decreased about 29.69%–75.02% compared to control (0% RHA). After 90 days, the BAC containing RHA (up to 15% replacement) was found approximately 2.28%–6.64% greater compressive strength than that of control concrete. In addition, water absorption and porosity of RBAC were around 17.59%–40.73% and 12.12%–35.68% lower than that of control concrete, respectively. Similarly, RBAC (up to 25% replacement) exhibited roughly 35.62%–54.79% higher resistance against chloride attack and 0.39%–4.56% better resistance against Na\textsubscript{2}SO\textsubscript{4} attack (up to 15% replacement), however, it exhibited inferior resistance against MgSO\textsubscript{4} attack compared to control. Meanwhile, BAC with 10% RHA showed about 5.35% and 1.00% superior performance than that of control concrete against HCl and H\textsubscript{2}SO\textsubscript{4} attack, respectively. The relationships between the strength and durability parameters of RBAC also suggested that RHA contributes to improving the strength and durability parameters of BAC.

1. Introduction

In the last few decades, increasing population growth augmented the demand for housing and infrastructure. This growth in construction increases the use of Portland cement. In 2019, about 4.1 billion tons of cement was produced in the world, which exceeded the previous year’s production (1.50 ± 0.12 billion tons) and projected about 6.0–13.5 billion tons nearly in 2050 [1]. This massive amount of cement production is responsible for substantial carbon dioxide emissions during its manufacturing process. Nowadays, about 5%–8% of worldwide CO\textsubscript{2} is produced by the cement manufacturing industries and is also responsible for the worldwide greenhouse gas emissions (about 7%), leading to global warming [1, 2]. In addition, the manufacturing process of cement is a very energy consumptive, costly, and cumbersome process. To reduce these problems, a growing global trend toward the use of waste materials, such as RHA, fly ash, coffee husk ash, silica fume, slag, metakaolin, and other pozzolanic materials, in concrete or palm oil fuel ash in cement bricks as supplementary cementitious materials has been observed in the construction industry [3–6]. If aptly managed and designed, concrete with agricultural wastes like rice husk ash shows parallel or even superior performance than usual concrete [7]. In 2018, estimation almost 769.9 million tons of rice paddy produced annually worldwide [8]. After peeling, about 78% of the weight is received as rice, broken rice, and bran. The remaining 22% of the weight of paddy is received as rice husk [9]. The husks typically contain cellulose, silica, and lignin. Without processing, the husks are used as animal food, thermal energy, or land filling. Therefore, combustion is a common option
After combustion, about 25% of the weight of the husk is received as RHA [9]. The ash produced from rice husk contains a vast amount of silica, which is not easily biodegradable [9, 10]. Hence, it becomes a disposal problem and eventually leads to environmental pollution. To reduce these problems, RHA could be used as cement substituted materials because it contains an enormous amount of amorphous silica, which has pozzolanic action and possesses cementitious property. In addition, the agricultural by-product RHA has already been substantiated as a pozzolanic material [11–13]. It is expected to add pozzolanic values in cement hydration, which, in turn, enhances strength and durability over a longer period [14, 15]. RHA could also reduce the cost of construction materials [16]. Currently, numerous wastes, such as blended waste, clay brick, expanded clays, shales, pumice perlite, rubber, plastic, and palm oil shell, are used to make the lightweight aggregate, thereby producing lightweight concrete [17–22]. Even the road construction industries try to utilize a considerable quantity of marble waste aggregate as coarse aggregate in the base course and use the waste materials (such as marble dust, rice husk ash, and cement) to improve the soil subgrade for minimizing the construction cost, natural resource, dumping problem, and environmental pollution [23, 24]. However, aggregate, especially coarse aggregate, plays an important role in the strength and durability parameters of concrete. In this era, the use of crushed brick (brick aggregate) as a coarse aggregate has been increased in making concrete in some regions because of the lack of availability of stone aggregate. Usually, this aggregate reduces the dead load and production cost of concrete compared to that of stone aggregate [21, 25, 26]. After 28 days, stone aggregate concrete (SAC) exhibited a better performance in terms of compressive strength with finer RHA particles than coarser RHA or OPC [27, 28]. After 7 days of curing, BAC containing RHA exhibited superior performance in terms of strength [9]. Moreover, brick aggregate greatly influences the durability properties of concrete [25, 29]. This aggregate content decreases chloride penetration in the concrete [25]. The compressive strength of concrete is a measure of its durability to a certain extent, however, it is not entirely true that strong concrete is always durable [30]. It is well-known that the two major sources of chemical aggression, namely the natural source (seawater, river water, and soil rich in sulfate, nitrates, chlorides, and carbonates) and the man-made sources (chemical manufacturing industries, textiles industries, sales, and usage of industrial chemical outlets and sewage tanks), are very destructive to concrete structures. The construction of concrete structures in these environments requires the use of admixtures to enhance the durability of the concrete. Muthadhi et al. [31] indicated that the use of RHA as a partial replacement for cement in concrete reduced the permeability and volume of void in concrete and enhanced the resistance of concrete against chloride attack, acid attack, and sulfate attack. Furthermore, Sakr [32] found that the compressive strength of control concrete was much lower than concrete containing 15% of RHA when immersed in a sulfate solution for 28 days. Countless efforts have been made to explore the strength and durability properties of concrete containing RHA in stone aggregate concrete [13, 15, 32–35]. However, crushed brick as a coarse aggregate including RHA may be an alternative option. Numerous attempts have also been made to determine the correlation between strength and some durability properties of stone aggregate concrete containing RHA [36–41]. Still, as far as the authors are concerned, the strength and durability parameters of BAC containing RHA have not been correlated yet. On the other hand, some research has been made on the durability properties of concrete with crushed brick as coarse aggregate [25, 29]. However, these studies [25, 29] did not use RHA as a supplementary cementitious material, including crushed brick as coarse aggregate to produce concrete. Rendering to the aforementioned research gaps and limitations, this study intended to investigate the strength (compressive strength) and durability parameters (water absorption, porosity, chloride resistance, sulfate resistance, and acid resistance) of brick aggregate concrete incorporating rice husk ash as a partial replacement of cement.

2. Materials and Methodology

2.1. Materials and Material Properties. In this experimental investigation, locally available brick was crushed manually and screened to a maximum of 19 mm (0.75 in.). Fine aggregate, such as Sylhet sand (coarser sand) and local sand (fine sand) known as river sand in Bangladesh, was used in the proportion of 1:1. The physical properties of coarse and fine aggregate were determined according to the ASTM standard test methods (shown in Table 1). To characterize each material in concrete, their experimental results are tabulated in Table 1. The table verifies that the aggregates used in the present study are analogous to those of past studies [9, 46]. RHA was collected from a local rice mill and used as 0% to 25% partial replacement for OPC in concrete. Locally available OPC was used as a cementitious material. The physical and mechanical properties of OPC (ASTM Type-I) were examined concerning the ASTM standard test method (shown in Table 2) and used as 0% to 25% partial replacement for OPC in concrete. Locally available OPC was used as a cementitious material. The physical and mechanical properties of OPC (ASTM Type-I) were examined concerning the ASTM standard test method (shown in Table 2), and the test results were confirmed to the requirements of [51]. The chemical composition of RHA and OPC was measured by X-ray fluorescence analysis. Image-j software was used to analyze the SEM image to evaluate the mean particle size of RHA. In addition, X-ray diffraction (XRD) analysis was performed by the XRD machine (PANalytical, Empyrean), and the XRD data were evaluated using data analysis software (Match 3.0) to know the silica structure of RHA.

2.2. Mix Proportion of BAC Specimens. To launch this experimental study, all concrete mixtures were made with 0% (control) to 25% RHA as a partial replacement for ordinary Portland cement (OPC) with a constant mix proportion of
1:1.5:3 and a water-to-binder (w/b) ratio of 0.50. The mix design for 1 m³ of BAC containing RHA is presented in Table 3 and is calculated by absolute volume method (all materials were used as a percentage by mass). The concrete mixture had a binder content of 403.2 kg/m³, while control BAC (containing 0% RHA) had 403.2 kg/m³ of ASTM Type-I Portland cement. The mix design was adopted from Noaman et al. [9, 52].

2.3. Preparation and Tests on Fresh RBAC. The graded aggregates (fine and coarse aggregates) were soaked in water for 24 h and then air-dried to saturated surface dry (SSD) condition before mixing with other ingredients. For a mix proportion of 1:1.5:3, all of the ingredients with appropriate proportions were added to the mixture machine, and mixing was done for about 2 minutes. To know the workability of fresh BAC, a slump test was performed according to the method of ASTM C143 [53]. RHA was used as a partial replacement for cement (by weight of cement) as 0%, 10%, 15%, 20%, and 25% in BAC, and the results were compared with the control BAC (0% RHA).

2.4. Casting of Specimens and Tests on Hardened RBAC. Specimens. After the accomplishment of workability test, the test specimens were cast in cylindrical steel moulds of size 100 mm diameter and 200 mm height and compacted with a tamping rod. These were demoulded after 24 h of casting, and the test specimens were placed in a normal water tank for curing. After 7, 28, and 90 days of water curing, the RBAC cylinders were subjected to the compressive strength, water absorption, and porosity test according to the ASTM standard C39 [54] and C642 [55], respectively. Before the chemical aggression test, all specimens were moist-cured for 28 days. For the chloride resistance test, the specimens were then immersed in a chemical water tank containing 3% NaCl solution for specified periods (30, 60, and 90 days). The test was carried out as per the NT (Nord Test) Build 492 [56]. After initial curing, the sulfate exposure test was conducted by immersing concrete specimens in a water tank containing 5% sodium sulfate (Na₂SO₄) solution and 5% magnesium sulfate (MgSO₄) solution for 30, 60, and 90 days of immersion periods separately. The sulfate resistance of RBAC was measured in terms of compressive strength and compared

| Aggregate       | Fineness modulus ASTM C136 [42] (σ) | Specific gravity (dry) ASTM C127 [43] (σ) | Absorption (%) ASTM C127 [43] (σ) | Unit weight (kg/m³) ASTM C29 [44] (σ) | Moisture content (%) ASTM C566 [45] (σ) | Ref.         |
|-----------------|-------------------------------------|-------------------------------------------|-----------------------------------|--------------------------------------|----------------------------------------|-------------|
| Coarse aggregate | Brick chips                         | 6.97                                      | 2.65 (0.07)                        | 16.28 (1.11)                        | 930 (2.14)                             | Present study |
|                 |                                     | 6.97                                      | 2.73                               | 15.80                                | 1089                                   | Rashid et al. [46] |
|                 |                                     | 7.00 (0.11)                               | 2.56 (0.133)                      | 16.38 (0.062)                      | 925 (2.05)                             | Noaman et al. [9] |
| Fine aggregate  | Sylhet sand                          | 3.10 (0.43)                               | 2.69 (0.08)                        | 1.03 (0.10)                         | 1510 (3.02)                            | Present study |
|                 | Local sand                           | 1.12 (0.07)                               | 2.68 (0.03)                        | 1.02 (0.02)                         | 1270 (2.40)                            | Present study |
|                 | Combined sand                        | 2.12 (0.13)                               | 2.75 (0.04)                        | 1.02 (0.03)                         | 1390 (2.33)                            | Present study |
|                 |                                     | 1.86                                      | 2.50                               | 2.60                                 | —                                      | Present study |
|                 |                                     | 2.10 (0.019)                              | 2.68 (0.05)                        | 1.04 (0.043)                        | 1386 (3.36)                            | Noaman et al. [9] |

Note. —values are not available; σ = standard deviation.

| Material properties | RHA | RHA200 (σ) | Cement (σ) |
|---------------------|-----|------------|-------------|
| Grinding time (min) | 0   | 60 90 120 180 | —           |
| Average particle size (μm) | 114.61 | 72.05 14.9 | 13.1 12.10 9.86 |
| Passing through sieve no. 200 (%) | 85 | 100 100 | — |
| Specific gravity, BS 1377 [47] | 1.78 (0.08) | 3.11 (0.07) | — |
| Bulk density (kg/m³), BS 1377 [47] | 0.394 (0.02) | — | — |
| Color               | Grey | Grey black | — |
| Normal consistency (%), ASTM C187 [48] | — | 29 (1.10) | — |
| Initial setting time (min), ASTM C191 [49] | — | 123 (4.21) | — |
| Final setting time (min), ASTM C191 [49] | — | 328 (1.26) | — |
| 3 days compressive strength (MPa), ASTM C109 [50] | — | 23.44 (0.90) | — |
| 28 days compressive strength (MPa), ASTM C109 [50] | — | 33.72 (1.27) | — |

Note. —values are not available; σ = standard deviation; RHA200 = RHA passing through No. 200 sieves.
with control (0% RHA) concrete. Sakr [32], as well as Chatveera and Lertwattanaruk, [57] also used this test method successfully to measure sulfate resistance for SAC and cement mortar, respectively. After initial curing, the acid resistance of RBAC was carried out by immersing concrete specimens in the acidic media containing 1% hydrochloric acid (HCl) and 1% sulfuric acid (H₂SO₄) solution for 30, 60, and 90 days of immersion periods separately. The acid resistance of RBAC was measured in terms of compressive strength and compared with control (0% RHA) concrete. A similar test was also carried out on high-performance metakaolin SAC in terms of compressive strength by Arunakanthi et al. [58] and Arunakanthi and Rao [59]. The authors [58, 59] immersed SAC samples in four different concentrations (50 mg/L, 100 mg/L, 400 mg/L, and 800 mg/L) of hydrochloric acid and sulfuric acid solutions for 7, 28, and 90 days, respectively.

3. Results and Discussions

3.1. Characteristics of RHA and OPC. The physical properties of RHA and OPC were presented in Table 2. The table and the SEM photograph of RHA (Figure 1) illustrate that the fineness of the RHA particle increases with an increase in grinding time. The table and figure also reveal that the natural RHA (114.61 μm) is asymmetrical in form, and grinding from 60 to 180 min, the average particle size of RHA decreases from 72.05 μm to 12.10 μm, respectively. The rate of ground RHA passed through sieve No. 200 (75 μm) was 85%. After passing, the average particles size of RHA was obtained as 9.86 μm, which was used in this study. Nearly similar observations were also made by former researchers [52, 60, 61]. The specific gravity and bulk density of RHA were obtained as 2.67 and 2.94 g/cm³, respectively. Similar observations were obtained by previous researchers [52, 62, 63] and reported that this type of RHA could be used successfully in concrete industries. The chemical compositions of RHA and OPC are presented in Table 4. The table shows that RHA contains about 89.37% of silica, which regulates the ceaseless hydration process (pozzolanic reaction) in concrete. Conversely, CaO in OPC is around 64.29%. Studying the previous researchers and ASTM requirements (shown in Table 4), it was verified that RHA used in this study was Class F pozzolana and the cement used in this study was Type-I OPC. In addition, the X-ray diffraction pattern of the RHA particle is illustrated in Figure 2, and it reveals the structure of silica contained in RHA as an amorphous solid because of the strong broad peak (the twice theta angle at about 20.84°). The acute sharp peak at around 26.62° (2θ) indicates the crystalline nature of silica, which is a trigonal structure with hexagonal axis, and the mineral name is quartz (Q = SiO₂). Hence, silica contained in RHA is an amorphous solid with a small amount of quartz. Nearly similar observations were made by past studies [9, 52, 60, 61] and stated that the twice theta (2θ) angles are around 20.85° and 26.97° for a strong broad peak and very sharp peak, respectively [52].

3.2. Workability of RBAC. The slump values of BAC containing RHA as a replacement for cement (0–25% RHA) are illustrated in Figure 3. The figure reveals that the slump values of BAC decrease steadily with an increase in the percentage of RHA. The control concrete shows a greater amount of slump (around 66.07 mm) compared to RBACs (Figure 3). The workability of BAC containing 10%, 15%, 20%, and 25% RHA progressively declined to about 29.69%, 43.27%, 67.33%, and 75.02%, respectively, of the control concrete. The workability of BAC decreases with increasing RHA content. It may be because of the fact that RHA absorbed more water because of its absorptive nature, which is derived from the cellular structure of RHA particles. Therefore, the workability of BAC containing RHA decreases with increasing the percentage of RHA. Similar observations were also made by Noaman et al. [9].

3.3. Compressive Strength of RBAC. Figure 4 illustrates the compressive strength of RBAC (0–25% RHA) after 7, 28, and 90 days of curing. The figure reveals that the compressive strength surges with the rising curing periods caused by the incessant hydration process. After 7 days of curing, control concrete shows 1.81%, 3.60%, 23.18%, and 26.09% greater strength than BAC containing 10%, 15%, 20%, and 25% RHA, respectively. It may be because of the cement hydration process. In addition, BAC containing 10% and 15% RHA achieves 3.43%, 2.41% and 6.64%, 2.28% greater strength than control concrete after 28 and 90 days of curing, respectively. These may occur due to two reasons. Firstly, the cement paste and brick aggregate generate a strong bond between them by using the irregular shape and rough surface of the brick aggregate [46, 65]. Secondly, at later ages (28 and 90 days), with the presence of water (contained in RHA cell), the unhydrated cement grains chemically react with silica content in RHA and produce a secondary glue named C–S–H gel, which leads to minimizing the permeable voids in BAC [52, 60, 66, 67]. However, BAC containing 10% RHA shows the greatest strength after 28 and 90 days of curing, respectively, than that of control concrete and other RHA-

| Mix no. | RHA (%) | RHA (kg) | OPC (kg) | Fine aggregate (kg) | Coarse aggregate (kg) | Water (kg) |
|--------|---------|----------|----------|---------------------|----------------------|------------|
| RBAC0  | 0       | 0.0      | 403.2    | 583.8               | 781.2                | 201.6      |
| RBAC10 | 10      | 40.3     | 362.9    | 583.8               | 781.2                | 201.6      |
| RBAC15 | 15      | 60.5     | 342.7    | 583.8               | 781.2                | 201.6      |
| RBAC20 | 20      | 80.6     | 322.6    | 583.8               | 781.2                | 201.6      |
| RBAC25 | 25      | 100.8    | 302.4    | 583.8               | 781.2                | 201.6      |

Note: RBAC0 to RBAC25 is the BAC containing 0% to 25% RHA, respectively.
based concrete. It may be owing to the ideal replacement for RHA [9]. On the other hand, BAC with 20% and 25% RHA shows a gradual loss of strength of about 10.17%, 10.59% and 15.78%, 12.07% than control BAC after 28 and 90 days of curing, respectively. The loss of strength occurred for the higher replacement of RHA (20% and 25% replacements) may be because of the increase in silica (contained in RHA) and gradually making the paucity of calcium oxide (contained in OPC) in concrete, resulting in weakening the bonding between the aggregate and cement paste [52]. Thus, after 28 days of curing, RBAC (up to 15% replacement) exhibited a significant strength than the control or other RHA-based concrete. Similar observations were also made by Noaman et al. [9].

3.4. Water Absorption of RBAC. Figure 5 shows the water absorption of RBAC (0–25% RHA) at 7, 28, and 90 days of curing periods. It is observed that the percentage of water absorption of RBAC gradually decreases with increasing the curing age from 7 to 90 days. BAC with 25% RHA shows higher water absorption than 20% RHA, however, it is
lower than the control BAC at all curing ages. It may be because of the higher percentage of RHA particles, which absorb more water resulting from its cellular structure. At 7 days of curing, BAC containing 10%, 15%, 20%, and 25% RHA shows 7.58%, 18.30%, 24.09%, and 12.70% lower water absorption than the control concrete, respectively. In addition, BAC with 10%, 15%, 20%, and 25% RHA displays 14.51%, 19.76%, 24.70%, and 13.06% lower water absorption than the control concrete after 28 days of curing, respectively. By 90 days, BAC with 10%, 15%, 20%, and 25% RHA shows 17.59%, 25.13%, 40.73%, and 37.82% lower water absorption than the control concrete, respectively. These results indicate that prolonged curing and increased percentages of RHA (up to 25%) in BAC can lead to a reduction in permeable voids. It may result from the filler effect and additional calcium silicate hydrate (C–S–H) products that fill the pores. The pore radius becomes finer.

### Table 4: Chemical composition of RHA and OPC.

| Materials          | Chemical composition (%) | Ref.          |
|--------------------|--------------------------|---------------|
| Materials          | SiO₂ | Al₂O₃ | Fe₂O₃ | MgO  | CaO  | Rb₂O | P₂O₅ | TiO₂ | SO₃ | Na₂O  | K₂O | MnO  | LOI |
| RHA                | 89.37 | 0.68  | 0.37  | 0.23 | 0.28 | 0.02 | 0.47  | 0.03 | 0.28 | 0.13  | 1.37 | 0.50  | 6.27 |
| RHA                | 87.32 | 0.22  | 0.28  | 0.28 | 0.48 | —    | —     | —    | 1.02 | 3.14  | —    | 2.10  | 87.32 |
| RHA                | 86.29 | 0.57  | 0.57  | 0.62 | 1.13 | —    | —     | —    | 0.23 | 0.12  | 2.30 | 0.22  | 7.35 |
| Class F pozzolana  | > 70 | —    | > 70 | —    | —    | —    | —     | < 5  | < 5  | < 5  | < 5  | < 5  | < 5  |
| OPC                | 20.40 | 5.22  | 3.45  | 1.92 | 64.29 | —    | —     | 2.72 | 0.45 | 0.46  | —    | 0.78  |
| OPC                | 20.25 | 5.04  | 3.16  | 4.56 | 63.61 | —    | —     | 0.08 | 0.51 | 3.12  | 20.25 | 5.04  |
| OPC                | 20.41 | 5.21  | 3.47  | 1.90 | 64.27 | —    | —     | 2.71 | 0.47 | 0.77  | —    | 0.79  |
| ASTM Type–I OPC    | —    | —    | —    | < 6  | —    | —    | —     | < 3  | —    | < 3  | —    | < 3  |
| Note. —values are not available.

### Figure 2: X-ray diffraction pattern of RHA sample.

### Figure 3: Slump of BAC containing RHA as a supplement of cement.
as a result of the formation of C–S–H gel during the hydration process and leads to a reduction in permeable voids in BAC. Similar observations were also made by other researchers [61, 68]. However, Saraswathy and Song [69] reported that the water absorption of RHA (5–30% RHA)-mixed stone aggregate concrete (RSAC) is lower than the control concrete, and the concrete with no addition of RHA showed the highest water absorption due to the existence of connected pores in the concrete. Therefore, it can be concluded that with prolonged curing, water absorption of RBAC continues to decrease gradually with the increase in RHA content.

3.5. Porosity of RBAC. Figure 6 illustrates the porosity of RBAC (0–25% RHA) at 7, 28, and 90 days of curing. The figure shows that the porosity of RBAC is lower than that of control BAC. It may be because of a continuous hydration process of cementitious materials. After 7 days, BAC containing 10%, 15%, 20%, and 25% RHA shows 11.27%, 20.32%, 27.86%, and 12.45% lower porosity than the control concrete, respectively. Furthermore, BAC with 10%, 15%, 20%, and 25% RHA displays 9.10%, 20.74%, 26.16%, and 18.92% lower porosity than the control concrete after 28 days of curing, respectively. Similarly, at 90 days, BAC containing 10%, 15%, 20%, and 25% RHA shows 12.12%,
22.19%, 35.68%, and 31.08% lower porosity than the control concrete, respectively. These results indicate that the porosity of BAC continues to decrease with the increase in RHA content up to 25% replacement. It may be because of the pozzolanic and filler effect of finer RHA particles, and at 20% RHA, BAC shows minimum porosity, which may be owing to the optimal replacement for RHA. Nearly similar observations were also made by Bakar et al. [70], and reported that the porosity of blended concrete decreased with the increase in pozzolanic materials that refine the porosity of concrete. It leads to improvements in the microstructure of blended concrete. Therefore, it can be concluded that prolonged curing and increasing percentages of RHA in the concrete lead to lower porosity than that of control BAC at all ages. It may be due to the higher filler and pozzolanic effects of RHA particles, which reduce the total porosity by providing a homogeneous microstructure. A similar conclusion was also made by previous researchers [69, 71] for mortar and SAC.

3.6. Chloride Attack on RBAC. Figure 7 illustrates the chloride penetration of RBAC (0–25% RHA) at 30, 60, and 90 days of immersion in the 3% NaCl solution. The figure illustrates that on 30 days of immersion, BAC with 10%, 15%, 20%, and 25% RHA shows 14.68%, 44.95%, 47.71%, and 33.03% greater resistance against chloride attack than that of control BAC, respectively. At 60 days, BAC containing 10%, 15%, 20%, and 25% RHA exhibits 32.56%, 44.96%, 51.16%, and 54.26% greater resistance against the chloride attack than control BAC, respectively. By 90 days, BAC using 10%, 15%, 20%, and 25% RHA exhibits 35.62%, 41.10%, 54.79%, and 49.32% greater resistance against chloride attack than control BAC, respectively. The test results reveal that RBAC had a lower chloride penetration depth as compared to the control BAC for 30, 60, and 90 days of immersion period. It may have occurred since the addition of RHA particles in BAC causes a reduction of porosity and pore diameter resulting from the formation of C–S–H gel. The concrete containing 20% RHA exhibited much better performance, which may be the optimal replacement. However, RBAC (25% RHA) shows little variation than BAC with 20% RHA, and it may be because of higher replacement for RHA. Anwar et al. [72] reported on the ability of RHA mixtures to reduce the potentially detrimental effects of chloride intrusion into SAC. Madandoust et al. [73] reported that the stone aggregate concrete with RHA (up to 10% replacement) shows a better performance against chloride penetration over the control specimens. Rattanachu et al. [12] stated that the recycled aggregate concrete (RAC) utilizing up to 50% RHA replacement for cement shows higher chlorine resistance compared to control. Therefore, the control BAC had significantly higher chloride penetration at any particular depth as compared to RBAC, and it may be because of the higher porosity of BAC compared to RBAC.

3.7. Sulfate Attack on RBAC. Figure 8 shows the compressive strength of RBAC against sodium sulfate attack for 30, 60, and 90 days. The figure illustrates that the compressive strength of BAC decreased with the length of the immersion period in the 5% Na₂SO₄ solution because of the higher porosity of BAC compared to RBAC. The figure also reveals that there is no loss of compressive strengths of BAC with 10% and 15% replacement at 30, 60, and 90 days. BAC with 10% and 15% RHA shows an improvement in the strength of about 3.91%, 5.98%, and 4.56% and 0.11%, 0.61%, and 0.39% than control BAC at 30, 60, and 90 days, respectively. One possible reason for such an improved
behavior of RBAC may be because of the presence of C–S–H gel, which possesses a low calcium silicate ratio (C/S), resulting from the pozzolanic reaction. The low permeability of this concrete prevents the sulfates from entering the cementitious matrix. On the other hand, BAC with 20% and 25% RHA shows a gradual loss of strength than control BAC at all ages. BAC with 20% and 25% RHA shows a loss of strength of about 13.24%, 10.96%, and 13.83%, 21.81%, 18.66%, and 17.24% than control BAC at 30, 60, and 90 days, respectively. BAC with 25% RHA shows the highest loss of strength as compared to other replacements. It may have occurred because of the higher replacement for RHA (20% and 25% RHA), which increases the water demand associated with its high surface areas, resulting in the increase of penetration of sulfate ion (SO$_4^-$), and thus, the compressive strength decreases. However, Ramezanianpour et al. [74] reported that RSAC specimens, except the control, showed a continuous increase in compressive strength up to 60 days of immersion. Therefore, it can be concluded that the control BAC is more susceptible to sodium sulfate attack than RBAC (up to 15% replacement).

Figure 9 shows the compressive strength of RBAC immersed in Na$_2$SO$_4$ solution for 30, 60, and 90 days.
The figure demonstrates that the compressive strength of BAC decreased with an increase in the immersion period, which is again attributed to the higher absorption capacity of porous BAC compared to RBAC. At 30 days, BAC with 10% and 15% RHA showed an improvement in the strength of around 10.61% and 1.37%, respectively, whereas 20% and 25% RHA shows the losses of the strength of approximately 4.64% and 16.65%, respectively, compared to control BAC. At 60 days, BAC with 10% and 15% RHA showed comparable strength than control BAC, while 20% and 25% RHA showed strength losses of about 15.73% and 16.42%, respectively, than control BAC. By 90 days, BAC with 10%, 15%, 20%, and 25% RHA shows strength losses of roughly 5.50%, 11.87%, 15.31%, 19.49%, and 19.54%, respectively, than control BAC. The improvement in the strength of RBAC may be because of the formation of ettringite (3CaO.Al₂O₃.3CaSO₄.32H₂O), which is generated by the reaction of gypsum (CaSO₄·2H₂O) and tricalcium aluminate (C₃A) contained in the cement paste with magnesium sulfate (MgSO₄). It, thereby, permits the sulfate ion (SO₄²⁻) to penetrate BAC and leads to the filling of the porosity of BAC. A similar reflection was also made by Habeeb et al. [75]. On the contrary, the loss in the strength of RBAC may be because of the accumulation of magnesium silicate hydrate (M–S–H) gel causing the magnesium to decompose the calcium compounds of C–S–H gel into M–S–H gel, which has no cementitious properties and results in the lowering of compressive strength. A similar observation was also made by Chatveera and Lertwattanaruk [57] for cement mortars, and they reported that the M–S–H gel has low binding ability, resulting in lower compressive strength. Therefore, RBAC is more susceptible to magnesium sulfate attack than BAC, and the sulfate resistance of RBAC seems to be quite rational.

3.8. Acid Attack on RBAC. Figure 10 illustrates the compressive strength of RBAC (0–25% RHA) immersed in 1% HCl solution for 30, 60, and 90 days. The figure illustrates that the compressive strength of BAC specimens decreased with the length of the immersion period because of the higher absorption capacity of brick aggregate. After 30 days, the strength of the RBAC increased by about 11.87% and 3.66% for 10% and 15% RHA replacement, respectively, than that of control BAC. At 60 days, BAC containing 10% RHA increased in strength of about 8.24% than control BAC, while BAC containing 15% RHA showed nearly parallel results of control BAC. Similarly, by 90 days, 10% RHA sustained their increment of the strength of about 5.35%, while BAC with 15% RHA showed a loss of strength of around 0.12% than control BAC. Thus, 10% and 15% RHA concrete showed their incremental behavior, which may be attributed to the filler effect of finer RHA particles. However, BAC containing 20% and 25% RHA showed a decrease in the strength of around 7.84%, 12.36%, and 16.77% and 16.43%, 16.07%, and 18.25% than the control for 30, 60, and 90 days, respectively, which may have arisen the higher absorption capacity of RHA. RBAC (20% and 25% RHA) is more susceptible to HCl attack may be because HCl destroys the C–S–H gel to produce soluble calcium chloride (CaCl₂), resulting in an increase in the porosity and penetrability of concrete cement paste and leading to a decrease in strength and durability. A similar observation was also made by Chatveera and Lertwattanaruk [57]. Therefore, it can be indicated that BAC is more susceptible to HCl acid attack than RBAC (up to 10% replacement).

On the other hand, Figure 11 demonstrates the compressive strength of RBAC (0–25% RHA) against 1% H₂SO₄ attack for 30, 60, and 90 days. The figure reveals that the compressive strength of BAC specimens decreased with the
length of the immersion period, once more because of the higher absorption capacity of brick aggregate. The figure also illustrates that the compressive strength of BAC with 10% and 15% RHA is higher than that of control BAC (about 4.66% and 4.12%, respectively) at 30 days, while other replacements of RHA (20% and 25% RHA) continue to show strength losses (around 7.01%, and 14.71%, respectively). After 60 days, the compressive strength of BAC with 10% RHA is 1.02% higher than that of control BAC but decreased compared to that after 30 days, while other replacements of RHA (15%, 20%, and 25% RHA) continue to show strength losses (about 8.07%, 23.44%, and 23.98% respectively). Moreover, by 90 days, the strength of BAC with 10% RHA is about 1.00% higher than that of the control BAC, while other replacements of RHA (15%, 20%, and 25% RHA) continue to show strength losses (about 11.82%, 23.23%, and 26.56%, respectively). The improved behavior of RBAC (10% RHA) may be owing to the filler effect of finer RHA particles and the existence of C–S–H gel having a low C/S ratio resulting from the pozzolanic reaction. However, the loss in strength of RBAC (15–25% RHA) may have occurred due to the production of CaSO₄ (salt) as H₂SO₄ chemically reacts with Ca(OH)₂ in concrete, which permits this salt into the pores of RBAC (created by the higher percentage of RHA grains) because of the cellular structure of RHA and leads to the disintegration of concrete. The compressive strength of metakaolin-mixed SAC decreases in acidic solution [58, 59]. Koushkbaghi et al. [36] indicated that RHA-based concrete exposed to acid had 8.0% less strength than water-cured concrete. In comparisons with Figures 10 and 11, RBAC exhibited more strength losses against H₂SO₄ attack compared to HCl attack. In addition, BAC with 10% RHA exhibited a higher resistance against HCl attack than against H₂SO₄ attack.

3.9. Correlation between Strength and Durability Parameters of RBAC

3.9.1. Relationship between Porosity and Water Absorption. Figure 12 draws a relationship between water absorption (W_A) and porosity (P) of RBAC after 90 days of curing. Based on this, it is observed that W_A is exponentially related to the P of RBAC. It confirms the fact for RBAC that W_A arouses exponentially with the proliferation of P, as shown by the regression coefficient (R² = 0.99) (shown in Figure 12). A similar observation was also made by Farhana et al. [41] for geopolymer paste. The W_A of RBAC can be expressed by the following relation:

\[ W_A = 1.44e^{0.12P}, \]

where W_A and P represent the water absorption and porosity of RBAC in percentage, respectively. The relation and higher regression coefficient also indicate that porosity has a pronounced effect on the water absorption of RBAC. Therefore, the present study suggests a convincing relationship between W_A and P for RBAC.

3.9.2. Relationship between Porosity and Compressive Strength. After 90 days of curing, a correlation between compressive strength (f'_c) and porosity (P) of RBAC is illustrated in Figure 12. The figure reveals that f'_c creates a polynomial relation to the P of RBAC. As expected, the strength of RBAC developed with the reduction in porosity up to 15% replacement but decreased at higher replacement for RHA (20–25% RHA). Putrajaya et al. [76] suggested that the
The compressive strength of SAC containing 15% RHA and superplasticizer decreased linearly with the increase in porosity. The $f'_c$ of RBAC can be expressed by the following relation:

$$f'_c = -0.64P^2 + 14.47P - 47.70, \quad R^2 = 0.86$$

where $f'_c$ and $P$ represent the compressive strength and porosity of RBAC in MPa and percentage, respectively. The higher regression coefficient ($R^2 = 0.86$) also implies that the porosity is strongly related to the strength of RBAC. Cheng et al. [37] found a linear relationship between total porosity and compressive strength of slag concrete. The authors [37] suggested that the total pore volume and compressive strength of slag concrete are not ideal. On the contrary, Lian et al. [38] stated that the compressive strength of porous concrete decreases exponentially with the increase in porosity. Therefore, the present study offers an altered relationship between $f'_c$ and $P$ intended for BAC containing RHA as a partial replacement for cement.

### 3.9.3. Relationship between Water Absorption and Compressive Strength

Figure 13 illustrates the relationship between water absorption ($W_A$) and compressive strength ($f'_c$) of RBAC after 90 days of curing. The figure reveals that $f'_c$ generates a polynomial relation with the $W_A$ of RBAC. The figure also reveals that the $f'_c$ of RBAC increases with the...
decrease in \( W_A \) up to 15% replacement, and beyond that, \( f'_{c} \) decreases. The relationship between \( f'_{c} \) and \( W_A \) of RBAC can be assumed by the following relation:

\[
f'_{c} = -2.20W_A^2 + 23.59W_A - 29.50, \quad R^2 = 0.94
\]  

(3)

where \( f'_{c} \) and \( W_A \) represent compressive strength in MPa and the water absorption of RBAC in percentage, respectively. The higher regression coefficient (\( R^2 = 0.94 \)) indicates that water absorption is strongly related to the compressive strength of RBAC. Mohseni [77] reported that the compressive strength of fiber-reinforced lightweight geopolymer concrete with rice husk ash decreases linearly with the increase of water absorption. Zhang and Zong [40] stated that the \( f'_{c} \) of stone aggregate concrete without RHA cannot be estimated by \( W_A \). Meanwhile, Medeiros et al. [39] stated that the compressive strength of stone aggregate concrete with 12% fly ash decreases logarithmically with the increase of water absorption. Thus, the present study offers a new relation between \( f'_{c} \) and \( W_A \) for RBAC.

3.9.4. Relationship between Water Absorption and Chloride Penetration Depth. Figure 13 also shows a relation between water absorption and chloride penetration depth of RBAC for 90 days of immersion ((RBAC)\(_{nw}\) = RBAC immersed in normal water, (RBAC)\(_{cl}\) = RBAC immersed in sodium chloride solution).

\[
H = 2.25e^{0.29W_A}, \quad R^2 = 0.97
\]  

(4)

where \( H \) and \( W_A \) represent the chloride penetration depth of RBAC immersed in NaCl solution in mm and water absorption of RBAC immersed in normal water in percentage. Zhang and Zong [40] stated that the relation between chloride ion diffusion coefficient and water absorption is exponential for stone aggregate concrete without RHA. Hence, the relation and regression coefficient also indicate that water absorption is responsible for the increment of chloride penetration depth in RBAC. As a result, the present study offers a convincing relation between \( H \) and \( W_A \) for RBAC.

3.9.5. Relationship between Water Absorption and Strength Ratio of RBAC due to Sulfate Attack. The relation between water absorption and the strength ratio of RBAC (measured because of control) immersed in sulfate solutions for 90 days is shown in Figure 14. The figure illustrates a polynomial relation between water absorption and the strength ratio of RBAC immersed in a sodium sulfate and magnesium sulfate solution, respectively. Based on the figure, the strength ratio of RBAC (up to 15% replacement) immersed in sodium sulfate solution shows a rise in strength with the decrease of water absorption. However, the strength ratio of RBAC immersed in magnesium sulfate solution shows a fall in strength with the decrease of water absorption. A higher strength ratio (more than control) indicates superior resistance against sulfate attack. The strength ratio of RBAC immersed in sulfate solution can be expressed by the following relations (equations (5) and (6)):
The strength ratio of RBAC immersed in acidic solutions can be expressed by relations (7) and (8):

\[
(f'_{cr})_{ha} = -0.08 W_A^2 + 0.86 W_A - 1.31, \quad (7)
\]

\[
(f'_{cr})_{sa} = -0.05 W_A^2 + 0.61 W_A - 0.84, \quad (8)
\]

where \((f'_{cr})_{ss}\) and \((f'_{cr})_{ms}\) represent the strength ratio of RBAC after 90 days of immersion into sodium sulfate and magnesium sulfate solution, respectively, and \(W_A\) represents the water absorption of RBAC after 90 days of curing in percentage. The higher regression coefficients point out a significant and strong relationship between water absorption and strength ratio of RBAC immersed in sulfate solutions. Moreover, Zhang and Zong [40] found a linear correlation between surface water absorption and relative strength for stone aggregate concrete without RHA because of 5% sodium sulfate attack. Hence, the present study offers a good relation for \((f'_{cr})_{ss}\), \((f'_{cr})_{ms}\), and \(W_A\) for RBAC, respectively.

### 3.9.7. Relationship between Average of Strength Ratio and Immersion Period of RBAC due to Sulfate Attack

Figure 15 illustrates a relationship between the average of strength ratio and immersion periods of RBAC because of 5% sodium sulfate attack. Hence, the present study offers a good relation for \((f'_{cr})_{ha}\), \((f'_{cr})_{sa}\), and \(W_A\) for RBAC, respectively.

**Figure 14: Relationship between water absorption and strength ratio of RBAC immersed in chemical water for 90 days ((RBAC)ss = RBAC immersed in sodium sulfate solution, (RBAC)ms = RBAC immersed in magnesium sulfate solution, (RBAC)ha = RBAC immersed in hydrochloric acid solution, and (RBAC)sa = RBAC immersed in sulfuric acid solution)**

\[
(f'_{cr})_{ss} = -0.07 W_A^2 + 0.75 W_A - 1.02, \quad (5)
\]

\[
(f'_{cr})_{ms} = -0.03 W_A^2 + 0.33 W_A - 0.09, \quad (6)
\]

\[
(f'_{cr})_{ha} = -0.07 W_A^2 + 0.75 W_A - 1.02, \quad (5)
\]

\[
(f'_{cr})_{sa} = -0.05 W_A^2 + 0.61 W_A - 0.84, \quad (8)
\]
3.9.8. Relationship between Average Strength Ratio and Immersion Period of RBAC due to Acid Attack. Figure 15 shows a correlation between the average of strength ratio and immersion period of RBAC immersed in acidic solutions (hydrochloric acid and sulfuric acid). The figure reveals that the average of strength ratio of RBAC immersed in both acidic solutions makes a powered relation with the immersion period, where the value of regression coefficient is 0.99 and 0.94 for hydrochloric and sulfuric acid solution, respectively. The average of strength ratio of RBAC is declined with the increase in the immersion period and vice-versa, which is highlighted by the power portion of the relation. The strength ratio of RBAC immersed in acidic solutions can be expressed by the following powered relations (equations (11) and (12)):

\[
(f'_{cr})_{ss} = -10^{-5}t^2 + 0.002t + 0.90, \quad (9)
\]

\[
(f'_{cr})_{ms} = 1.30t^{-0.08}, \quad (10)
\]

where \((f'_{cr})_{ss}\) and \((f'_{cr})_{ms}\) represent the average of the strength ratio of RBAC immersed in a sodium sulfate and magnesium sulfate solution, respectively, and \(t\) represents the immersion periods in days. In addition, the higher regression coefficient indicates a strong and significant relationship among \((f'_{cr})_{ss}\), \((f'_{cr})_{ms}\), and \(t\), respectively. As a result, the present study offers a good relation among \((f'_{cr})_{ss}\), \((f'_{cr})_{ms}\), and \(t\) for RBAC, respectively.

3.9.9. Relationship between Average of Chloride Penetration Depth Ratio and Immersion Period. A relationship between the average of chloride penetration depth ratio and immersion period of RBAC is illustrated in Figure 15. Based on this figure, the average of chloride penetration depth ratio of RBAC decreases with the increases in immersion periods, which is also indicated by the power portion of the relation. The average of chloride penetration depth ratio of RBAC can be expressed by the following relation:

\[
H_r = 1.06t^{-0.12}, \quad (13)
\]

where \((f'_{cr})_{ha}\) and \((f'_{cr})_{sa}\) represent the average of the strength ratio of RBAC immersed in hydrochloric and sulfuric acid solution, respectively, and \(t\) represents the immersion period in days. Besides, the higher regression coefficient also indicates a noteworthy and strong relation among \((f'_{cr})_{ha}\), \((f'_{cr})_{sa}\), and \(t\) respectively. Thus, the present study has suggested a reliable powered relation among \((f'_{cr})_{ha}\), \((f'_{cr})_{sa}\), and \(t\) for RBAC, respectively.
present study offers a convincing relation between $H_r$ and $t$ for RBAC.

3.9.10. Relationship between the Compressive Strength of RBAC Immersed in Normal Water and Chemical Water. Figure 16 plots a relationship between the compressive strength of RBAC immersed in normal water and chemical water for 90 days. According to this figure, the compressive strength of RBAC immersed in normal water made a linear relation with the chemical water. The figure also reveals that the compressive strength of RBAC immersed in chemical water increases with the increase in the compressive strength of RBAC immersed in normal water. The compressive strength of RBAC immersed in chemical water can be expressed by the following relations (equations (14)–(17)):

$$f''_{cs} = 0.88 f'_c,$$

$$f''_{cm} = 0.80 f'_c,$$

$$f''_{ch} = 0.86 f'_c,$$

$$f''_{cs} = 0.81 f'_c,$$

where $(f''_{cs})$, $(f''_{cm})$, $(f''_{ch})$, and $(f''_{cs})$ represent the compressive strength of RBAC immersed in Na$_2$SO$_4$, MgSO$_4$, HCl, and H$_2$SO$_4$ solution, and $f'_c$ represents the compressive strength of RBAC immersed in normal water in MPa, respectively. In addition, the higher regression coefficient (shown in Figure 16) indicates that a significant relationship exists between the compressive strength of RBAC immersed in normal water to the chemical water.

Thus, the present study proposed a convincing relationship between the compressive strength of RBAC immersed in normal water and chemical water.

4. Conclusions

Based on experimental results, the conclusions that can be drawn only for a mixed proportion of 1:1.5:3 and a w/b ratio of 0.50 are as follows:

(i) The workability of RBAC decreases about 29.69% to 75.02% with an increase in RHA replacement from 10% to 25%, respectively.

(ii) After 90 days of curing, RBAC (up to 15% RHA replacement) achieves about 2.28%–6.64% greater compressive strength than that of concrete.

(iii) After 90 days, RBAC (up to 25% RHA replacement) demonstrated around 17.59%–40.73% and 12.12%–35.68% lower water absorption and porosity than that of control, respectively, while 20% RHA shows the minimum water absorption and porosity.

(iv) Compared to control, RBAC (up to 25% RHA replacement) possesses roughly 35.62%–54.79% higher resistance against chloride attack by 90 days of immersion.

(v) After 90 days of immersion, RBAC (up to 15% RHA replacement) develops approximately 0.39%–4.56% better resistances against Na$_2$SO$_4$ attack, and RBAC (up to 25% RHA replacement) exhibits nearly...
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