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Investigating the Viability of Recycling Rice Husk Ash and Plastic Bag Waste to Enhance Durability of Lightweight Concrete

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Abstract: The disposal of waste plastic bags (WPB) represents an environmental challenge. Recycling (WPB) in the concrete industry would represent a huge environmental advantage if proven effective and economic. This study aims to investigate the viability of recycling rice husk ash and plastic bag waste to enhance the durability of lightweight concrete (LWC). Rice husk ash (RHA) is used as a cement replacement to reduce the health and environmental hazards originating from the cement industry. The mutual influence of using WPB and RHA on the mechanical properties and durability of LWC is investigated in this study. The effect of various WPB contents (10, 20 and 30%) as natural sand substitution with RHA of (5, 10 and 15%) as partial cement replacement on the flow-ability, self-weight, compressive and tensile strengths, water permeability, chloride resistance, and fire resistance was examined and reported. The results of this study consolidated the idea of recycling WPB in the construction field. In summary, the optimal content of WPB is 10% by volume of fine aggregate and 10% of RHA by weight of cement.

Keywords: waste plastic bag (WPB) concrete; rice husk ash (RHA); RCP test; fire resistance

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1. Introduction

Plastic bags have played a significant role in purchasing habits, and consequently, supermarkets and grocery stores are considered the biggest providers of plastic shopping bags. The consumption of plastic bags has rapidly increased worldwide. In Egypt, Egyptians use over 12 billion plastic bags each year, and 6% of the huge amount of solid waste is composed of plastic bags, which amounts to about 970,000 tons. Therefore, Egypt is ranked as the biggest plastic polluter in the Mediterranean [1,2]. Despite the striking properties of plastic bags, their lifespan and mode of degradation are considered the most important characteristics of plastic [3]. Plastic never fully degrades but only breaks into smaller pieces, which can become microplastics that easily enter every marine trophic level. During this process, plastic releases toxic chemicals into the oceans, destroying and causing death to marine habitats [4]. Moreover, plastic bags cause harm to the growth of agricultural plants as they do not fully decompose in soil but remain on agricultural lands and retard the progress of plant growth [5].

In the Middle East region, Egypt, as an agricultural country, is considered one of the largest rice producers, which is planted in the Nile Delta area [6]. Rice milling generates rice husk as an agricultural residue through this process. During the milling process, about 22% of the weight is received as husk [7]. The process of open burning rice husk as a means of rapid disposal is a disastrous habit. This process is the main suspect in the development of a well-defined thick layer of smog, known as "the black cloud", which first appeared in Egypt about 25 years ago, in 1997, over the Nile Delta and Cairo. Nearly 42,000 Egyptians die yearly because of diseases related to poor air quality, and as a result, the life expectancy of Egyptians is shortened by 1.85 years, which can be attributed to air pollution [6]. Controlled burning of rice husks can notably reduce CO and CO_2 emissions.

Green concrete is a solution to eliminate environmental risks and air pollution issues. Green concrete is addressed when at least one of its components is substituted by waste material [8]. Rice husk ash (RHA) partially replaces ordinary Portland cement (OPC), which involves the emission of enormous pollutants during its manufacturing process. This industry has been enlisted as the third-largest industrial source of air pollution [9]. 3.5% of global anthropogenic greenhouse gas emissions are attributed to the cement industry, and 5–6% of all CO_2 greenhouse gases generated by human activities originate from cement manufacturing [9,10].

In the construction industry, reducing weight is a crucial target, due not only to the high thermal insulation response of the building but also to the cost reductions in money and time spent on handling and manufacturing [11]. The performance of lightweight concrete structures is distinguished as the earthquake impact is notably reduced as the self-weight decreases, as illustrated by Farzampour et al. [12–16]. When plastics are used in concrete, either to replace coarse aggregate or fine aggregate with lower bulk density, the unit weight of concrete decreases to less than 2000 kg/m^3 and, therefore, can be classified as lightweight concrete [2,17].

WPB mortar is known to have lower bulk density and fluidity than cement mortar. Youcef Ghernouti et al. [18,19] stated that the inclusion of 10–40 vol. % of sand plastic produced from WPB significantly improved the fluidity of concrete, as WPB does not absorb water. On the other hand, a reduction in both flexural and compressive strengths was recorded as the content of WPB increased. However, the influence on chloride and fire resistance was not investigated. Ibrahim Almeshal et al. [11] agreed with the previous study that the compressive and splitting tensile strengths were notably reduced as the amount of shredded polyethylene terephthalate (PET) bottles as partial sand replacement increased from 10–50% PET replacement levels, suggesting that recycling plastic bottles in concrete can be successfully used in highway medians and highway pavements or in structures where strength is not an important factor.

Abhishek Jain et al. [20] investigated the use of WPB as a partial cement replacement with 5–20 vol. %. They revealed that the optimal replacement content of 5% WPB produced mortar with reasonable compressive strength and a medium permeability range. WPB concrete is a good choice for construction applications where higher toughness and resistance to impact are more important than strength. WPB with 5% replacement is used in lightweight and low-strength construction for paver blocks, driveways, concrete barriers, and walkways.

Baboo Rai et al. [21] stated that the workability and compressive strength of concrete were negatively affected as waste plastic flakes replaced fine aggregate in concrete increased. Nevertheless, this could be an added feature to the WPB concrete in numerous civil applications that require low-degree workability, such as canal linings, partition wall panels, and precast bricks.

In addition, Raghatate Atul M. [19] stated that the optimal content (0.8 vol. %) of WPB significantly improved the tensile strength of concrete and slightly reduced the compressive strength. Yet, the influence of this content on other durability properties was not reported. Zainab Z. Ismail et al. [19] also stated that the inclusion of 10, 15, and 20 vol. % of plastic waste collected from plastic manufacturing plants lowered the flexure and compressive strengths of green concrete mortar compared to mortar containing 100% natural sand. This reduction is attributed to lower adhesion between cement and plastic waste particles. At the same time, it was reported that plastic concrete could arrest the propagation of microcracks and is applicable in applications requiring high toughness.

Agreeing with these findings, Suganthy et al. [19] showed that up to 25% plastic replacement of sand, the compressive strength gradually decreased, but afterward, a rapid decrease in strength was obtained as more replacement contents than 25% up to 75% were investigated.

Most of the previous studies have limited the focus to the compressive strength of WPB concrete, which is insufficient to evaluate the concrete behavior clearly and neglects the other properties that require more detailed investigation [19].

Ganesan K et al. [22] stated that the addition of RHA in concrete mortars with optimum cement replacement levels less than 20% can improve their compressive strength, while an improvement in durability, measured by chloride permeability, requires higher optimum replacement dosages compared to compressive strength.

However, recycling RHA with WPB to produce sustainable concrete with acceptable strength and durability for use in construction has not been reported and remains unclear. To resolve these uncertainties, this study investigates the impact of incorporating various contents of RHA (5%, 10%, and 15% by weight of cement) with WPB contents (10%, 20%, and 30% by volume of fine aggregates) to produce lightweight green concrete with improved performance. The study evaluates the mechanical properties of the prepared concrete, including compressive strength, tensile strength, and resistance to chloride penetration and temperature rise.

This present work is an effort to explore the effect of incorporating ground waste plastic bags as a partial replacement of fine aggregates on concrete durability in terms of water permeability, chloride ion penetration, and fire resistance. Such effects have not been fully studied in the literature, as most relevant research has focused on mechanical properties. Furthermore, the viability of introducing recycled rice husk ash as a pozzolanic admixture to control the reduction of compressive strength in WPB concretes is investigated. The combined effect of recycling both RHA and WPB in one concrete mix has not been reported in the literature.

2. Experimental Plan

2.1. Materials

In this study, Ordinary Portland cement type I labeled CEM I 52.5 N was supplied from MISR BENI-SUEF Cement Company and complied with BS EN 197-1 (2004) and ESS4756-1 (2009) [18]. Silica Fume (SF) was supplied from the Sika Company and is imported as Sika fume. Typical Egyptian rice husk ash was collected from an open dump around a local milling farm in El Bhaira, located in the west of the Delta; Figure 1 shows the process of preparing rice husk ash.

Figure 1. Rice husk agriculture disposed as waste.

The produced ash was burned at a temperature of about 700 °C for 60 min and then grounded by small mill to produce finer ash. The physical properties, typical chemical analysis, and mechanical properties of the used cement and mineral admixtures are listed in Table 1.

Two types of natural coarse aggregate of crushed dolomite with a maximum nominal size of 25 and 12.5 mm were used to prepare concrete specimens. Natural sand with a fineness modulus of 2.6 was sieved on sieve 4.76 before use. Waste plastic shopping bags WPB are torn and ground in a mall mill to produce finer particles used in concrete mixtures. The physical properties of sand and WPB are shown in Table 2. A high-performance super-plasticizer SP admixture of the aqueous solution supplied by CMB, Egypt, under the brand name of addicrete BVF, was used to increase the workability of concrete mixtures. Figure 2 shows a sample of the raw materials used in preparing concrete samples.

Table 1. Properties of cement and mineral admixtures (Data for Cement and SF from M. Abd El-Hameed M. Bakr et al. [23]).

Chemical Composition (%)			
Constituents	**Cement**	**SF**	**RHA**
Fe_2O_3	3.55	0.45	0.24
CaO	61.60	0.16	1.31
MgO	1.90	0.26	-
Al_2O_3	5.20	0.25	0.51
SiO_2	19.14	96.81	87.50
Na_2O	0.45	0.14	1.22
K_2O	0.20	0.28	3.31
SO_3	3.17	0.14	1.72
CI^-	0.085	0.030	0.053
LOI	2.88	1.30	3.05
Physical Properties			
Specific gravity	3.15	2.40	2.05
Blaine (cm^2/g)	3320	209,600	17,960
Mechanical properties (Compressive strength MPa)			
2 days	25.20	-	-
28 days	55.10	-	-

Table 2. Physical Properties of sand and waste plastic bag.

	Sand	WBP
Apparent density (g/cm^3)	1.45	0.53
Specific gravity (g/cm^3)	2.56	0.87
Visual equivalent (%)	80	-
Fineness modulus	2.6	2.5

Figure 2. Sample of raw materials used in concrete mix.

2.2. Mixes and Variables

Table 3 shows the proportions of the produced mixtures. The mixtures were coded such that the ingredients were identifiable from their IDs. The WPB content as partial sand replacement was 10, 20, and 30% by volume of sand. Cement was replaced by weight with Rice Husk Ash (RHA) or Silica Fume (SF) at four proportions: 2.5, 5% for SF and 5, 10, 15% for RHA, to better understand their influence on the physical and mechanical properties of concrete. The ratio of fine aggregates to coarse aggregates was maintained at 1:2.

Mixes were categorized into six different groups, from A to F. In group A, WPB, SF, and RHA were introduced individually with the replacement ratios aforementioned to illustrate their effect separately in comparison to one control mix: M1 OPC. In group B, SF and RHA were introduced together as pozzolans at different replacement ratios with no

WPB. In groups C, D, and E, the 3 replacement ratios of RHA (5, 10, 15%) were tried in each group, with one ratio for WPB for each group: 10%, 20%, and 30%, respectively. In group F, both replacement ratios of SF were tried once with 10% WPB, then with 20% WPB.

Table 3. Proportions of concrete mixes.

Group	Mix No.	Mix ID	Cementitious Materials			Aggregates			SP %	W/C
			Cement Kg/m^3	RHA %	SF %	Sand Kg/m^3	Coarse Kg/m^3	WPB %		
A	M1	OPC	400	0	0	600	1110	0	3	0.4
	M2	P0R0S2.5	390	0	2.5	597.5	1109.8	0	3	0.4
	M3	P0R0S5	380	0	5	636	1181	0	3	0.4
	M4	P0R5S0	380	5	0	636	1181	0	3	0.4
	M5	P0R10S0	360	10	0	633.5	1176.5	0	3	0.4
	M6	P0R15S0	340	15	0	631	1172	0	3	0.4
	M7	P10R0S0	400	0	0	539.5	113.5	10	3	0.4
	M8	P20R0S0	400	0	0	446.8	1037.5	20	3	0.4
	M9	P30R0S0	400	0	0	370	981.7	30	3	0.4
B	M10	P0R5S2.5	370	5	2.5	634.7	1178.8	0	3	0.4
	M11	P0R5S5	360	5	5	6.33.5	1176.4	0	3	0.4
	M12	P0R10S2.5	350	10	2.5	632.1	1174.2	0	3	0.4
	M13	P0R10S5	340	10	5	631	1172	0	3	0.4
C	M14	P10R5S0	380	5	0	537.6	1109	10	3	0.4
	M15	P10R10S0	360	10	0	535.3	1104.7	10	3	0.4
	M16	P10R15S0	340	15	0	533.5	1100.4	10	3	0.4
D	M17	P20R5S0	380	5	0	473.3	1007	20	3	0.4
	M18	P20R10S0	360	10	0	445.4	1034	20	3	0.4
	M19	P20R15S0	340	15	0	443.8	1030	20	3	0.4
E	M20	P30R5S0	380	5	0	369.4	980	30	3	0.4
	M21	P30R10S0	360	10	0	368	976	30	3	0.4
	M22	P30R15S0	340	15	0	366.5	972.3	30	3	0.4
F	M23	P10R0S2.5	390	0	2.5	538.5	1111.3	10	3	0.4
	M24	P10R0S5	380	0	5	537.5	1109	10	3	0.4
	M25	P20R0S2.5	390	0	2.5	448.1	1040.2	20	3	0.4
	M26	P20R0S5	380	0	5	445.2	1033.5	20	3	0.4

The prepared materials were initially mixed; the mixing water was then added to the mixer with respect to the addition of the super-plasticizer. After mixing, surface-oiled molds were filled with the fresh mixture. Six cylindrical specimens (150 × 300 mm) and fourteen cubical specimens (150 × 150 × 150 mm) were cast for each group. After 24 h, all specimens were de-molded and placed in a water tank for curing until the test ages. Figure 3 shows the steps of mixing and curing concrete samples.

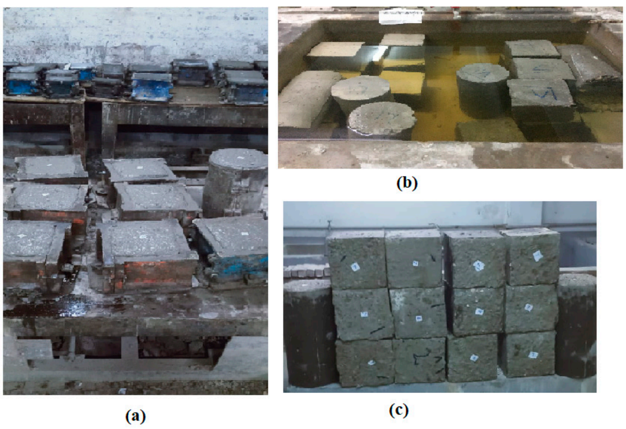

Figure 3. Steps of mixing and curing: (**a**) molding concrete samples; (**b**) Samples in curing tank; (**c**) de-molding concrete samples.

2.3. Test Techniques and Procedures

2.3.1. Slump

The consistency and workability of all fresh concrete mixtures were measured to understand the ease with which the concrete could be implemented through a slump test (according to NF P 18-451).

2.3.2. Unit Weight

The unit weight of fresh concrete represents how the concrete is mixed using the correct proportions and batch-to-batch uniformity (according to ASTM C 138).

2.3.3. Compressive Strength

To understand the effect of various concrete syntheses on the change in mechanical properties, the tests for compressive strength were conducted by loading the hardened concrete specimens under a monotonic uniaxial compressive load up to failure using a hydraulic testing machine. Tests were conducted at ages 7, 14, 28, and 90 days.

2.3.4. Splitting Tensile Strength

The splitting tensile strength tests were conducted at 28 days of cured cylindrical concrete specimens by placing the tested specimen horizontally between the loading surfaces of the hydraulic machine (125 mm × 550 mm steel plates) shown in Figure 4.

Figure 4. Testing of concrete tensile strength with sample of cylinder.

2.3.5. Water Permeability

The water permeability test is an indirect measurement of concrete durability. The tests were performed on specimens at least 90 days old. Figure 5 shows the apparatus used in performing the test.

Figure 5. Testing of concrete water permeability.

2.3.6. Rapid Chloride Penetration (RCP)

The rapid chloride penetration test was conducted on each type of concrete mix following ASTM C1202 and adopted from AASHTO T277 [18]. The test was carried out using the three-cell RCP apparatus shown in Figure 6. The readings are used to evaluate the resistance of concrete specimens against chloride ion penetration; the greater the total charges passed, the greater the chloride permeability of the concrete.

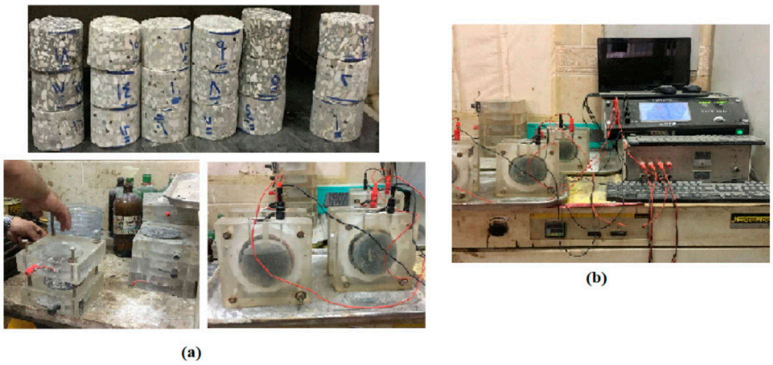

Figure 6. Conducting RCP test for concrete mixes: (**a**) preparing samples for RCPT; (**b**) RCPT apparatus.

2.3.7. Fire Resistance

This test was conducted to investigate the influence of elevated temperatures on concrete's strength and durability properties. After 90 days of curing, cubic specimens from each batch were placed in an electric furnace for 3 h at 400 °C, as shown in Figure 7. After 24 h, the compressive strength test was obtained for the naturally cooled samples at room temperature. The results were analyzed to determine the residual compressive strength and the loss in compressive strength.

Figure 7. Elevated temperature test of concrete specimens: (**a**) electric furnace device; (**b**) placing samples in furnace before test; (**c**) cubic concrete specimens after fire; (**d**) compressive strength testing after fire.

3. Experimental Results and Analysis

3.1. Fluidity of Concrete

The fluidity of WPB concretes (WPBC) with replacement content of 10% decreased by 11.5%; a further increase in the WPB content of 20 and 30% caused a massive reduction of the workability by 26% and 40%, respectively, as indicated by slump values as shown in Figure 8, but they were still workable. Table 4 shows the slump values of all the concrete mixtures.

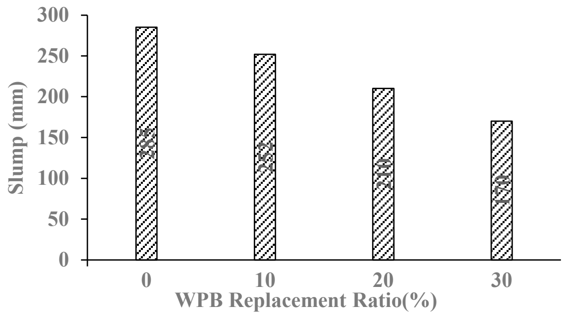

Figure 8. Slump values of concrete mixes containing WPB in different percentages.

Table 4. Physical properties of concrete mixes (Slump, fresh and dry unit weight).

Mix Type	Slump	Fresh Unit Weight	Dry Unit Weight		
	mm	KN/m^3	7 Days KN/m^3	14 Days KN/m^3	28 Days KN/m^3
OPC	285	24.450	23.988	24.003	24.012
P0R0S2.5	270	24.113	23.689	23.704	23.721
P0R0S5	255	23.970	23.532	23.547	23.561
P0R5S0	190	23.443	22.996	23.016	23.037
P0R10S0	130	23.046	22.477	22.489	22.513
P0R15S0	90	22.599	22.110	22.127	22.145
P10R0S0	252	23.665	23.161	23.173	23.194
P20R0S0	210	22.779	22.293	22.311	22.326
P30R0S0	170	21.585	21.239	21.250	21.274
P0R5S2.5	235	23.354	22.883	22.901	22.919
P0R5S5	250	23.096	22.643	22.661	22.679
P0R10S2.5	215	22.809	22.400	22.421	22.436
P0R10S5	240	22.619	22.148	22.163	22.178
P10R5S0	205	22.919	22.436	22.453	22.465
P10R10S0	170	21.733	21.813	21.834	22.037
P10R15S0	125	21.526	21.286	21.301	21.319
P20R5S0	185	22.329	21.852	21.870	21.887
P20R10S0	145	21.742	21.283	21.304	21.327
P20R15S0	110	21.556	20.927	20.945	20.963
P30R5S0	120	21.487	20.871	20.889	20.904
P30R10S0	95	21.052	20.661	20.681	20.696
P30R15S0	70	20.729	20.293	20.305	20.311
P10R0S2.5	260	22.779	22.127	22.142	22.163
P10R0S5	270	22.453	21.781	21.801	21.822
P20R0S2.5	230	22.095	21.665	21.686	21.704
P20R0S5	242	22.024	21.487	21.508	21.526

3.2. Unit Weight

The fresh and dry unit weights of concrete decreased as the sand- replacing content of WPB increased. A decrease in the unit weight of concrete by 3%, 7%, and 11.7% was noted for samples containing 10, 20, and 30% of WPB, respectively. A further decrease in the unit weight of fresh concrete, as shown in Figure 9, resulted from the incorporation of WPB as a partial sand replacement with RHA of lower unit weight and as a partial cement replacement that decreases the density of concrete, thereby resulting in lighter concrete.

Figure 10 shows the unit weight of hardened concrete at ages 7, 14, and 28 days. Table 4 shows the unit weight of the fresh and dry mixtures.

3.3. Compressive Strength

Figure 11 shows a decrease in the compressive strength of the cubic specimens as the WPB replacement content of the natural sand increased at each curing age. At 28 days, the compressive strength of the 10% and 20% WPB replacement ratios declined by 13% and 25%, respectively, and significantly decreased by 48% at the 30% replacement ratio.

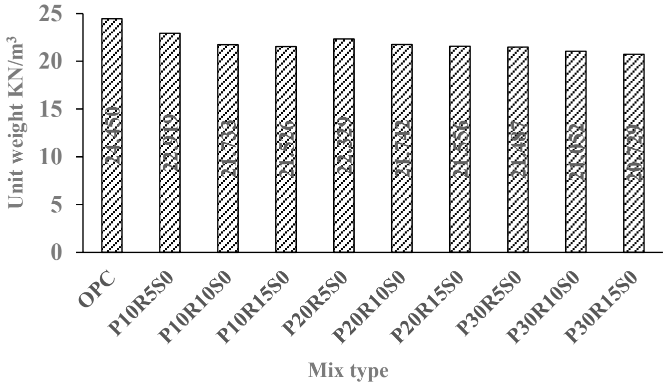

Figure 9. Effect of recycled WPB and RHA on fresh unit weight of concrete.

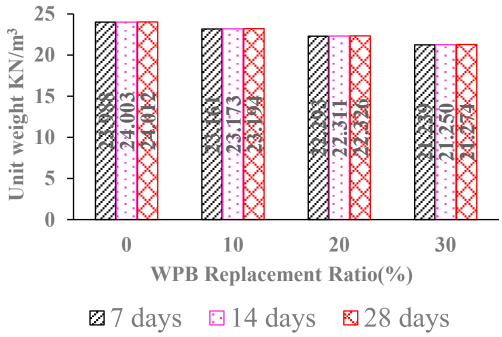

Figure 10. Effect of recycled WPB on dry unit weight for different ages.

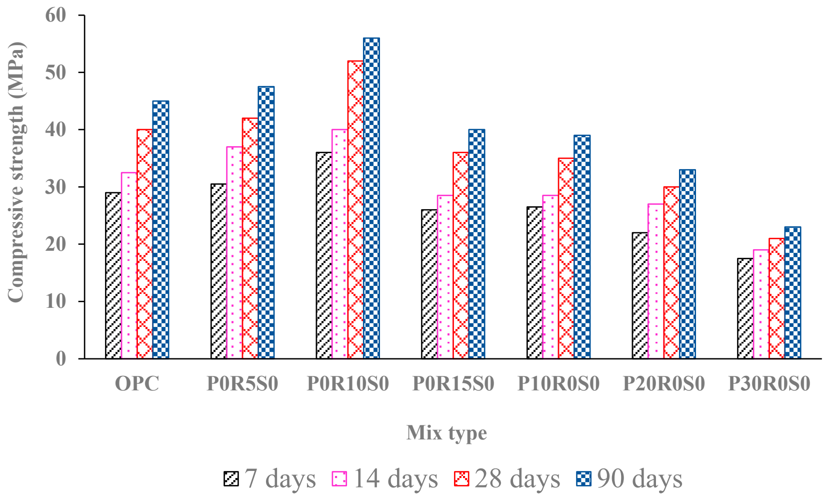

Figure 11. Influence of recycled RHA and WPB on the concrete compressive strength for different ages.

At 5% and 10% RHA replacement contents, the cube compressive strengths increased by 5% and 30%, respectively. On the other hand, the compressive strength decreased by 10% at a 15% RHA replacement ratio but was still within accepted ranges of 36 MPa at 28 days and 40 MPa at 90 days. Figure 12 shows that at 10% RHA with 10% WPB replacement ratios, the compressive strength was 42 MPa at 28 days with a slight increase in 5% compared with the 40 MPa of the OPC control mix. This indicates that the compressive strength was increased by adding RHA as a cement replacement in a WPBC.

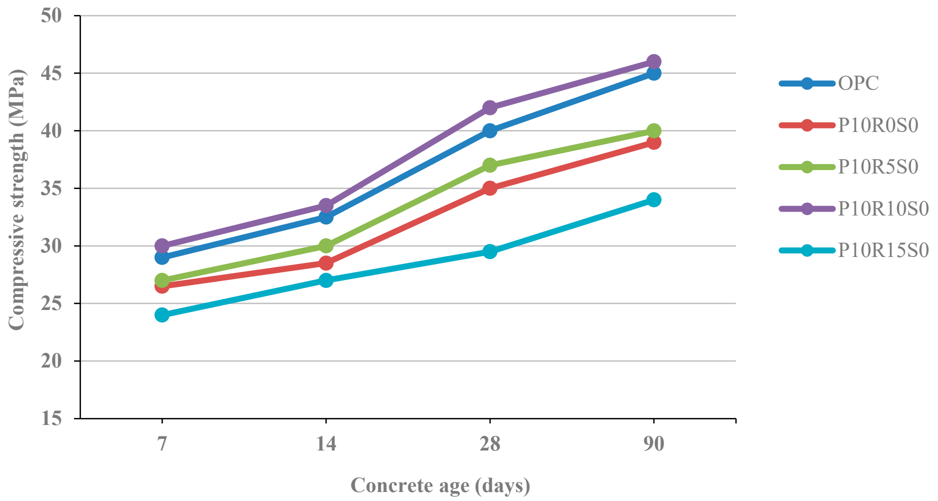

Figure 12. Compressive strength of recycled RHA with 10% WPB replacement ratio.

Figure 13 shows that a concrete mix with 10% replacement of RHA and 5% replacement of SF obtained the highest compressive strength of 60 MPa without high- temperature curing, a 50% increase over conventional concrete containing 0% cementitious replacement ratios.

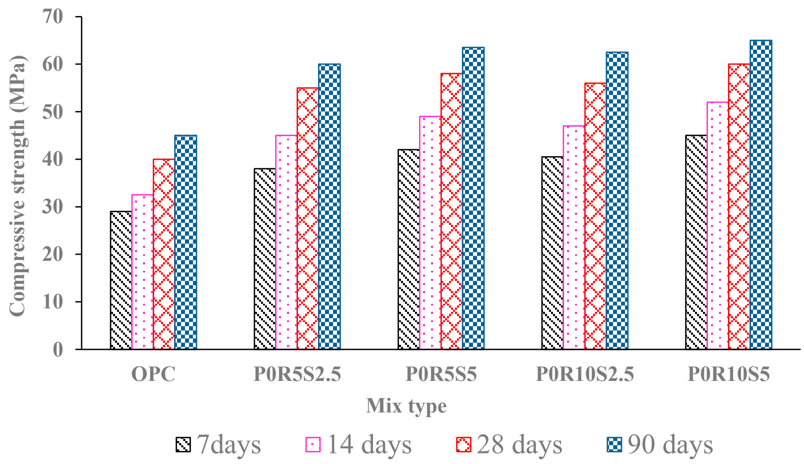

Figure 13. Effect of RHA with SF on the compressive strength of concrete mixes.

A slight increase in the cylinder compressive strength by 3% was recorded at 39.5 MPa for the P10R10S0 mix, suggesting that using RHA has a good impact on improving the WPBC compressive strength.

Table 5 shows the compressive strength values of all cubic and cylindrical concrete samples at all curing ages.

3.4. Splitting Tensile Strength

The incorporation of RHA and SF together notably increased the tensile strength by 13% and 19% for P0R5S2.5 and P0R10S5, respectively, as shown in Figure 14. On the contrary, the tensile strength decreased by 12% and 46% as the RHA ratio increased from 5% to 15%, respectively. The tensile strength also decreased as the WPB ratio increased by 31% and 62% for P10R0S0 and P30R0S0, respectively.

3.5. Water Permeability

Figure 15 shows that the water permeability of WPBC specimens was found to increase as the amount of WPB increased. At 10% replacement of sand, the depth of water penetration increased by 65 mm, while at 30% WPB of sand replacement, the water was completely transported through the concrete specimen. In conclusion, the WPBC was classified into the category of high permeability as the penetration depth was higher than 60 mm [20].

Table 5. Compressive and Tensile strength of all concrete mixes.

Mix Type	Cubic Compressive Strength								$f_{c'}/f_{cu}$	Cylinder Compressive Strength		f_t/f_{cu}	Split Tensile Strength	
	7 Days MPa		14 Days MPa		28 Days MPa		90 Days MPa			28 Days MPa			28 Days MPa	
	Mean	SD *	Mean	SD *	Mean	SD *	Mean	SD *		Mean	SD *		Mean	SD *
OPC	29.0	1.22	32.5	1.24	40.0	1.16	45.0	1.53	0.96	38.5	1.42	7.69	5.20	1.13
P0R0S2.5	34.5	1.35	43.5	1.35	51.0	1.14	55.0	1.24	0.88	45.0	1.57	7.76	5.60	1.50
P0R0S5	42.0	1.30	46.0	1.05	58.0	1.06	62.0	1.00	0.84	49.0	1.42	10.36	5.80	1.27
P0R5S0	30.5	1.19	37.0	1.25	42.0	1.02	47.5	1.29	0.75	40.0	1.36	16.80	4.60	1.27
P0R10S0	36.0	1.46	40.0	1.14	52.0	1.18	56.0	1.36	0.68	42.0	1.59	31.25	4.00	1.31
P0R15S0	26.0	1.38	28.5	1.32	36.0	1.29	40.0	1.27	0.69	37.0	1.61	29.62	2.80	1.34
P10R0S0	26.5	1.35	28.5	1.29	35.0	1.42	39.0	1.27	0.91	33.5	1.36	8.56	3.60	1.41
P20R0S0	22.0	1.46	27.0	1.25	30.0	1.20	33.0	1.36	0.79	28.0	1.59	8.39	2.80	1.34
P30R0S0	17.5	1.36	19.0	1.07	21.0	1.32	23.0	1.35	0.83	18.5	1.15	10.00	2.00	1.13
P0R5S2.5	38.0	1.19	45.0	1.23	55.0	1.15	60.0	1.49	0.85	47.0	1.75	9.40	5.85	1.20
P0R5S5	42.0	1.37	49.0	1.04	58.0	1.42	63.5	1.37	0.86	50.0	1.32	11.91	6.00	1.20
P0R10S2.5	40.5	1.41	47.0	1.35	56.0	1.14	62.5	1.36	0.88	49.0	1.51	9.03	5.42	1.27
P0R10S5	45.0	1.39	52.0	1.55	60.0	1.33	65.0	1.48	0.88	53.0	1.27	11.07	6.20	1.48
P10R5S0	27.0	1.14	30.0	1.47	37.0	1.16	40.0	1.35	0.71	35.0	1.44	8.75	3.91	1.27
P10R10S0	30.0	1.42	33.5	1.21	42.0	1.29	46.0	1.61	0.74	39.5	1.41	9.16	4.33	1.06
P10R15S0	23.0	1.35	25.0	1.22	28.0	1.25	33.0	1.40	0.74	31.0	1.36	8.15	3.65	1.27
P20R5S0	21.0	1.27	24.5	1.25	28.0	1.06	31.0	1.50	0.78	27.0	1.50	8.21	3.17	1.56
P20R10S0	23.0	1.10	26.5	1.27	30.0	1.16	32.5	1.33	0.77	29.0	1.58	8.13	3.46	1.20
P20R15S0	18.0	1.20	20.0	1.02	23.5	1.27	25.5	1.59	0.80	24.0	1.53	7.69	2.67	1.27
P30R5S0	19.0	1.10	20.5	1.23	23.0	1.26	27.0	1.51	0.93	20.0	1.42	6.00	2.26	1.27
P30R10S0	20.0	1.10	21.5	1.50	25.0	1.59	28.5	1.55	0.86	19.0	1.53	6.25	2.80	1.27
P30R15S0	12.5	1.48	16.0	1.29	18.5	1.29	23.0	1.51	0.97	16.0	1.31	8.41	1.87	1.48
P10R0S2.5	27.0	1.42	29.5	1.26	36.5	1.38	40.0	1.22	0.67	34.0	1.40	8.29	4.20	1.27
P10R0S5	28.0	1.36	31.0	1.19	37.5	1.17	41.5	1.42	0.66	35.5	1.29	8.10	4.52	1.13
P20R0S2.5	23.0	1.41	28.0	1.48	31.0	1.32	34.5	1.59	0.78	29.5	1.34	8.44	3.28	1.34
P20R0S5	24.0	1.16	29.0	1.19	32.5	1.42	36.0	1.53	0.88	32.0	1.19	7.70	4.02	1.13

SD *: Standard deviation.

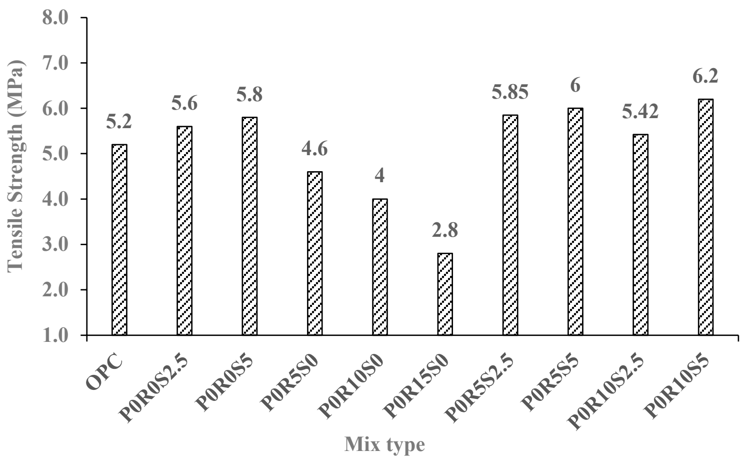

Figure 14. Effect of SF and RHA on the tensile strength of concrete mixes.

The penetration depth of water notably decreased as the replacement amount of RHA increased in WPBC specimens, as shown in Figure 16. The incorporation of RHA beyond 10% of cement replacement in WPBC enhanced the durability of concrete against water permeability and altered it from being classified as high permeability to the category of medium permeability with a water penetration depth between 30 and 60 mm [20].

3.6. RCP

Table 6 shows that the highest average value of charges passed was for the OPC control mix, while the charges passing inside (P0R5S0-P0RA5S0) were reduced by 51–61%, respectively, and the addition of RHA remarkably increased the chloride resistance. This is attributed to the additional cement gel (C-H-S) produced by rice ash. This gel reduces the voids and blocks the capillaries inside the concrete, making it less permeable to chloride and other chemical attacks [24]. Furthermore, incorporating RAH with SF as in (P0R5S2.5-P0R10S5) mixes significantly reduces the charges passed by 66–78%, respectively.

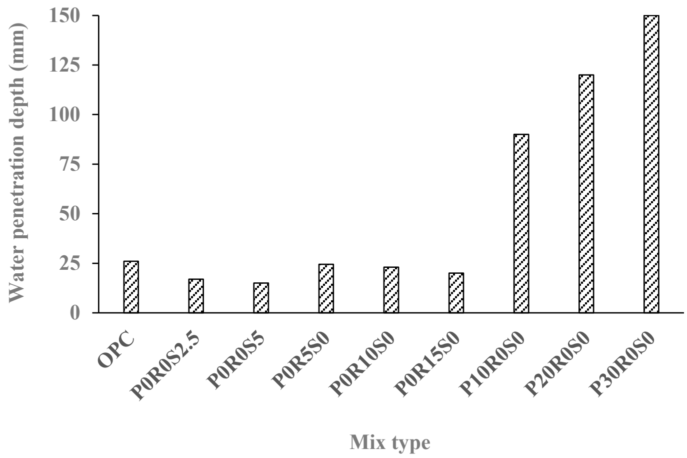

Figure 15. Influence of SF, RHA and WPB on water permeability.

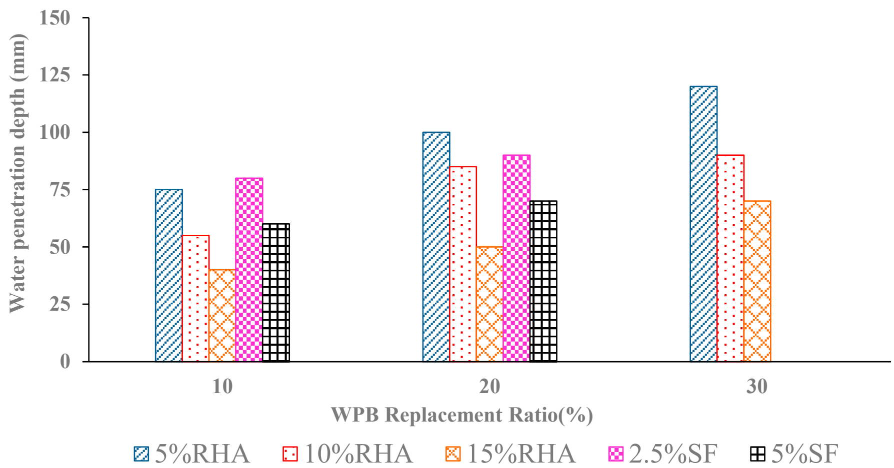

Figure 16. Influence of SF, RHA on WPBC water permeability.

Table 6. Charges passed in RCP of AM1-FM26.

Mix Type	Charges Coulomb (C)	Mix Type	Charges Coulomb (C)
OPC	2750	P10R5S0	919
P0R0S2.5	1800	P10R10S0	732
P0R0S5	1280	P10R15S0	681
P0R5S0	1360	P20R5S0	750
P0R10S0	1200	P20R10S0	656
P0R15S0	1073	P20R15S0	612
P10R0S0	1022	P30R5S0	587
P20R0S0	868	P30R10S0	556
P30R0S0	626	P30R15S0	527
P0R5S2.5	935	P10R0S2.5	978
P0R5S5	681	P10R0S5	872
P0R10S2.5	646	P20R0S2.5	832
P0R10S5	611	P20R0S5	779

The incorporation of WPB lessens chloride ions' diffusion inside the concrete and prevents them from reaching the steel bars. Moreover, suggesting that using RHA in WPBC reduces the electric charges passed, as shown in Figure 17. The P30R15S0 mix had the lowest average value of charges passed. This is explained by the fact that, by hydration, the smaller particles of WPB and RHA create products that fill the space between the larger particles of cement [25]. Hence, all the WPBC mixes are categorized as having very low chloride penetrability according to ASTM C1202-19 as the average charges passed were between 100 and 1000 C.

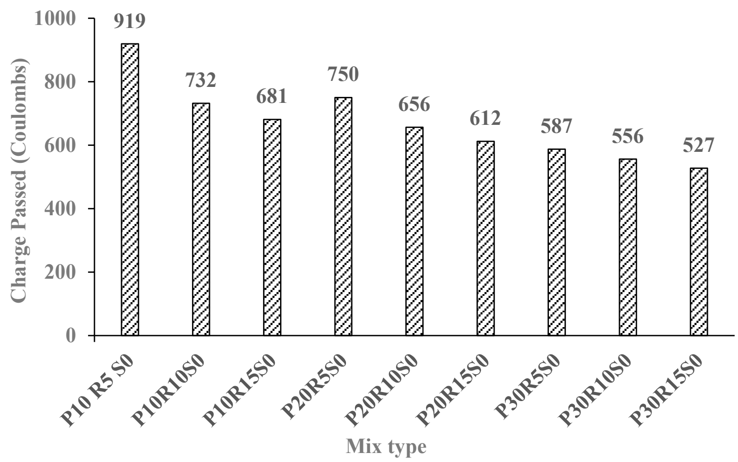

Figure 17. Effect of RHA and WPB replacement ratio on charges passed.

3.7. Fire Resistance

After heating for 3 h at 400 °C, only 10.3% of the original strength was lost for P10R0S0, and as the content of WPB increased, the reduction in the compressive strength increased. Mixes P0R5S2.5 and P0R5S5 maintained a higher value of residual strength percentage between 76.8% and 78.4% compared to P0R10S2.5 and P0R10S5, which had 58.4% and 62.9% of residual compressive strength, respectively. When concrete is exposed to rapid temperature rise during a fire, significant changes in porosity due to absorbed water release, dehydration of C-S-H, and probable formation of micro and macro cracks occur [26]. Residual strength is the result of a comparative analysis of the compressive strength of the concrete that has been heated with sound concrete [27]. The residual strength of concrete samples after heating is described in Table 7.

Table 7. The cubic compressive and its loss rate after fire test.

Mix Type	Cubic Compressive Strength before Fire Test (MPa)		Residual Cubic Compressive Strength after Fire Test (MPa)	Loss Rate of Cubic Compressive Strength after Fire Test (%)
	Mean	SD *		
OPC	45.0	1.10	31.0	31.1
P0R0S2.5	55.0	1.07	45.2	17.8
P0R0S5	62.0	1.06	49.5	20.2
P0R5S0	47.5	1.06	37.2	21.7
P0R10S0	56.0	1.05	44.3	20.9
P0R15S0	40.0	1.02	31.9	20.3
P10R0S0	39.0	1.10	35.0	10.3
P20R0S0	33.0	1.19	20.2	38.8
P30R0S0	23.0	1.10	11.1	51.7
P0R5S2.5	60.0	1.12	49.3	17.8
P0R5S5	63.5	1.08	56.5	11.0
P0R10S2.5	62.5	1.15	36.5	41.6
P0R10S5	65.0	1.06	40.9	37.1
P10R5S0	40.0	1.21	25.1	37.3
P10R10S0	46.0	1.02	31.2	32.2

Table 7. *Cont.*

Mix Type	Cubic Compressive Strength before Fire Test (MPa)		Residual Cubic Compressive Strength after Fire Test (MPa)	Loss Rate of Cubic Compressive Strength after Fire Test (%)
	Mean	SD *		
P10R15S0	33.0	1.04	19.6	40.6
P20R5S0	31.0	1.29	23.3	24.8
P20R10S0	32.5	1.17	26.0	20.0
P20R15S0	25.5	1.12	17.0	33.3
P30R5S0	27.0	1.18	21.5	20.4
P30R10S0	28.5	1.12	23.4	17.9
P30R15S0	23.0	1.36	16.0	30.4
P10R0S2.5	40.0	1.35	31.5	14.9
P10R0S5	41.5	1.12	32.0	16.9
P20R0S2.5	34.5	1.14	18.2	40.3
P20R0S5	36.0	1.17	18.0	44.6

SD *: Standard deviation.

Figure 18 shows that the residual strength percentages of (P10R5S0-P30R15S0) were between 62.8% and 69.6%, while P20R0S5 concrete only has a 55.4% residual strength. At 400 °C, concrete strength exceeding 45 MPa shows a residual strength of over 60%, indicating that concrete that has been fired up to 400 °C is feasible for reuse, but with construction property improvements [27].

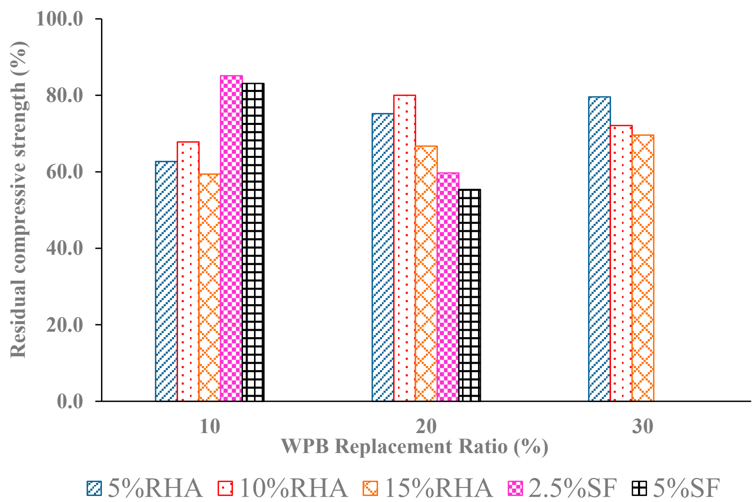

Figure 18. Effect of RHA and SF replacement ratios on residual strength of WPB concrete mixes.

4. Conclusions

The effect of using waste plastic bags (WPB) as a partial replacement of fine aggregate in the construction field and the influence of recycling rice husk ash (RHA) in WPB concretes (WPBC) have been studied. The experimental work was conducted to understand the influence of incorporating RHA at various replacement ratios (5, 10, and 15%) by weight of cement with various WPB sand replacement ratios by volume (10, 20, and 30%). The impact on self-weight, flow-ability, compressive and tensile strength, water permeability, chloride, and fire resistance of the resulting concrete mixes has been analyzed. Based on the objectives of the study, the following conclusions were drawn.

1. The unit weight of the mixed concrete specimens varied between 24.0 and 20.3 KN/m^3. Concrete could be classified as structural lightweight concrete up to a certain amount of WPB in the mixture. The unit weight values of fresh WPBC mixture decreased by 13% and 15% for mixes containing 30% WPB with 5% and 15% RHA replacement ratios, respectively. Mix P30R15S0, having 30% WPB with 15% RHA had the lowest dry unit weight (20.29 Kg/m^3) after 28 days of curing.

2. The flow-ability of fresh concrete, as noted by slump values, decreased with increasing WPB replacement ratios of 10–30%, which may also have a negative impact on the compressive strength of concrete. The low density and smooth surface of WPB caused segregation and improper cohesiveness, leading to a decline in workability. However, the flow-ability (252–171 mm) is still workable and complies with construction standards. Using RHA in WPBC caused a reduction in concrete workability (205–70 mm), but a slight increase in workability (260–242 mm) was recorded when using SF. Workability can be further enhanced by using suitable super-plasticizer amounts.
3. As the proportion of WPB increased, the compressive strengths decreased but remained close to the reference control mix at 10% WPB. At 28 days, a fall in compressive strength between 13% and 48% for mixes containing 10% and 30% WPB, respectively, was recorded. For the 10% WPB of sand replacement in concrete, the 28-day compressive strength values were still in a reasonable range of 30 MPa. The lower values of WPBC compressive strength compared to control concrete may be attributed to the weaker interface between cement paste and WPB. However, the strength could be enhanced up to 42–37.5 MPa by incorporating RHA at certain replacement amounts or using a suitable mineral admixture such as silica fume. The optimum replacement ratios of WPB and RHA when incorporated together were 10% for both at a cement content of 400 Kg/m^3. This mix (P10R10S0) exhibited even higher compressive strength than the control mix (OPC).
4. The splitting tensile strength decreased as the replacement ratio of WPB increased. For replacement levels of 10%, 20%, and 30% WPB, the tensile strength was reduced by 31%, 46%, and 62%, respectively. Meanwhile, incorporating 10% RHA in the WPBC mix with 10% WPB lowered the reduction in tensile strength, which was recorded at 4.3 MPa compared with 5.2 MPa of the control mix, with only a 17% reduction in tensile strength.
5. The reduction in tensile strength was more pronounced than the reduction in compressive strength for WPBC mixes, as the tensile strength is more sensitive to the interface bond strength between the cement base and the aggregates. This interface bond is weaker in the case of WPB in comparison with natural sand. This reduction was increased by increasing the WPB content when no pozzolanic admixture (RHA or SF) were used.
6. Increasing the ratio of WPB as fine aggregate replacement increases the water permeability of concrete specimens. Utilizing WPB as a fine aggregate substitution in concrete forms relatively large gaps and voids that increase the water permeability of WPB concrete. Using 10–30% WPB increased the water penetration depth from 90 mm to 150 mm. Meanwhile, using 10% WPB with 15% RHA reduced the permeability of concrete by 55%, measured at a 40 mm water penetration depth.
7. Using either RHA or SF as a partial replacement for cement reduced concrete permeability as they both had good pozzolanic action. The reaction of both admixtures, which have active silica and alumina, with the calcium hydroxide present in the cement hydrates created additional calcium silicate and aluminate hydrates that filled the voids in the concrete and reduced permeability.
8. The simultaneous replacement of lightweight aggregate and cement by WPB and RHA, respectively, reduced chloride ion penetration. The 10% replacement of RHA had the least chloride penetration. Furthermore, concrete mixes with both RHA and WPB notably had the lowest chloride ion penetration and gave lower values of chloride penetration compared to the reference concrete mix OPC.
9. Residual compressive strength values of concrete subjected to elevated temperatures are higher in WPBC mixes than in the reference control concrete mix, up to a 10% replacement ratio in WPB. However, the incorporation of 15% RHA in WPBC mixes with 10%, 20%, and 30% contents exhibited higher residual compressive strengths than the concrete control mix. Strength loss increased as the amount of WPB increased.

As a general conclusion, recycled WPB can be used in concrete production up to certain replacement ratios of natural sand without negatively affecting the properties of the concrete. To a certain limit, the WPB concrete mixes have durability properties comparable to the control concrete. The durability of WPB concrete with RHA against chloride attacks was enhanced as the permeability of the concrete was reduced, leading to high-performance properties that are suitable for structures in severe conditions. Based on the results, it can be concluded that partial substitution of sand by WPB up to 10% by volume reduces the self-weight and can be used in construction that requires lightweight concrete with good compressive strength. Moreover, incorporating rice husk ash (RHA) as partial cement replacement up to 10% by weight along with 10% WPB sand replacement by volume helps conserve natural resources, reduce hazardous gas emissions by producing environmentally sustainable concrete, and even enhance the mechanical properties of concrete.

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