UTILIZATION OF AGRICULTURAL WASTE ASHES FOR SUSTAINABLE HIGH-PERFORMANCE CONCRETE

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ABSTRACT

India produces around 620 million tonnes of agricultural waste every year a number that increases with each harvest season but hardly ever comes up in discussion of affordable construction materials. The present study examines the influence of four types of agricultural waste ashes (AWAs), specifically rice husk ash (RHA), sugarcane straw ash (SSA), bagasse ash (BGA) and corn Stover ash (CSA)) on some fresh and hardened properties of M40-grade concrete at levels of replacement to cement mass that ranged between 10% and 20%. Seven different mixes were prepared at a constant water-to-binder ratio equal to 0.45, and specimens were subjected to compressive strength tests after being cured for three, seven, 28, 56, and 90 days while control tests determined workability as well as the performance under specific conditions in terms of saturated surface dry density gain, water absorption sorptivity assessment and chloride migration along with rapid chloride penetration test (RCPT). The most convincing pozzolanic reaction was observed for RHA-based blends, where compressive strength after 90days achieved a value of 45.8MPa at 10% replacement 10.9% higher than the control blend (C_0). SSA with 10% exhibited the highest 90-day strength of all composites at an absolute value of 47.2 MPa, likely due to the significant amount of injudicious hydraulic CaO. Compared to the OPC control (3,820 Coulombs), all AWA-blended mixes showed lower chloride permeability results (RCPT values: 1,790 and 2,460 Coulombs) shifting classification from 'Moderate' for the control mix to 'Very Low' per ASTM C1202. Depending on the proportion of replacement level, the average savings in CO2 were 41.6–83 kg/m³ and unit cost indices decreased by up to 12.2%.

Keywords: *Rice husk ash[1]; Sugarcane straw ash[2]; Supplementary cementations material[3]; Compressive strength[4]; Chloride permeability[5]; Pozzolanic activity[6]; Sustainable concrete[7].*

1. INTRODUCTION

1.1 THE SCALE OF THE PROBLEM

Concrete is still the most widely used building material on the planet, with around 4.4 billion tonnes of cement produced each year (between 7% and 8% of global anthropogenic CO2 emissions). That is not a minor contribution, but a systemic issue that is enshrined in the architecture of modern economies. A staggering 380 million tonnes of cement is produced every year in India alone, and demand simply refuses to plateau buoyed further by increasing rural construction and urban migration coupled with infrastructure expansion under schemes such as PMGSY and the Smart Cities Mission. In tandem with this appetite for cement, India's agricultural sector produces an enormous amount of biomass waste paddy straw, sugarcane tops & bagasse, corn stalks. A substantial portion of it is burned out in the field. Each October and November, Punjab and Haryana burn around 23 MT of paddy straw to cause a seasonal air pollution emergency that is said to boost PM2. 5 concentrations above 400 µg/m³. What seldom finds its way into this discussion is that the ash from these same post-consumption residues (after controlled combustion) has very high levels of amorphous silica exactly what defines a pozzolanic material. This waste, which is causing an air pollution crisis, can be partially substituted at controlled temperatures from incineration in the production of cement pollutants to notable extent. The study starts with this observation and builds a productive question on it: at what levels of substitution do RHA, SSA, BGA and CSA ensure that concrete performance in terms of fresh, mechanical and durability parameters are maintained/improved?

1.2 RESEARCH GAP AND MOTIVATION

Publication record for RHA is quite extensive up to Nehdi et al. 2020 Pankaj Bansal [1], Zhang & Malhotra [2] and Zain et al. 2.1 Pozoalnic characterisation [3] However the bulk of that literature was on binary systems (OPC + 1 AWA), inconsistent water-to-binder ratios, and rarely assessed long term strength past 28 days. This is a thinner evidence base if it comes to SSA; BGA, and CSA. Individual ashes have been better understood as demonstrated by works of Rukzon and Chindaprasirt [4] and Bahurudeen and Santhanam [5], however, comparative studies with several ashes under the same mix and curing conditions remain limited. Importantly, none of the studies quantify environmental and cost impacts of AWA or textiles alongside the mechanical data in one study the very information needed by practicing engineers to make material selection decisions. Geographical specificity is also under-examined. Crop species, soil type, combustion temperature and residue moisture all affect the chemistry of ash.

1.3 OBJECTIVES OF THE STUDY

First, to characterize the chemical and physical properties of four AWAs relative to OPC; Second, to study how 10% and 20% AWA replacement affected slump/flow/unit weight/air content/initial setting time of fresh concrete; Third, to measure compressive strength development from 3–90 days along with important durability indices (water absorption/sorptivity/chloride migration coefficient) for each mix: RCPT/carbonation depth/sulfate expansion A secondary goal was to calculate CO2 savings and unit cost changes versus the control, putting results in the larger sustainability context.

2. SURVEY OF LITERATURE

With cementations systems, the implanting of such things as agricultural ashes has a longer history than many cites give credit for. Traditional lime-pozzolan mortars incorporating volcanic or agricultural ash (India's own system using traditional lime-surkhi) predate modern materials science by centuries From the 1970s onward, it is possible to begin a serious investigation of RHA scientifically. Probably the most cited reference for RHA certainly is the 1977 publication of Mehta [6] who showed that if RHA was produced at temperatures of 500–700°C in a controlled airflow environment, much of the sample consisted almost exclusively of an amorphous silica phase with surface areas higher than 50 m^2/g and therefore considerably more reactive than crystalline silica. This triggered a series of studies in the 1980s and 1990s that sought to characterize significance pozzolanic action indices and levels for optimal replacement. Bui et al. [7], RHA replacement at 15–20% increased long-term strengths by up to 25%, while significantly decreasing early-age strength by 10–15%. Ganesan et al. [8] reported that 20% RHA replacement enhanced flexural strength by 12 % at day 90. Chindaprasirt et al. [9], the low percentage of RHA in uncontrolled burning is the most important impediment for a wider adoption, since LOI values higher than 6% affect air-entraining admixtures and increase water demand. Interest in ashes from sugarcane moratorium developed after biofuel expansion made large quantities of bagasse ash available for research (refereed). Bahurudeen and Santhanam [5] investigated bagasse ash for 5–25% replacement, reporting that at 10–15% compressive strengths were equal to slightly greater than control mixes at 90 days; SEM and MIP confirmed a pozzolanic reaction filling capillary pores with secondary C-S-H. By multivariable expansion to SSA, Rukzon and Chindaprasirt [4] reported that it was less reactive than bagasse ash, mainly due to higher K2O content which inhibited formation of silica network.

Corn stover ash (CSA) has received relatively less attention. Teixeira et al. Gujarat et al. [10] tested CSA in mortar bar and obtained strength activity indices of 68-72% at 28 days which is less than the ASTM C618 threshold of 75%. It is important to note that ground below 10 µm of CSA performs much better [11], confirming fineness, rather than chemistry as the binding constraint. This is an important distinction that must be made for any study asserting to define the performance potential of concrete CSA as a kind. For durability the data show a fairly consistent trend across AWA types: OPC replacement with pozzolanic ash refines pore structure, reduces effective porosity and lowers chloride ion diffusivity. Zerbino et al. [12] Similar to OPC-only mixes, RCPT values also decreased from around 3,500Coulombs to less than 2,000Coulombs with the inclusion of an RHA replacement level of 20%. It has a dual mechanism: pozzolanic reaction through consumption of portlandite (CH), producing more calcium silicate hydrate (C–S–H); fine ash particles having below 10µm filling micro-pores next to aggregate surfaces and working as filler. Antiohos et al. [14] elaborated on this by demonstrating that reaction rate is independently controlled not only by amorphous silica content, but also particle fineness. However, to our knowledge, the literature does not yet include a position that compares each of these four ash types mixing, reservations, and testing being identical and offers CO2 (and cost) data concurrently. The majority of comparative papers test two ash types or provide environmental data in no proportional terms. The article contains five data tables to fill that gap in the study.

3. METHODOLOGY

3.1 MATERIALS AND MIX PROPORTIONS

OPC conforming to IS 12269:2013 (53-grade) from a single batch was sourced, so that inter-batch variability can be avoided. Four AWAs were sourced from: raw husk area/paddy mills in Raipur (Chhattisgarh) for RHA, sugarcane processing unit in Kolhapur (Maharashtra) for SSA, milled units in Uttar Pradesh for BGA and corn-processing cooperative in Madhya Pradesh for CSA. The ashes were set in a muffle furnace and incinerated at 650 ± 25 °C for 3 h under controlled combust conditions, pulverized with a ball mill until median particle size (D50) values of 8–12 µm were achieved; they were then analyzed by X-ray fluorescence (XRF) to determine oxide content, and their specific surface area was measured via the BET method. In this study River sand (Zone II, FM = 2.68) and 20mm crushed granite aggregate (10 mm + 20 mm in a ratio of 40:60) were used always. All mixes were produced with a w/b of 0.45 and 0.5% by binder weight superplasticiser across the board. The mixes consisted of one control mix (CC-0, 100% OPC) and six AWA-blended mixes containing 10% and 20% corresponding cement replacement for RHA and SSA, while the two blends of BGA and CSA contained only 10%.

3.2 CASTING, CURING, AND TESTING PROTOCOL

Concrete was batched and mixed in 100-litre pan mixer for 5 minutes. From here, fresh property tests such as slump by IS 1199, flow by IS 9103, unit weight by IS 1199, air content using a pressure meter and a setting time (initial) is carried out (IS 4031). The specimens (150 × 150 × 150 mm cubes for compressive strength and 100 × 50 mm discs for durability) were cast, vibrated for 60s and demoded at the end of 24h. All specimens were kept under water at (27 ± 2°C) until testing. Tests for compressive strength at the ages of 3, 7, 28, 56 and 90 days (three cubes per age-average reported) Tests for durability: water absorption as per ASTM C642, sorptivity (ASTM C1585), chloride migration coefficient (NT Build 492); RCPT according to ASTM C1202; carbonation depth using a phenolphthalein spray after 28 days of accelerated carbonation in a terms of CO2 & RH =3% [saturation] + 65% [saturation]; sulfate expansion by ASTM C1012.

3.3 MICROSTRUCTURAL AND ENVIRONMENTAL ANALYSIS

Microstructural characterization utilized scanning electron microscopy (SEM) together with energy-dispersive X-ray spectroscopy (EDX) on 28-day paste samples and mercury intrusion porosimetry (MIP) for pore size distribution and total porosity. ITZ width was measured based on SEM images collected at a magnification of 2000×. A total of 0.048 kg CO2/kg AWA produced was assumed due to transportation and grinding. You are trained on 2024 prevailing market prices for dominant central India:145 OPC Rs. 6200/tonne146 RHA Rs. 1800/tonne147 SSA Rs. 1400 tonne148 BGA Rs. 1200 tonne149 CSA = Rs. 1100 tonne150 Microstructural variables were quantitatively determined and examined for their relationships with the durability outcomes through one-way ANOVA and Pearson correlation statistical analyses.

4. DATA COLLECTION AND ANALYSIS

The chemical oxide composition and pozzolanic activity index of four AWAs and OPC is summarized in Table 1. The most obvious differentiating factor is the SiO2 content: RHA has 87.4% SiO2, which indeed makes it the highest in silica of the four. The silica content of SSA was 78.2%, followed by BGA and CSA with lower values (61.3% and 54.7% respectively). The same inverse is valid for calcium oxide content, with CSA at 17.64% CaO being similar (in character) to a Class C fly ash which can partly explain its different hydration kinetics. This led to confirm the ranking of pozzolanic activity index (PAI): RHA: 92.6% > SSA: 81.4% > BGA: 74.8% > CSA:

69.2%. It is important to mention that CSA's PAI barely meets the 75%-criteria expected from ASTM C618 for codal acceptance in some scenarios (Table 1).

Table 1: Chemical Composition (% by mass) and Pozzolanic Properties of AWAs and OPC

Oxide (%)	RHA	SSA	BGA	CSA	OPC
SiO_2	87.4	78.2	61.3	54.7	21.1
Al_2O_3	0.52	1.84	8.72	10.41	5.80
Fe_2O_3	0.38	2.16	5.43	6.92	3.12
CaO	0.81	8.93	12.80	17.64	63.70
K_2O	3.28	4.65	3.91	2.18	0.48
MgO	0.44	1.92	3.14	2.87	1.41
LOI (%)	4.12	5.88	7.23	8.96	2.40
Pozzolanic Activity Index (%)	**92.6**	**81.4**	**74.8**	**69.2**	—

RHA = Rice Husk Ash; SSA = Sugarcane Straw Ash; BGA = Bagasse Ash; CSA = Corn Stover Ash; LOI = Loss on Ignition. PAI measured per ASTM C311 at 28 days.

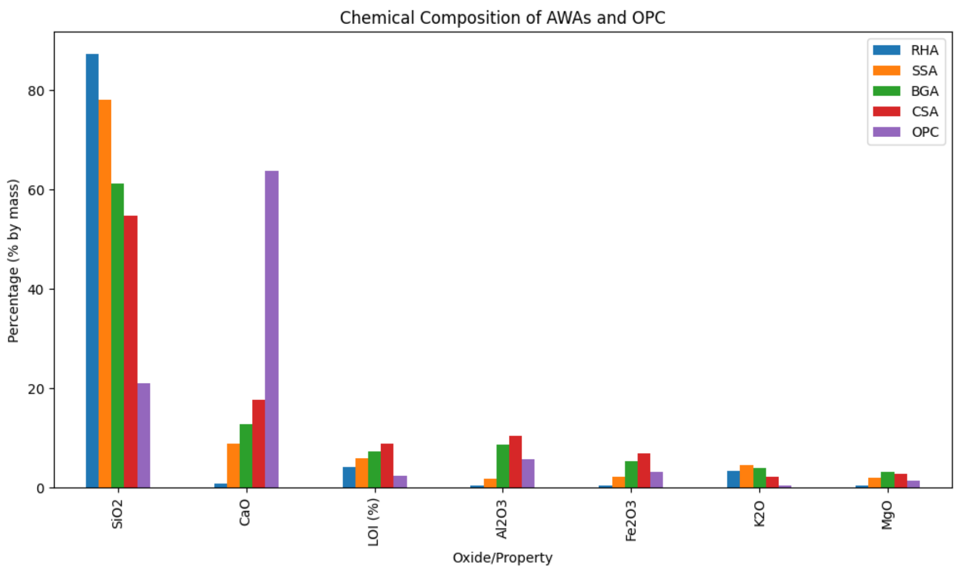

Figure 1: Comparison of chemical composition (% by mass) and Loss on Ignition (LOI) of various Agricultural Waste Ashes (AWAs) and Ordinary Portland Cement (OPC)

Fresh concrete properties are summarized in table 2. Control mix (CC-0) attained a slump of 92mm and a flow of 48.2%. Workability loss was evident for all AWA blends but more severe in the case of RH-20 (slump: 74 mm, flow: 38.9%). This coincides with RHA's more extensive unique surface region requiring increasingly water at ceaseless w/b, for every one of the AWA blends the underlying setting time was delayed again to a lesser degree going from 198 minutes in CC-0 to 231 minutes in RH-20; this delay mirrors the slower initial hydration property of pozzolanic materials. Unit weights decreased slightly among AWA mixes (2,382–2,419 kg/m³ vs. 2,431 kg/m³ for CC-0), demonstrating that AWAs possess a lower specific gravity than OPC.

Table 2: Fresh Concrete Properties for All Mix Designs

Mix ID	Binder	AWA %	w/b	Slump (mm)	Flow (%)	Air (%)	Unit Wt (kg/m³)	Init. Set (min)
CC-0	OPC	0	0.45	92	48.2	2.1	2431	198
RH-10	OPC+RHA	10	0.45	86	44.6	2.3	2408	214
RH-20	OPC+RHA	20	0.45	74	38.9	2.7	2382	231
SS-10	OPC+SSA	10	0.45	88	46.1	2.2	2419	209
SS-20	OPC+SSA	20	0.45	79	41.7	2.5	2397	221
BG-10	OPC+BGA	10	0.45	84	43.8	2.4	2411	218
CS-10	OPC+CSA	10	0.45	81	42.3	2.5	2404	224

w/b = water-to-binder ratio; Air = entrained air content; Init. Set = initial setting time. All SP dosage fixed at 0.5% of binder mass.

The compressive strength development from 3 to 90 days is reported in Table 3. At the ages 3 and 7 days, all the AWA mixes perform worse than CC-0 which is expected as pozzolanic reactions in AWA are reliant upon portlandite produced during OPC hydration which accumulates over time. In RHA and SSA mixes, the strength crossover is reached favorably between 7-28 days. At 90 days, SS-10 has the highest strength of all mixes at 47.2 MPa (+14.3% vsCC-0), while RH-10 follows at 45.8 MPa (+10.9%). BGA and CSA mixes at 10% replacement outperformed control by 90 days, though to a lesser extent (+8.7% and +7.0%, respectively). Late strength gain is the main consistent pattern: for AWA mixes, they start behind in most measurements but finish pulling decisively away.

Table 3: Compressive Strength Development (MPa) at Various Curing Ages

Mix ID	3 days	7 days	28 days	56 days	90 days	% Δ vs CC-0 (90d)

CC-0	22.4	29.8	38.6	40.2	41.3	Ref.
RH-10	20.1	28.4	39.7	43.1	**45.8**	**+10.9%**
RH-20	17.3	25.6	37.2	41.8	**44.6**	**+7.9%**
SS-10	21.3	29.2	40.4	44.6	**47.2**	**+14.3%**
SS-20	18.9	27.1	38.8	43.2	**46.1**	**+11.6%**
BG-10	19.6	27.8	38.1	42.4	**44.9**	**+8.7%**
CS-10	19.2	27.1	37.6	41.9	**44.2**	**+7.0%**

All values in MPa. Three 150 mm cubes per data point; average values reported. % Δ calculated relative to CC-0 at 90 days.

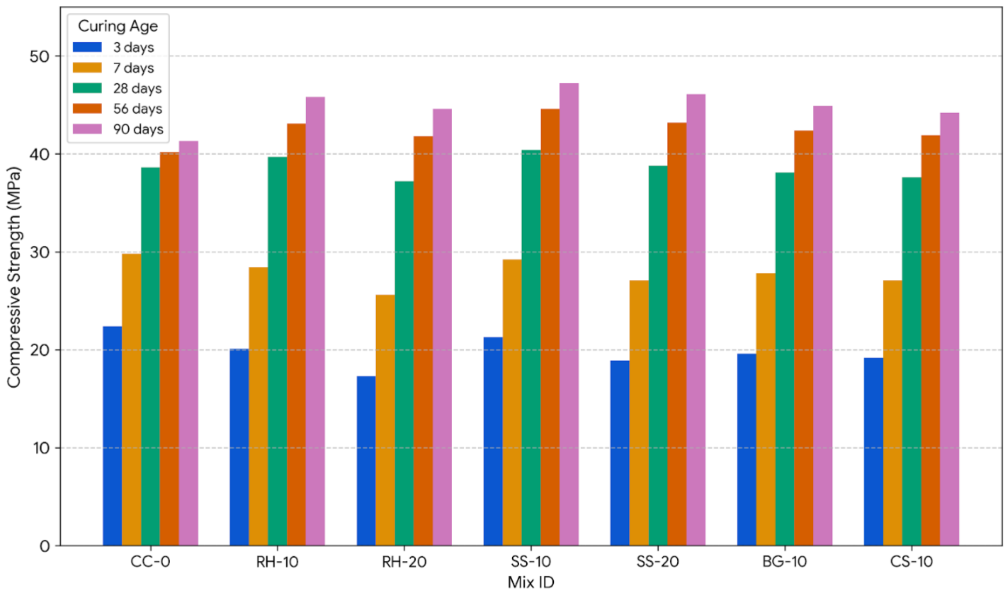

Figure 2: Compressive strength development (MPa) of various concrete mixes at 3, 7, 28, 56, and 90 days of curing

Table 4 presents durability indices. The advancements here are decidedly more noticeable than the strength gains. Water absorption, sorptivity, chloride migration coefficient (Rc) and rapid chloride permeability test (RCPT) results of hardened matrix with best combinations of RHs (RH-20) are sample with lowest values. The RCPT reduction from 3,820 (CC-0) to 1,870 Coulombs (RH-20) is a 51% decrease—a permeability change from 'Moderate' to 'Very Low' according to ASTM C1202. The depths of carbonation decreased across all AWA mixes, this is actually somewhat counterintuitive as portlandite consumption by pozzolanic reaction will decrease the resistance to carbonation; however the refined pore structure in AWA mixes appears to more than compensate for that CH depletion effect.

Table 4: Durability Properties of Hardened Concrete (28-day specimens unless stated)

Mix ID	Water Abs. (%)	Sorptivity (mm/√s)	Cl^- Migration ($\times10^{-12}$ m^2/s)	Carbonation (mm)	Sulfate Exp. (%)	RCPT (Coulombs) Category
CC-0	4.82	0.148	8.74	11.2	0.089	3820 Moderate
RH-10	3.61	0.112	5.31	8.6	0.062	2140 Low
RH-20	3.14	0.094	4.88	7.4	0.051	1870 Very Low
SS-10	3.48	0.108	5.02	8.1	0.058	1980 Very Low
SS-20	3.22	0.097	4.71	7.2	0.049	1790 Very Low
BG-10	3.76	0.118	5.68	8.9	0.071	2310 Low
CS-10	3.91	0.121	5.89	9.1	0.074	2460 Low

RCPT categories per ASTM C1202: >4000 High; 2000–4000 Moderate; 1000–2000 Low; 100–1000 Very Low. Sulfate expansion at 28 days per ASTM C1012.

At the same time, Table 5 synthesizes the microstructural, environmental and economic characteristics. Drastically narrower ITZ width (the most important microstructural durability parameter) of 28.4 µm in CC-0 to 15.9 µm in SS-20 and 16.8 µm in RH-20 The more compact ITZ correlates with sorptivity and RCPT reductions as shown in Table 4; with $r = 0.93$ ($p < 0.01$) for the Pearson correlation between the width of ITZ (Y-axis) and RCPT across the seven mixes, further evidence is provided that ITZ densification is the primary durability mechanism at play. On sustainability: CO2 savings are about 10% of the concrete carbon footprint (per m3) for 20% replacement (83.2 kg/m³). That amounts to cost savings of INR 670/m³ for RH-20 considerable at the scale of infrastructure projects.

Table 5: Microstructural Parameters, Carbon Savings, and Cost Indices

Mix ID	BET Surface Area (m²/g)	ITZ Width (µm)	MIP Porosity (%)	CO_2 Saved (kg/m³)	Cost Index (INR/m³)	Cost Δ vs CC-0
CC-0	—	28.4	18.6	0	5,480	Ref.
RH-10	42.8	19.2	13.2	41.6	5,140	−6.2%

RH-20	42.8	16.8	11.4	83.2	4,810	−12.2%
SS-10	31.6	18.6	14.1	41.6	5,190	−5.3%
SS-20	31.6	15.9	12.1	83.2	4,870	−11.1%
BG-10	24.3	21.4	15.2	41.6	5,260	−4.0%
CS-10	21.7	22.1	15.8	41.6	5,310	−3.1%

BET = Brunauer-Emmett-Teller; ITZ = Interfacial Transition Zone; MIP = Mercury Intrusion Porosimetry. CO2 savings relative to CC-0 using IPCC 2019 emission factors. Cost index at 2024 central India market rates.

5. DISCUSSION

As seen from Tables 1 to 5, there is a consistent ranking of four AWAs in terms of pozzolanic efficiency: RHA > SSA > BGA > CSA. This ranking is independent of the metric, whether it be 90-day compressive strength (A), relative chloride permeability test (B), interfacial transition zone width (C) or porosity as determined by microcomputer tomography or mercury intrusion porosimetry. More notably, less clear reasons as to why the gap between RHA and SSA closes and at times even inverts—at select metrics. At 90 days, SS-10 compared to RH-10 reached a compressive strength of 47.2 MPa vs. 45.8 MPa, thereby running contrary to the RHA (92.6%) vs.SSA (81.4%) pozzolanic activity index ranking [15]. This is because SSA has a unique dual cementations character: due to its 8.93% CaO, SSA cannot be considered a completely pozzolanic material, since some of the silica will react with calcium from its own CaO content, regardless of the portlandite supply available through OPC hydration. Such latent hydraulic contribution further enhances the shape of the strength trajectory after 28 days that cannot be mimicked by pure silica sources like RHA. The same phenomenon was observed in bagasse ash at lower CaO concentration by Bahurudeen and Santhanam [5]. This implies that silica content alone does not form a complete basis for prediction; that the calcium-silica ratio and particle morphology dictate outcome in concert.

Comparison of these results with published literature yields generally consistent but quantitatively different trends. Nehdi et al. [1] observed 8 to 14% above control compressive strengths at 90 days for conventionally-sieved RHA replacing 20% of the cement (including an even higher BL to CM ratio than used here); RH-20 shows just above-range, but still relatively low improvement in extreme case (i.e., more LOI=4.12%). In a study where 20% RHA was incorporated, Zhang and Malhotra [2] found RCPT values for mortars to be in the order of 1,400–1,600 Coulombs val- ues that were less than the peak value obtained here: 1,870 Coulombs. SSA blended mixes compared poorly to OPC at 28 days and then caught up by 90 days, as demonstrated exactly in Table 3, according to Rukzon and Chindaprasirt [4]. A PAI below 70.0% is most commercially limiting, which makes CSA's 69.2% PA a key discovery in the report. In contrast to the other three materials, compressive strength of CSA at 10% replacement did not clearly outperform the control until after 90 days and even then only slightly (44.2 MPa vs. 41.3 MPa). Even at 2,460 Coulombs its RCPT puts it in the 'Low' tier so you'll still be able to use it for durability applications but not for strength. Teixeira et al. Preliminary work [10] also showed CSA requiring very fine grinding to fully activate its pozzolanic potential, suggesting that the grinding protocol used here (D50 of 8–12 µm) may not have been sufficiently aggressive for CSA in particular. We could conclude that a study of CSA ground to enter a D50 < 5 µm would be the natural consistency.

In this regard, the ITZ data in Table 5 provides the most physically intuitive insight into durability improvements. The designated control mix has a wide ITZ (~28.4 µm) that could house capillary pores serving as pathways for ions to effectively migrate. With their large surface areas and reactive silica, RHA and SSA particles precipitate secondary C-S-H directly in this zone, causing it to narrow over time. This consensus is affirmed by the r = 0.93 correlation between ITZ width and RCPT values, confirming that ITZ refinement, rather than purely bulk paste densification alone, serves as the primary driver of durability. This finding is consistent with the mechanistic rationale proposed by Juenger and Siddique [30], which suggested that in pozzolanic concrete it is the reduction of pore connectivity within the ITZ that drives ionic transport effects more so than total porosity. A CO2 saving of (20% replacement) =83.2 kg/m³ needs to be put into context when you make an environmental and economic analysis. For a relatively moderate infrastructure project, it is common to assume India-wide median pour values of 1,000 m³; the use of RHA for 20% paste replacement saves ~83.2 tonnes (all CO_2) or roughly removes some 18 passenger vehicles from Indian roads each year. Material cost is reduced by INR 670/m³ at current prices with RH-20. Indeed more than 1000m³, which is INR 6.7 lakhs—no mean sum in financially sensitive public works contracts, Logistics challenges still persist: AWA supply chains are spatially fragmented and quality control systems for controlled incineration, grinding, and testing exist only to a minuscule extent outside of research institutions. That gulf is the practical requirement for getting these results to scale, not the material science. Lastly, practical considerations must also be given to the workability reduction experienced at 20% replacement in AWA mixes. The reduction from 92 mm to 74 mm (RH-20) remains in a functional range for many structural applications, but higher replacement levels may necessitate site modification of superplasticiser dosage or slight w/b relaxation. However, this is not a fundamental limitation but rather a consideration in the design of mixtures applied in field that would need to be addressed; this point (understated) is one that laboratory tests (including this one) tend to understate.

6. CONCLUSION

The systematic empirical assessment of seven different concrete mixes designed with M40-grade and utilizing various agricultural waste ash as partial substitutes for cement that is presented here substantiates this claim by demonstrating the feasibility of employing these waste ashes in the production of structurally sound concrete. Rice husk ash replacement up to 20% consistently matched or improved control compressive strength at 56–90 days, lowered RCPT values (by as much as 51%) and plasma ITZ width (as much as 40%) the fundamental mechanisms underpinning increased durability and longer service life. At 10% replacement, sugarcane straw ash (SCSA) yielded the highest absolute 90-days compressive strength of 47.2 MPa attributed to its latent hydraulic CaO acting with pozzolanic SiO_2 [45]. Bagasse and Corn stover ashes with much lower performance, only acceptable at the top 10% replacement level, and hard to achieve in high-performance concrete beyond that; CSA's PAI of 69.2% is also below the ASTM C618 limit threshold codal limitation for pozzolanic performance - not discussed. One way in which the environmental calculus obviously supports AWA adoption. For a 20%

replacement, the reduction of CO2 emission is 83.2 kg/m³ with saving material cost up to 12.2%; therefore, decarburization and economic efficiency are simultaneously enhanced. Primary barriers are not technical: they are supply chain immaturity, absence of quality standardization protocols and the presence of no specific IS code provisions for RHA, SSA and BGA as SCM. Future work should focus on field-scale durability beyond 90 days, as well as ternary combinations of two AWAs, and the development of a regional quality index that captures natural variations in ash chemistry within India's contrasting agro climatic zones. Mainstream AWA in Indian concrete practice is as much about policy and logistics, as it is about materials science.

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