

Performance Assessment of Durable Concrete with Supplementary Cementitious Materials

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Abstract

The purpose of this study is to assess the role of the blended supplementary cementitious materials (SCMs) such as Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), and Waste Glass Powder (WGP) on concrete for durability, sustainability, and mechanical performance. The aforementioned waste products, which are generated from industry and agriculture, are highly reactive in silica and serve as very pozzolanic materials because of their strengthening contributions to the compressive strength of concrete, their permeability reduction, and the resistance to environmental attacks. Apart from giving SCMs to the concrete an opportunity in reducing the huge demand for Portland cement, the SCMs' advantages contribute a considerable amount to reduction of greenhouse gas emissions as compared to Portland cement. The use of RHA, SCBA, and WGP in concrete for local availability and low embodied CO₂ and in favour of circular economy practices has been highlighted as being beneficial environmentally and economically. In addition, machine learning and deep learning models-CatBoost, GBM, CNN, GRU, XGB, and RF-have been used for compressive strength prediction for various inputs. Of the high accuracy-built machine learning models ($R^2 > 0.95$), GRU and hybrid XGB-lgb-based models were better than the remaining models. Also, evaluated were the elevated temperature effects, and water re-curing and SCM dosage regarded on mechanical behaviours and microstructure durability improvements under aggressive conditions. Overall, the research validates the practical application of RHA, SCBA, and WGP into sustainable concrete for resilient infrastructure and eco-efficient construction systems Practices.

Keywords: Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), Waste Glass Powder (WGP), supplementary cementitious materials (SCM), sustainable concrete, compressive strength, machine learning, durability, pozzolanic activity, circular economy, carbon emission reduction, recycled materials, microstructure, thermal resistance, and eco-friendly construction.

I. Introduction

Construction with concrete becomes sustainable with durable concrete, since such concrete assures the lasting strength and resistance of buildings, reducing recurrent requirements for repairs, rehabilitations, or even reconstructions. It is the type of concrete expected to withstand extreme conditions, such as freezing-thawing cycles, chemicals, corrosion, and mechanical action, thereby maintaining the integrity of the structure for several decades [1]. This durability would result in less extraction, processing, and movement of raw materials during the life of a building or infrastructure project, which saves natural resources and reduces the overall environmental burden. Besides, durable concrete minimizes the disruption of communities due to rare maintenance and long service intervals, which convert into lower life maintenance costs. From a sustainability perspective, durable concrete also contributes to the reduction in greenhouse gas emissions, in particular those from cement production, which is among the primary sources of global CO₂ emissions [2]. For the lifetime of concrete structures, that corresponds to a longer period over which construction material embodied energy and emissions are accommodated, thus improving sustainability in the built environment. Also, it is concrete that ensures to develop infrastructures to face climatic disasters: increased temperature, flooding, and increased environmental aggression. Durability, therefore, is not just a measure of performance; it is also the very principle of infrastructure design that is environmentally and economically sound and social over the long term [3].

SMCs are a term that refers to Supplementary Cementitious Materials, and Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), and Waste Glass Powder (WGP) are such materials, which, when used in concrete, provide excellent performance improvements while effectively minimizing the carbon footprint associated with the production of regular cement [4]. The agricultural and industrial waste from which these SCMs are produced

offers a greener avenue by means of which they can partially replace Portland cement, the production of which requires a good amount of energy and inflicts a tremendous charge on the atmosphere as far as production of CO₂ is concerned. This indicates that RHA has a high silica content and fine particles that accelerate strength, while concurrently reducing permeability and enhancing the durability of concrete [5]. SCBA, with high pozzolanic activity because of the reactive silica content, increases the pozzolanic activity, leading to dense microstructure and better resistance to harsh environments. With finely ground glass powder wastes, WGP is an effective pozzolan, as it participates together with calcium hydroxide to produce C-S-H, thus improving strength and durability. Its utilization also contributes to the recycling of non-biodegradable glass, which alleviates the pressure on landfills and decreases environmental pollution [6]. Combining the use of RHA, SCBA, and WGP provides improved mechanical and durable properties for concrete, which, in turn, provides a good example of implementing the principles of the circular economy-giving back to waste as important construction materials. Since it reduces the clinker requirement in cement, greenhouse gas emissions and energy consumption are lowered, resulting in sustainable concrete-making. They also show how innovative lateral thinking around valorization of waste can translate into substantial environmental and performance gains for the cement and concrete sectors [7].

The most important reason for the application of Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), and Waste Glass Powder (WGP) into concrete is the environmental as well as sustainability aspects associated with their utilization. All of these three materials are obtained from waste—RHA from rice milling, SCBA from the waste of sugar production, and WGP from the rejection of glass-make-it-an effective waste management. Instead of ending as landfill or incinerated material, they are processed and reused in construction in a way coinciding with the principles of a circular economy [8]. By re-enterprise agricultural and industrial waste, their use helps to lesser the environmental load of disposal and complements other sustainable material cycles. From a performance interval, RHA, SCBA, and WGP are pozzolanic because they react with calcium hydroxide in concrete and result in additional formation of calcium silicate hydrate, thus improving strength and durability. RHA is very rich in silica and highly fine material; thus, it positively reduces permeability and improves resistance to aggressive environments in concrete. SCBA may also show strength and durability gain if processed effectively to maximize the activity [9]. WGP, containing amorphous silica, works as a strong replacement of cement, and contributes to strength gain over time, improving long-term durability. Combined, these add up to enhancing the mechanical properties along with life service of concrete structures. Using RHA, SCBA, and WGP proves beneficial from the economic aspect as well in cutting down the cost of building; it demands a less amount of Portland cement, one of the most expensive and carbon-intensive ingredients in concrete [10]. Localized easily available in regions rich with rice, sugarcane, or glass waste, they provide a simple affordable option toward sustainable construction. Incorporating these SCMs contributes to carbon footprint reduction of cement production while upholding national and global climate commitments. Thus, the use of these is a synergetic win of economy and performance boost against the backdrop of environmental accountability-providing credible ground for their adoption into modern construction practices [11].



Figure 1 Rice Husk Ash [12]



Figure 2 Sugarcane bagasse ash [13]



Figure 3 Waste Glass Powder [14]

Figures 1-3 demonstrate all the SCMs to be utilized in sustainable concrete development. Figure 1 demonstrates Rice Husk Ash (RHA), a by-product of rice milling, which is rich in amorphous silica and contributes to superior strength and durability [12]. Figure 2 depicts Sugarcane Bagasse Ash (SCBA) resulting from the incineration of sugarcane waste, which is well known for its pozzolanic activity [13]. Figure 3 deals mainly with Waste Glass Powder (WGP), a concentration mainly for short-term use which provides increased ultimate strength and decreased negative effect on the environment [14]. Another point in favour of all of these materials in sustainable construction is that we efficiently utilize industrial and agricultural wastes as per the schemes.

II. Materials Overview and Characterization

Such materials as Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), and Waste Glass Powder (WGP) stem from abundant waste sources generated through agricultural and industrial processes. RHA is the ash that results from burning rice husks, which are by-products of rice milling, under controlled conditions so that high silicate content may be preserved in an amorphous form, thereby enabling its usage as a pozzolanic material. Since rice is one of the main crops grown in many countries worldwide, particularly in Asia, there is considerable availability of husks, thus guaranteeing RHA availability in a sustainable way [15]. SCBA is obtained from the burning of sugarcane bagasse-the fibrous residue left after juice extraction in sugar industries. When burned and processed properly, SCBA carries reactive silica for use in concrete. Cultivation of sugarcane is wide in tropical and subtropical regions, especially in Brazil, India, and Thailand, hence it could serve as a waste resource with the prominence of valorization-related activities in such areas [16]. Waste Glass Powder (WGP) is produced by the collection, cleaning, and pulverization of discarded glass (e.g., bottles, windows, and other glass products) into a fine powder. The process of converting non-biodegradable municipal solid waste into useful construction material involves collection, cleaning, and grinding. The glass is largely made up of amorphous silica; therefore, WGP becomes pozzolanic when finely processed and is effective as a partial cement replacement. Due to the steady increase in urbanization and increased consumption, glass waste generation remains at a very high level in all parts of the globe, thus ensuring the long-term availability of raw material for WGP [17]. In addition, the RHA, SCBA, and WGP production technologies are low-tech, with easy adaptability to small-scale and industrial applications. These materials are, therefore, available and are thus inexpensive and sustainable options for reducing the construction industry's environmental footprint where large tracts of land may be found that are rich in rice, sugarcane, and glasses [18].

The enhancement of reactivity of Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), and Waste Glass Powder (WGP) will render them effective supplementary cementitious materials in concrete. The secret behind increasing their pozzolanic activity lies in carefully controlled processing techniques to leave behind amorphous silica-the-all-surface area and purify them as well [19]. For RHA, the most important would be the controlled burning of rice husks usually between 500°C and 700°C. At that temperature, silica is usually retained in the extremely amorphous form so that it can react greatly with calcium hydroxide in the cement. If the husks are burnt at a higher or uncontrolled temperature, this amorphous silica will crystallize and nullify that pozzolanic property. Usually, this ash will be sieved after combustion and the particles mechanically reduced to a very fine size, usually lower than 45 microns, using ball milling or jet milling to increase their surface area and facilitate better dispersion and reaction within the cement matrix [20]. This also applies to SCBA reactivity, which depends on the burning temperature and post-treatment processes. Under-controlled conditions, the bagasse will be burned to avoid the incidence of unburned carbon or crystalline phases. Typical treatment post-burning has SCBA being ground and

sometimes subjected to acid treatment or other beneficiation processes for impurity removal and silica availability enhancement. The need for fine grinding of SCBA is underscored in that it improves fineness of particle, hence reduced porosity of concrete, and thus promotes pozzolanic reaction [21]. The Waste Glass Powder (WGP) starts from sorting and cleaning the different glasses to remove impurities such as paper, plastics, and metals from the various types of glass. The glass is then crushed and milled into fine powder-usually below 45 microns-so that its amorphous silica content becomes reactive in the cementitious environment. Another option is for the treatment with heat or chemical activation using alkaline solutions like sodium hydroxide to further improve reactivity. In short, these processes are crucial, not only maximizing RHA, SCBA, and WGP efficiency improvement in mechanical and durability properties of concrete but also bringing a real sponsorship in the area's contribution to reducing environmental impact of cement production [22].

The physical, chemical, and mineralogical properties of Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), and Waste Glass Powder (WGP) are what make them suitable as supplementary cementitious materials in concrete. Physically, RHA, SCBA, and WGP are all fine powdery materials, usually treated to particle sizes below 45 microns to enhance their reactivity and dispersion in a cement matrix. RHA has a low density and a high specific surface area due to its porous structure, which explains its great pozzolanic activity [23]. SCBA in finely powdered form might show fairly good surface area, but can contain unburnt carbon that, depending on insulation techniques, might affect the workability of concrete. WGP from glass has thicker and more angular particle shapes as compared to the other two, where its surface will help improve the flow characteristics of fresh concrete if used properly [24]. Chemically, all three materials have a high silica (SiO_2) content, which is the most important in the pozzolanic reactions. RHA generally contains more than 85-90% of amorphous silica, manufactured by controlled burning methods, which is again responsible for its high reactivity. SCBA will contain substantial silica up to 60-80%, but may also contain other oxides like alumina and iron oxide, depending upon source and combustion method [25]. Irrespective of the type of glass, these oxides mostly relate to the silica content with an approximate of 70-75% contributing some sodium, calcium, and aluminum oxides, which in turn influence the pozzolanic potentials of distinct materials and hence with further change in strength and durability within cementitious systems [26]. At the mineralogical level, the efficacy of these SCM derives essentially from their amorphous silica content, which exhibits reactivity with calcium hydroxide present from cement, thereby producing constituent C-S-H (Calcium Silicate Hydroxide), which is responsible for strength in concrete. RHA and WGP will carry good quantities of amorphous silica when well processed; the mineralogical structure of SCBA is difficult to determine, as it could also contain both amorphous as well as crystalline phases depending on the burning method and temperature [27]. A well-cooled crystalline phase will impede this method; hence a near-glassy structure is preferred for activated pozzolanicity. Therefore, these materials enhanced in their performance and sustainability in concrete due to their physical fineness, chemical richness in silica, and largely amorphous mineralogical nature [28].

III. Influence on Fresh and Mechanical Properties in Concrete

The addition of RHA, SCBA, and WGP into concrete highly modifies its fresh properties, chiefly workability, setting time, and water demand. Because of their large surface area and porous nature, both RHA and SCBA introduce additional water demand into the mix. Since RHA is highly porous in structure and has a fine particle size, it may absorb a lot of water, causing a reduction in workability unless compensated by additional water or the use of superplasticizers [29]. Likewise, SCBA can also add to the water requirement due to unburned carbon, if present, or irregularly shaped particles. In contrast, WGP possesses a relatively smooth texture and lower porosity than both RHA and SCBA, insinuating that it may not affect much the water demand or even induce an improvement in workability under some circumstances. Concerning the setting times, however, the reactive silica present in such SCMs may slightly delay the initial setting time, as its pozzolanic reaction is slower compared to cement hydration. But this delay is normally within acceptable limits of variation, yet the setting behaviours tends to vary depending on the fineness and dosage of the SCM, mix design, and ambient conditions [30].

RHA, SCBA, and WGP, if wielded in the correct spirit, can be relied upon to increase the mechanical properties of concrete. Their pozzolanic reaction with calcium hydroxide results in more calcium silicate hydrate (C-S-H) that improves microstructure and strength development. RHA particularly enhances its compressive strength,

besides large silica and fineness, in later curing ages [31]. However, SCBA adds to this compressive strength, but its efficacy is highly influenced by the combustion quality and reactive silica. Both RHA and SCBA contribute flexural and tensile strength improvements besides taking finer pore structures into account with better bonding between the paste and aggregates. For example, WGP with densely vibrating, glassy particles do contribute to compressive strength, considering it is such fine ground and improves tensile and flexural strengths, too. But only in very high replacement levels, especially caused by coarse or less reactive particles, will such SCM reduce strength by dilution of cementitious content or poor packing of particles [32].

The optimum replacement levels for RHA, SCBA, and WGP vary with their source, fineness, and reactivity, as well as the application intended. Ten to twenty percent replacement of cement by weight is often employed, this range usually being effective in balancing strength gain and workability. In this regard, SCBA has shown good performance at replacement levels of ten to fifteen percent, provided it is finely ground and has a low carbon content. WGP can be also used proportionately with best performance generally seen at ten percent to twenty percent replacement, though some studies have implemented higher dosages effectively with suitable adjustments of the mixes [33]. Going above the nominal amounts induces lower strength or workability issues, given that hydraulic activity is less in these materials relative to cement. The efficiency of these supplementary cementitious materials is also subject to some influencing factors such as particle size distribution, specific surface area, chemical composition, curing conditions, and presence of other admixtures. Full characterization, optimization, and proper mix design are crucial to their proper utilization. Strengthening the durability and sustainability of the concrete matrix requires synergetic applicability of RHA, SCBA, and WGP [34]. Long-term strength and less permeability provided by these materials also support resistance to chloride ingress, sulphate attack, and alkali-silica reaction. Synergetic interplay in the diminished water-to-cement ratio, particle packing, and pozzolanic reactions will create a denser, more refined microstructure. The sustainability view imparts lesser demand for Portland cement leading to lower carbon footprint of concrete. The addition of these locally available waste materials decreases environmental pollution and aids waste valorization. When thoughtfully utilized to cater for their influence on fresh and hardened states, RHA, SCBA, and WGP can boost concrete performance and eco-efficiency and will be a powerful means of modern sustainable construction practice [35].

IV. Durability Performance

Incorporating RHA, SCBA, and WGP into a concrete mix will considerably reduce water absorption, sorptivity, and overall permeability, which is important concerning long-term durability. These SCMs enhance the pore structure of concrete due to their pozzolanic activity, leading to the additional formation of calcium silicate hydrate (C-S-H) gel, which fills the capillary pores and mitigates the connectivity of voids in the cement matrix, thus slowing the absorption rate of water and moisture [36]. RHA, with its high surface area and silica content, is particularly effective in reducing sorptivity and permeability. Finely ground SCBA and WGP also play a role in creating a denser, more compact concrete matrix. The reduced permeability decreases the chances for aggressive agents to enter the concrete, thus enhancing the resistance of concrete against environmental deterioration [37]. Chloride ion penetration is a major durability issue, especially in structures exposed to marine environments or affected by deicing salts. RHA, SCBA, and WGP reduce chloride ingress by blocking pore connectivity and increasing the binding of chlorides through pozzolanic reactions. These materials reduce and consume calcium hydroxide while creating additional C-S-H that is responsible for the densification of the matrix and the consumption of free calcium hydroxide that would otherwise react with chlorides to form expansive compounds [38]. Therefore, the sulphate resistance is enhanced by these SCMs. In particular, RHA and SCBA help in reducing the expansion from sulphates by lowering the availability of calcium hydroxide and aluminates that react with sulphates to form expansive ettringite. WGP is chemically stable and not reactive with sulphates; thus, it helps in limiting deterioration under sulphate exposure, making these materials suitable for the aggressive environment [39].

Carbonation, a reaction of the carbon dioxide with calcium hydroxide in concrete, reduces the pH of the pore solution and can induce corrosion of embedded steel reinforcement. While the presence of pozzolanic SCMs that are RHA, SCBA, and WGP reduces calcium hydroxide content owing to secondary types of reactions (thereby allowing the potential for increasing the depth of carbonation), their overall effect on durability is balanced with

the positive improvement in pore structure and permeability [40]. With the correct mixture design and adequate curing methods, carbonation is maintained in control. Furthermore, these materials counteract effectively alkali-silica reaction (ASR), which is an expansive destruction mechanism involving reactive aggregates and alkalis of cement. RHA, SCBA, and WGP reduce alkalis in the concrete and bind free alkalis within cement matrixes. Hence there is reduced availability of the reactive components that promote ASR [41]. Their high silica content promotes the formation of non-expansive reaction products to reduce ASR-induced distress. Durability advantages of RHA, SCBA, and WGP stem from performance modifications within the concrete that these materials induce on a microstructural level. These SCMs contribute to pore refinement by filling up voids existing in the parent concrete and promoting the synthesis of additional C-S-H, which enhances the bond between the aggregates and the paste. Density and cohesion of the interfacial transition zone (ITZ), which is usually the weakest link within the concrete microstructure, improve with the addition of these finely divided materials [42]. The ITZ density improves multifold through the effect of RHA and SCBA due to their highly reactive silica content and fine particle size. WGP, with its glassy texture and amorphous silica, improves ITZ upon acting as micro-fillers and reacting with portlandite. These improvements in microstructure translate into enhanced mechanical performance and greater resistance against the ingress of harmful agents, contributing to the durability and service life of the concrete structures in which they were added [43]. RHA contributes as a supplement to SCBA and WGP in cement mortar and concrete not only to improve individual durability parameters but also to promote synergistically the long-term performances and sustainability of structures. In this way, the workability of concrete against severe environmental exposure conditions is enhanced by reducing water absorption, increasing resistance to chloride and sulfate attacks, alleviating alkali-silica reaction, and improving microstructure. Their advantages are all the more useful for infrastructure related to marine, industrial, or arid condition location, in which durability is an essential requirement for minimizing maintenance cost and prolonging service life. Besides giving these oxides, the added qualification of being made from agricultural and industrial waste in support of eco-friendly constructions, they thus become practical and sustainable solutions for enhancing concrete durability in present-day civil engineering applications [44].

V. Environmental and Economic Implications

RHA contributes as a supplement to SCBA and WGP in cement mortar and concrete not only to improve individual durability parameters but also to promote synergistically the long-term performances and sustainability of structures. In this way, the workability of concrete against severe environmental exposure conditions is enhanced by reducing water absorption, increasing resistance to chloride and sulphate attacks, alleviating alkali-silica reaction, and improving microstructure. Their advantages are all the more useful for infrastructure related to marine, industrial, or arid condition location, in which durability is an essential requirement for minimizing maintenance cost and prolonging service life. Besides giving these oxides, the added qualification of being made from agricultural and industrial waste in support of eco-friendly constructions, they thus become practical and sustainable solutions for enhancing concrete durability in present-day civil engineering applications [45]. Economically, RHA, SCBA, and WGP are the most affordable alternatives to conventional cement, especially in parts of the world where these waste materials are highly available. The cost of processing-such as grinding and controlled burning-is normally less than producing clinker, especially where infrastructures for waste collection and processing are established. RHA and SCBA can be sourced locally using very minimal resources in typical rice and sugarcane-producing agricultural areas. Like that of increased urbanization and increasing consumption, glass waste is therefore becoming widely available; WGP keeps on being produced. Apart from reducing the material cost in concrete production, these materials make a great contribution to reducing the long-term costs of maintenance and repair of structures due to their influence on durability. When applied wisely, these SCMs will make the economic sustainability of concrete production high, particularly for developing countries that juggle high construction demands and waste management challenges [46]. The utilization of RHA, SCBA, and WGP in concrete serves to underline waste valorization and circular economy that have been integrated into the construction sector. Instead of sending agricultural residues and industrial wastes to either a landfill or open burning-a practice which adds to pollution and wastage on resources-these materials are recycled or rather converted into very valuable inputs for building up infrastructures. Thus, apart from tackling the looming crisis in waste management, it also closes the loop between waste generation and consumption of materials. The transformation of these wastes into durable construction materials moves the industry closer to establishing itself

within the circular economy, or production by continuously cycling back within productive use all materials to create value. With this, not only raw materials are conserved, but also the area for innovations in developing sustainable materials is facilitated while at the same time benefiting local economies through new value creation chains. The environmental and economic synergy presented by RHA, SCBA, and WGP valorization furthers more extensive goals of sustainability while engendering resilience, as well as efficiency in the built environment [47].

These studies highlight the innovative application of supplementary cementing materials such as rice husk ash (RHA), sugarcane bagasse ash (SCBA), and waste glass powder (WGP) for concrete, showing that these materials can reduce greenhouse gas emissions while having enhanced mechanical and durability properties and being more sustainable. The effective application of several machine learning (ML) and deep learning (DL) models-such as CatBoost, GBM, CNN, GRU, XGB, RF, and hybrid methods-to predict compressive strength and other performance parameters of RHA, SCBA, and WGP-based concretes have been reported [48, 49, 51, 56]. Experimental investigations and thermal exposure analyses have further attested to the enhanced thermal resistance and re-curing benefits of RHA concrete [50], while SCBA addition is noted to improve lightweight concrete attributes and economic viability considerably [51, 52, 53]. The studies combining RHA and WGP have also shown a synergistic improvement in strength and durability [54], while WGP was included in alkali-activated concrete to significantly reduce permeability, CO₂ emissions, and costs [55]. These results together support the need to extend advanced ML technologies for waste valorization into the construction field for the development of eco-efficient high-performance concrete solutions.

Table 1 Comparative Summary of Studies on RHA, SCBA, and WGP in Concrete

Ref	Methods Used	Materials Used	Parameters Considered	Key Findings	Outcomes
48	CatBoost, GBM, CNN, GRU; ML & DL; Statistical evaluation (R ² , RMSE, MAE, MAPE, d, CE)	Rice Husk Ash (RHA)	Cement, water, RHA, fine & coarse aggregates, age, superplasticizer	GRU achieved highest R ² (~0.99 training, ~0.97 testing)	Accurate prediction of RHA concrete strength; supports sustainable design
49	LightGBM, XGB, RF, Hybrid (XGB-LGB, XGB-RF); SHAP analysis	Rice Husk Ash (RHA)	Cement, RHA, curing age, water, aggregates, superplasticizer	Hybrid XGB-LGB gave R ² =0.95; cement, RHA, and SP most influential	Effective forecasting of strength; supports rapid low-cost assessment
50	Experimental study; Thermal exposure; Re-curing; RSM	Rice Husk Ash (RHA)	Temp (300–700°C), re-curing time, strength, modulus	RHA concrete better under high temps; strength recovery up to 36%	Shows RHA enhances thermal resistance and post-fire recovery
51	Experimental; Fresh, mechanical & microstructure tests; ANN, RF models	Sugarcane Bagasse Ash (SCBA)	SCBA % (0–20%), slump, compaction, strength tests	10% SCBA gave 10–30% strength gain; RF model R ² =0.989	SCBA improves LWC workability & strength; ML models accurate
52	Systematic review; Binary, ternary, quaternary blends	SCBA in binary/ternary/quaternary blends	Compressive strength, permeability, chloride resistance	Up to 40% replacement viable; ternary blends enhanced durability	Promotes high-performance, multi-blend eco-concretes
53	Experimental; Varying NaOH molarity; Slump, strength tests	SCBA + Fly Ash	NaOH molarity, SCBA % (0–20%), mechanical properties	10M NaOH sufficient; 20% SCBA optimum; strength increased up to 10.2%	Eco-friendly GPC with SCBA; balance between strength and emissions
54	Experimental; Slump, water absorption, strength, simulation	RHA + WGP	Slump, uniaxial strength, cyclic & shear strength	15% RHA + GP had best pozzolanic	RHA-WGP blend enhances

				effect; ductile behavior observed	mechanical and durability traits
55	Experimental; FA-GGBS AAC with WGP; Microstructural analysis	WGP + FA + GGBS + RCA	WGP % (0–25%), strength, sorptivity, chloride, CO ₂	20% WGP gave peak strength; 60% CO ₂ reduction	WGP improves AAC microstructure and lowers environmental impact
56	ML (BPNN, XGB, SVR, RF); Hybrid with SSA; PDP analysis	Glass Powder (GP)	Cement, moisture, sand, coarse agg., GP, curing age	SSA-XGB gave R ² =0.9645; cement & age most influential	ML models reliable for GPC strength; database of 1045 samples created

VI. Conclusions

Overall, this study describes the good prospects set by supplementary cementitious materials like Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), and Waste Glass Powder (WGP) to reinforce the sustainability, performance, and durability of concrete. Derived from the land and industrial waste, these materials reduce not just the conventional dependence on Portland cement but also greatly mitigate the carbon footprint associated with concrete production. Through their pozzolanic activity, these SCMs enhance mechanical strength, refine microstructure, and improve resistance to environmental aggressors like chloride ingress, sulphate attack, and alkali-silica reaction. If RHA, SCBA, and WGP are processed and incorporated to the required level, these materials will improve their workability and enhance durability and performance in situations of need, including when exposed to high temperatures. Prediction of compressive strength and other performance measures of SCM-based concrete has been shown with reports on high accuracy applying Machine Learning (ML), deep learning (DL), CatBoost, GRU, and hybrid XGB-LGB algorithms. This system helps evaluate concrete properties efficiently, economically, and in real-time, thus aiding mix design and optimization of materials. The assembly of AI-based prediction techniques with sustainable material use sets a new benchmark for intelligent eco-efficient construction practices. From an economic and environmental standpoint, the use of these SCMs encourages the principles of waste valorization and circular economy. They are inexpensive alternatives, especially where these waste materials are readily available. Their adoption will lessen raw material demand, landfill usage, and greenhouse gas emissions, along with improving longevity of infrastructure and maintenance costs. Hence, the synergistic approach presented by RHA, SCBA, and WGP modelling therefore delivers a creative way of developing concrete products that is durable, cost-effective, and environmentally conscious: a giant leap into sustainable construction.

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