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Development of Concrete using different Industrial Waste Materials

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Abstract*— The traditional production of concrete contributes significantly to environmental degradation, primarily due to cement manufacturing, which accounts for approximately 8% of global CO2 emissions and overuse of natural aggregates. At the same time, the construction industry continues to produce massive industrial wastes posing a two-fold sustainability problem. Sustainable construction of concrete entails utilizing industrial waste products as additional cementitious materials (SCMs)and aggregate substitutes. This paper critically reviews the applications of fly ash, coal bottom ash, ground granulated blast furnace slag (GGBS), silica fume, rice husk ash, metakaolin, recycled concrete aggregate, steel slag, copper slag, quarry dust and waste foundry sand in the development of concrete. The scope of this study encompasses mechanical performance durability characteristic environmental benefits and economic feasibility. The results of the literature show that the ternary SCM with optimized compositions (7.5% fly ash, 7.5% silica fume, and 7.5% GGBS) can attain compressive strengths of more than 85 MPa with high durability, as shown by the value of chloride permeability. The replacement of coal bottom ash by 20 % results in similar strength and high chloride resistance. Rice husk ash is found to increase strength and cut down on water uptake whereas the recycled concrete aggregates to a 50% replacement will still be able to provide structural capability that is below-average in mixes mixed with SCM. Life cycle assessment embodied carbon savings of as much as 19% and massive economic savings. In spite of these benefits, there are still problems associated with material variability, standardization, and long-term performance. This review suggests applying the circular economy's tenets to concrete technology.

***Keywords*— Industrial waste materials, Sustainable concrete, fly ash, Coal bottom ash, Silica fume, GGBS, Rice husk ash, Recycled concrete aggregate, Steel slag, Waste foundry sand, Durability.**

I. INTRODUCTION

This is a result of the construction industry unparalleled global expansion brought on by high levels of urbanization, infrastructural development, and population growth. Due to its strength, flexibility and affordability, concrete has been the most widely used building material worldwide. Over 10 billion cubic meters of concrete are produced annually. Nevertheless, due to large-scale use, it has a serious effect on the environment, especially in the production of cement and the natural extraction of aggregates.

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The direct contribution of Portland cement manufacturing to the global anthropogenic carbon dioxide (CO2) emissions is about 7-8 per cent and the amount of carbon dioxide (CO2) emitted per ton of cement is close to one ton of CO2 [1], [2]. Moreover, massive mining of natural aggregates in the form of sand, gravel, and crushed stones results in the exhaustion of limited resources, ecological disproportion, and the use of a lot of energy. In line with the growing need of construction materials, industrial and agricultural processes produce massive amounts of by-products and waste materials. Through coal-based thermal power plants, fly ash and coal bottom ash are generated and through iron and steel industries, blast furnace slag and steel slag are produced. The agro-processing results in the generation of agricultural residues like rice husk ash, and the construction and demolition processes generate recycled concrete aggregates. Conventionally, these wastes have been sent to landfills or dumping areas whereby they have posed severe environmental issues such as occupation of land, contamination of groundwater, air pollution, and chronic health hazards. The scarcity of landfill capacity and the increased restrictions of the environmental laws also serve as additional indicators of the necessity of the sustainable approach to waste management. The presence of the growing demand of construction materials and the growing industrial waste creation creates a great prospect of sustainable development. Use of industrial by-products in the manufacture of concrete is also a viable approach of minimizing reliance on virgin raw materials and solving problems of waste disposal. The strategy helps the principles of sustainable building and the circular economy as it encourages resource efficiency, reuse of materials, and protecting the environment. Various researches have also demonstrated that some industrial wastes are cementitious or pozzolanic in nature, and thus, can be utilized as partial cement substitute or as an aggregate without affecting the performance of concrete. The use of industrial waste products in the manufacture of concrete helps in minimization of greenhouse emissions, natural resource saving, diversion of waste products in landfills and general improvement of sustainability in development of infrastructures. Although there is comprehensive experimental research done on each waste material, there is not much practical implementation because of the piecemeal research and lack of overall comparisons. Review studies are critical to summarizing experimental results, pointing out performance patterns and pointing out research gaps. To facilitate evidence-based decision making, mix design optimization, as well as standardization in sustainable concrete production, a systematic review that assesses various industrial waste materials in terms of mechanical, durability, environmental, and economic aspects is required. Categorize and assess industrial waste products utilized in concrete, such as cementitious products (fly ash, coal bottom ash, silica fume, ground granulated blast furnace slag, rice husk ash and metakaolin), fine aggregate substitutes (waste foundry sand, quarry dust and copper slag), and coarse aggregate substitutes (recycled concrete aggregate and steel slag).Examine the impacts of these products on mechanical properties, including compressive, split tensile, and flexural strength and durability attributes, including water absorption, permeability, resistance to chemical assault. Evaluate environmental and economic advantages by determining the reduction of CO2 emissions, conservation of natural resources, life-cycle performance and cost-effectiveness are shown in Figure 1. Determine some of the biggest gaps in research and future directions in regard to material variability, standardization, long-term durability and field applications on a large scale.

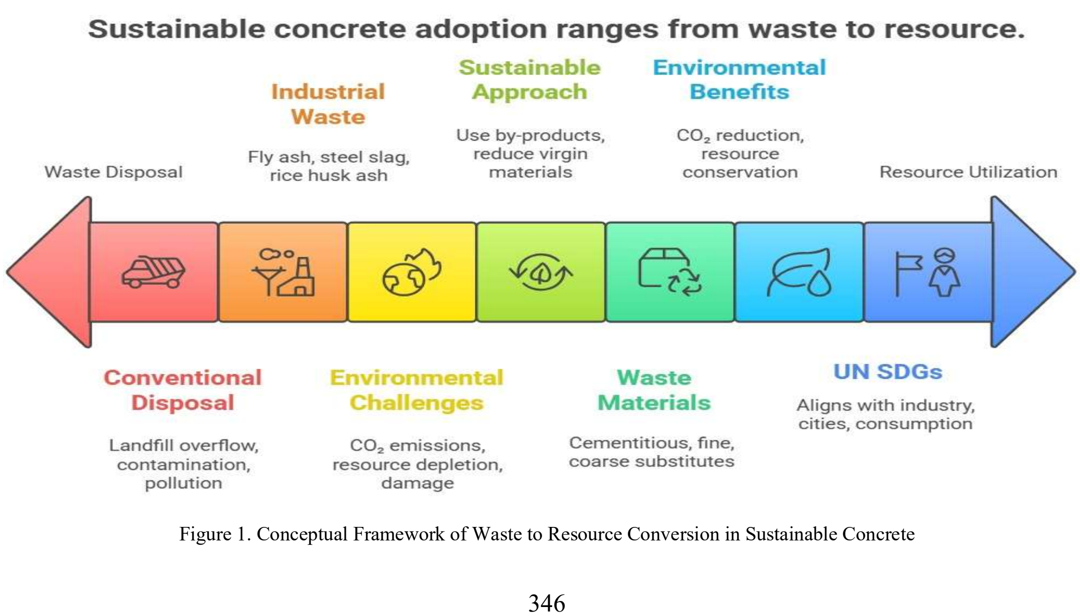

Figure 1. Conceptual Framework of Waste to Resource Conversion in Sustainable Concrete

II. Classification of Industrial Waste Materials used in Concrete

Portland cement is partially replaced by other cementitious ingredients which give concrete performance through latent hydraulic or pozzolanic interactions. Fly ash a byproduct of burning coal, is mostly composed of amorphous silica and alumina. It is typically used as replacement levels, ranging from 15 to 35 percent, with 7.5 percent actually functioning under ternary mixes. FA increases workability because of its spherical particles and increases long-term strength by interacting with calcium hydroxide and also improves pore structure and decreases permeability and chloride ingress [5], [6], [7]. The mechanically ground coal bottom ash (CBA), which has the finer particles, has both the pozzolanic and filler effects. Ground CBA with a 10-20% cement replacement offers virtually 97.7% of control strength and offers an outstanding chloride penetration protection, as well as a carbon footprint reduction of about 18-19% [8], [9], [10]. Due to its high concentration of amorphous silica, silica fume (SF), a by – product of the production of silicon alloys is extremely reactive. Taken in 5-10 percent form, SF substantially enhances strength early and long-term, microstructure densification and has a significant negative impact on the rapid chloride permeability [6], [11], [12]. Iron production results in ground granulated blast furnace slag (GGBS), which is a latent hydraulic binder, normally substituted with 40-60% and in low-clinker systems, up to 70%. GGBS increases the strength in the long-term, resistance to chlorides and sulfates, and reduces the heat of hydration, and this type of cement is appropriate in marine and aggressive environments [6], [13], [14]. Agricultural waste, specifically rice husk ash (RHA) which contains a lot of amorphous silica is viable at approximately 10% substitution, causing large-scale pore refinement, water uptake, and compressive strength enhancement [15], [16]. Metakaolin (MK) is a calcium silicate altered to form a calcified material and is a highly reactive additive that is used at 5-15 percent replacement to enhance early strength, the quality of interfacial transition zone, and acid resistance, especially in recycled aggregate concrete [17], [18], [19].Raw coal bottom ash, copper slag, quarry dust, and waste foundry sand are some of the commonly used fine aggregate replacements that are used in replacement levels of 10-50%. These materials enhance the packing and interlocking of the particles mechanically at the expense of workability necessitating use of chemical admixtures. Waste foundry sand is effective with 10-30 percent replacement rate, but it is only effective when quality control is applied [8], [10], [20], [21], [22], [23], [24]. Cause aggregate Replacements Cause aggregate can be recycled concrete aggregate (RCA), steel slag, or coarse coal bottom ash. Combined with SCMs, RCA can be applied up to 50 percent in structural concrete, whereas, after stabilization, steel slag can be used to increase the abrasion resistance and durability of 30-50 percent replacement [17], [25], [26], [27], [28] as shown in Figure 2.

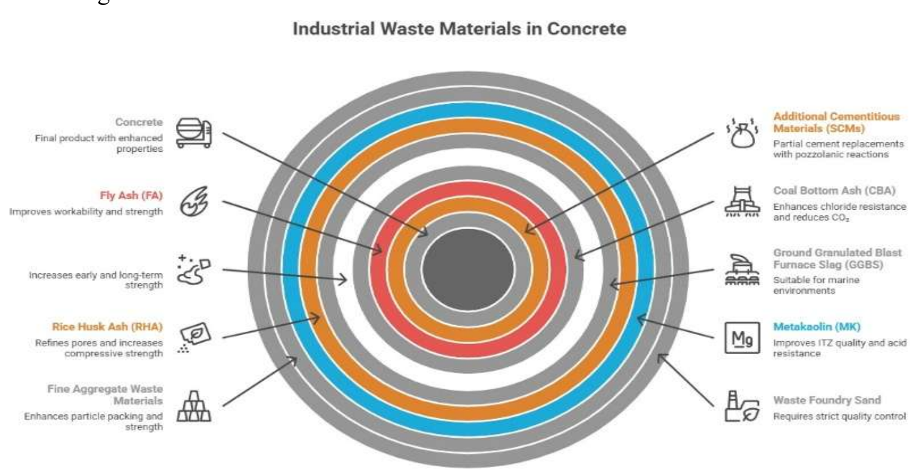

Figure 2. Type of Industrial Waste Material and Their Effect on Concrete Properties

III. Effect of Industrial Waste Materials on Mechanical Properties of Concrete

The fly ash tends to decrease the compressive strength in early ages because it is less pozzolanic. A decrease in strength is often observed by 10-20% in 7-days at 20-30% replacement levels [5], [7]. Strength gain however, is significant at the advanced ages. At 28days, a 20-25% fly ash replacement usually developed similar strength as control mixes with optimized fly ash pavement concrete achieving 50.8 Mpa at 28days [29]. Ultra-fine fly ash enhances the early strength build up and a balance of between 15-30% is good to replace performance and sustainability [29]. Ground coal bottom ash (GCBA) has a pozzolanic effect at a fine enough size. The replacement of GCBA 20% gave 97.7% control strength at 91 days, which proved its viability as an SCM [9]. The fly ash had been noted to be of higher strength (114 percent of control) of the same source; nevertheless, it does not exclude GCBA as a potential replacement at 10-20 percent [9], [10]. Raw CBA as a fine aggregate works best at 25-40 percent particularly when used together with SCMs [8], [20]. The high-performance mix with 40% raw CBA and 15% ultra-fine slag recorded a 58 percent enhancement in the strength of the control concrete [20]. Silica fume greatly increases the compressive strength because it is very fine and reactive. The 5-10% replacements usually add 15-30% to the 28-day strength [12], [30]. In ternary mixtures, 7.5% fly ash, 7.5% silica fume, and 7.5% GGBS recorded an 85.69 MPa after 28 days and thus, exhibited a high degree of synergistic action [6]. GGBS allows cement replacement levels (40-70) and does not harm or negatively affect long-term strength. High GGBS low-clinker high-performance concrete with a high 76-92 Mpa at 28 days and keeping the strength until two years [14]. GGBS works well especially at high curing temperatures. When well processed, rice husk ash (RHA) boosts compressive strength by 9.7-20% in a 10% replacement in alkali-activated systems [16]. Metakaolin improves the early strengths and quality of ITZ, particularly in recycled aggregate concrete and the maximum replacement rates are 10-15% [17]. Compressive strength is retained or enhanced when combined with cementitious SCMs with the assistance of enhanced mechanical interlocking of angular particles by using Raw CBA as a fine aggregate replacement at a 25-40% level [8], [20]. The 21.8% GCBA (cement replacement) and 24.2% raw CBA (aggregate replacement) were found to be an efficient combined solution [8]. Nonetheless, more CBA content leads to decreased workability, which requires superplasticizers [9], [31]. The presence of RCA will usually lower the compressive strength by 10-25% when fully replaced because it has a greater porosity and less strong ITZ [25], [26]. The loss of strength can adequately be alleviated with the help of SCMs. RCA-based (50 percent) and ternary SCM-based concrete mixes had the same strength as natural aggregate concrete, particularly when 0.5 percent steel fibers are added [17], [26]. When treated properly, steel slag enhances compressive strength at a 30-50 percent replacement of coarse aggregate because it is dense and angular [28], [32]. Copper slag is also known to promote strength, and in reactive powder concrete, 40 percent sand displacement and 10 percent Alccofine produced 176.5 MPa compressive strength [22]. Split tensile strength tends to follow the same trends compressive strength, but has a more direct relationship with microstructural refinement. It was done by a ternary SCM blend (7.5% FA + 7.5% SF + 7.5% GGBS) that obtained 5.82 MPa split tensile strength after 28 days [6]. The tensile behavior is enhanced by silica fume and RHA to a significant degree by densifying the ITZ [16]. Tensile strength can be decreased by tensile strength by up to 30 percent, and the performance of SCMs and fiber reinforcement can be successfully restored [26]. Flexural strength is essential to pavements and slabs. Fly ash pavement concrete had flexural strength of 8.2 Mpa after 28 days (Kumar Mehta, n.d.), and ternary SCM blend had flexural strength of 9.64 Mpa [6]. CBA aggregate mixes with high volumes were stronger than control flexural strength at subsequent ages [31]. The flexural strength of steel slag aggregate concrete was similar or better in 30-50 percent replacement [27], [32]. The increase of strength is due to the formation of more C-S-H gel by pozzolanic reactions, the effect of fillers on particle packing, the densification of the ITZ, and the refinement of the pore structure [6], [14], [18]. Multi-SCM systems also capitalize on such synergistic actions, such as early reactivity, sustainability over the long term, and enhanced durability [6], [8]. Alkali-activated systems also increase the reactivity especially in RHA and metakaolin, and provide high strength potential [16], [19], [33]

IV. Durability Performance of Concrete Containing Industrial Waste Materials

Improved durability of coal bottom ash (CBA) concretes is observed under optimal conditions. The application of both, ground CBA and raw CBA as a cement replacement and an aggregate replacement respectively led to the diminished accelerated chloride penetration and an enhanced pore structure both during the 28 and 90 days [8]. Even though the water absorption tends to be lower with mix design, optimized CBA concretes tend to have similar or slightly higher absorption rates as fly ash concrete but lower rates compared to control OPC concrete [8], [31]. Other studies involving serviceability also helped to ensure good microstructural properties of CBA-based concretes [34]. Rice husk ash (RHA) has outstanding use in decreasing the absorption of water. Water absorption in AAS with 10 percent RHA was 42 percent lower than plain AAS systems because of its ultra-fine particles and high pozzolanic activity [16]. Sorptivity was also low which showed less connectivity of the capillaries. Likewise, ternary SCM blend containing 7.5% fly ash, 7.5% silica fume and 7.5% GGBS recorded very low water absorption of about 1.21% at the age of 90 days, which indicates a very refined pore structure [6]. Silica fume can contaminate water absorption and sorptivity by a significant margin because it is very fine (reductions of 30-50% were reported at 8-10% substitution rates). Absorption of water is also lower in high-volume GGBS systems (50-70) especially when latent hydraulic reactions are observed in later ages [13], [14]. Fly ash makes the mix more durable (primarily at later ages) and optimized mixes, with the resulting water absorption 20-35% lower in 90 days [29]. Metakaolin also refines the pores, lowering the absorption by 25-40 percent at 10-15 percent replacement [17], [18]. The effectiveness of SCMs is evidently portrayed in the findings of rapid chloride permeability test (RCPT). Optimally ground CBA recorded a very low RCPT value of 559 Coulombs, which was better than fly ash of the same power plant, which had a 4,108 Coulombs [9]. Ternary SCM mixes obtained approximate of 815 Coulombs, which is appropriate under severe exposure conditions [6]. The high-volume GGBS concrete which reached very low permeability rates (500-1,200 Coulombs) was always associated with dense microstructure and chloride binding capacity [13], [14]. The 8-10% replacement of silica fume decreased the RCPT values by 60-80% [12], [30]. CBA combined with cementitious and aggregate use minimized the chloride penetration further at 28 days and 90 days [8]. RCA in a pure form enhanced the permeability, whereas tertiary SCM in mixture form reclaimed the performance [17], [25]. CBA concretes were also found to be resistant to sulfuric acid and sulfate conditions especially when they were mixed with silica fume [31]. FA, GGBS, and silica fume-based geopolymer concrete had a better resistance to sulfuric acid, and retained more than 80 percent compressive strength during a long period [6]. GGBS concrete was reported to perform well in sulfate resistance with high volumes, and it is higher than that of sulfate-resistant OPC [13], [14]. The overall sulfate resistance order is: geopolymer/AAS> high volume GGBS> silica fume> fly ash ground CBA> OPC [6], [31]. Freeze-thaw resistance is enhanced by SCM application because of a decreased capillary porosity, but ensured air entrainment is still a prerequisite. GGBS/FA/SF level of low-clinker HPC demonstrated a high level of frost resistance [14]. When treated well, steel slag aggregates also showed froze-thaw performance [27], [32]. Environmental safety was proved by the leaching studies that revealed no trace of heavy-metals discharge of coal ash concrete [31]. The long-term tests revealed a further improvement of durability over a two-year period in high-GGBS and CBA concretes because the pozzolanic reactions were still going on [14], [31]

V. Environmental and Economic Benefits

Replacements of aggregates and use of industrial waste materials as supplementary cementitious materials (SCM) has in place of aggregates offer significant environmental and economic advantages. The CO2 released by cement production is about 7-8 percent of anthropogenic CO2 in the world with a ton of cement releasing about 0.8-1.0 tons of CO2. The use of cement can be substituted with SCMs which directly lower these emissions. The carbon footprint reductions to the conventional concrete were around 18-19% with optimized carbon bottom ash (CBA) concrete using both ground CBA as cement replacement and raw CBA as aggregate replacement [8]. The embodied carbon of recycled aggregate concrete that included SCMs, and fibers had a reduction of up to 15.6% [26]. The fly ash, GGBS, silica fume, rice husk ash, and ternary blends also lower the CO2 emissions per m3 of concrete by 15 to 60 percent depending on the replacement content and type of material used. The use of industrial waste will save the natural resource as it will cut down the mining of limestone and aggregate. CBA productions in the world amount to more than 200 million tons every year, and its utilization as aggregate would help to avoid over 60 million tons of natural sand annually [8], [31]. The energy consumption is also decreased in connection with the use of the SCMs since their embodied energy is much less in comparison with that of Portland cement [9], [10]. It has a positive environmental impact because it helps to divert waste in landfills, lessens land use, and the country promotes the principles of a circular economy [31]. SCM concrete can be optimized economically making material cost 15-30% lower and the life cycle cost 30-50% lower because of the improved durability and decreased maintenance [9]. Table 1 shows the comparative summary of waste materials.

TABLE I. Comparative Summary of Industrial Waste Materials used in Concrete

Industrial Waste Material	Typical Replacement Range	Effect on Strength	Durability Performance	Environmental and Economic Benefits	References
Fly Ash [FA]	15 – 30 % cement	Lower early strength and improves long – term strength	Reduces permeability and chloride entrance	Reduces cement demand and CO2 emissions	[5],[13],[16],[29]
Ground granulated blast furnace slag [GGBS]	40 - 60% cement	Comparable or higher long -term strength	Excellent sulfate and chloride resistance	Major CO2 reduction	[6],[13],[14]

Silica Fume [SF]	5-10% cement	Significant increase in compressive and tensile strength	Very low permeability and refined pore structure	Extends service life in harsh environments	[6],[11],[12],[30]
Rice Husk Ash [RHA]	10-20% cement	Improves compressive strength	Reduces water absorption and sorptivity	Converts agricultural waste to resource	[6],[15],[16]
Coal Bottom Ash (CBA)	10-20% cement 20-40% aggregate	Comparable strength when optimized	Good chloride and chemical resistance	Reduces landfill burden and sand mining	[8],[9],[10],[31],[35]
Recycled Concrete Aggregate [RCA]	Up to 50% coarse aggregate	Slight strength reduction unless SCMs used	Higher porosity improved with SCMs	Reduces natural aggregate extraction	[7],[17],[25],[26]
Steel Slag	30-50% coarse aggregate	Comparable or higher strength	Good abrasion and durability resistance	Utilizes iron and steel by product	[5],[26],[27],[32]
Waste Foundry Sand [WFS]	10-30% fine aggregate	Comparable strength at moderate levels	Depends on quality control and improves packing	Addresses waste disposal issues	[20],[21],[22]

V. Challenges, Research Gaps, and Future Research Directions

Although the use of industrial waste materials in concrete is evidently advantageous in terms of its technical, environmental, and economic benefits, its application at large scale is still limited by a number of factors. The major problem is that chemical and physical properties of the waste materials are very variable, since they are by-products of the industrial process that is not designed to produce concrete. Coal bottom ash (CBA), specifically, has a large degree of variability, as it depends on the source of coal, the conditions of combustion, the size of the particles, and the content of the glass that directly affects the performance and reactivity [9], [10]. The same applies to steel slag because it contains free lime and it can be expanded [32]. This variability influences the strength development, workability, durability, and performance over the long term, which requires sound quality control mechanisms and quicker testing procedures. The other significant impediment is the no standardized specifications. In contrast to fly ash, CBA does not have detailed performance-based standards that underlie crafting a conservative design and restrict its adoption regardless of its performance [8], [9]. The lack of the unified international principles makes procurement and approval even more complex. There is a research gap in limited long-term durability data. The majority of the works are based on the performance in the short term (28-90 days), and there is little field data after one year, especially concerning CBA concrete [8], [31]. There is a lack of understanding of long-term behavior in the conditions of combined exposures and extreme events. In practical terms, angular shapes of raw CBA aggregates and fineness of ground CBA can lead to workability and constructability issues that may be addressed by using more admixtures and optimizing the mix [8], [9]. Future research should prioritize performance-based design approaches, integration of life cycle assessment (LCA) into mix design, long-term field monitoring, and advanced tools such as AI-driven mix optimization. Emerging directions include multi-SCM systems, geopolymer concretes, circular economy frameworks, and climate-resilient materials. Addressing these challenges through coordinated research, standardization, and field validation will unlock the full potential of industrial waste materials, particularly coal bottom ash, in sustainable concrete construction [8], [10], [33].

VI. Conclusions

In this review, it was synthesized that industrial waste materials can be used as a viable and high-performance substitute of the conventional concrete constituents. Recycled aggregates and industrial slags, silica fume, GGBS, rice husk ash, and metakaolin, and fly ash, coal bottom ash (CBA), and recycled aggregates are additional cementitious materials that can sustain or improve the performance of mechanical, as well as durability when well-designed. Optimized ternary SCM blends with high compressive strengths (over 85 MPa) and high durability show that the high-performance sustainable concrete is a reality. One of the most promising, but little used materials is coal bottom ash. At a fine ground, CBA with a replacement of cement at about 20% attains virtually the same strength as to control concrete and superior chloride resistance performance, compared to fly ash in direct comparisons. Its two-fold capability of working either as SCM or aggregate allows the optimization of mixes that save the carbon footprint by about 18-19 but do not affect the structural performance. The GGBS, ground CBA and silica fume are particularly applicable in applications that require durability where they are more resistant to chloride intrusion, sulfate attack and harsh environments. The achievements of environmental and economic gains are significant, and the embodied carbon cuts vary between 15-60, material cost cuts between 15-30, and life-cycle cost cuts up to 50. There are still problems such as material variability, absence of long-term data, absence of standards and problems with workability. The next endeavors must be on improving performance-based standards, durability testing, built in life-cycle assessment and the coal-to-renewable transition plan. Waste-based concrete is an industrial waste, which provides a valid path to circular and low-carbon and resilient construction.

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