

Sustainable Alternatives in Concrete: A Comprehensive Review of Industrial Byproducts as Cement and Aggregate Replacements

Navdeep Singh Phougat¹ and Nitu²

Civil Engineering Department, Matu Ram Institute of Engineering & Management, Model Town, Rohtak, Haryana 124001

Abstract - The environmental impact of conventional concrete production, primarily due to high cement consumption and CO₂ emissions, has driven the search for sustainable alternatives. This study explores the integration of various industrial and construction byproducts—such as Iron Ore Sludge, Fly Ash, Ground Granulated Blast Furnace Slag (GGBFS), Brick and Mortar Waste, and Ceramic Waste—as partial replacements for cement, fine aggregates, and coarse aggregates in concrete. These replacements not only reduce the reliance on natural resources but also enhance the mechanical properties and durability of concrete. A detailed analysis was conducted on the physical, chemical, and structural contributions of each byproduct. The research also examines the use of advanced optimization tools like Response Surface Methodology (RSM) and predictive modeling techniques, including machine learning, to improve mix design and performance forecasting. The findings confirm that using these waste-derived materials can significantly contribute to environmental conservation, cost reduction, and structural efficiency in modern construction. However, the successful adoption of such materials requires further standardization and validation under varying environmental and loading conditions. This study contributes valuable insights for the development of eco-efficient concrete mixes, supporting sustainable infrastructure development.

Keywords: Sustainable concrete, Cement replacement, Industrial byproducts, Aggregates, Waste recycling, Fly ash, GGBFS, Optimization, Machine learning, Response Surface Methodology.

1 INTRODUCTION

This Concrete is the most widely used construction material globally, with its production reaching billions of tons annually. However, the high demand for conventional concrete has significant environmental consequences, including excessive energy consumption and CO₂ emissions, primarily due to the production of cement. The cement industry is responsible for approximately 5-7% of global CO₂ emissions, making it a major contributor to environmental degradation. The challenge of reducing the carbon footprint of concrete production while meeting the growing global demand for infrastructure is at the forefront of research into sustainable construction materials.

1.1 Why replacement needed

The need for replacement of traditional materials in concrete production stems from several environmental, economic, and resource-related challenges. Firstly, the construction industry relies heavily on natural resources, such as cement, sand, and aggregates, which are finite and often sourced from environmentally sensitive areas. The extraction of these raw materials leads to habitat destruction, soil erosion, and depletion of natural reserves. Moreover, cement production is a major contributor to global CO₂ emissions, responsible for approximately 7-8% of total emissions worldwide. This calls for the adoption of more sustainable alternatives to reduce the environmental footprint of concrete manufacturing. Secondly, the rapid growth of industrial activities generates large quantities of waste byproducts, such as iron ore sludge, fly ash, and plastic waste, which, if left unmanaged, contribute to landfills and pollution.

By replacing conventional concrete materials with these byproducts, the construction industry can not only reduce waste and promote recycling but also lower production costs. This figure 1 reflects the annual cement production in million tons from FY16 to FY23.

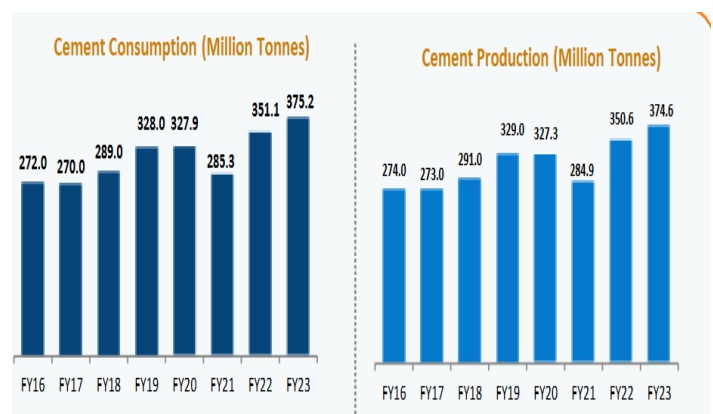


Figure 1: Consumption and production of cement in last years

1.2 Cement Replacement Byproducts

Several byproducts, such as Iron Ore Sludge, Fly Ash, and Ground Granulated Blast Furnace Slag (GGBFS), can effectively replace cement in concrete. These materials not

only reduce the environmental impact of cement production by lowering CO₂ emissions but also enhance the concrete’s workability, strength, and durability. The use of Rice Husk Ash and Wood Ash further supports sustainability goals while improving long-term strength and reducing reliance on conventional cement. The potential replacement range for cement varies from 5% to 50%, depending on the specific byproduct.

1.3 Fine Aggregate (Sand) Replacement Byproducts:

Various waste materials, such as Brick and Mortar Waste, Plastic Waste, and Spent Foundry Sand, offer viable alternatives to conventional sand in concrete mixes. These byproducts help reduce waste generation, lower dependence on natural sand, and contribute to improved concrete durability and strength. Additionally, materials like Crushed Glass and Quarry Dust enhance workability and resistance to chemical attacks, offering a sustainable solution for fine aggregate replacement. The replacement range for fine aggregates can vary from 0% to 50%, depending on the byproduct and the desired properties of the concrete.

Table 1: Cement Replacement Byproducts

Byproduct	Use in Concrete	Replacement Range	Potential Benefits
Iron Ore Sludge	Partial replacement for cement	0-20%	Improves workability, Enhances compressive strength, Reduces cement consumption, lowering CO ₂ emissions
Fly Ash	Partial replacement for cement	15-30%	Improves long-term strength, Enhances durability, Reduces heat of hydration, Lowers environmental impact
Ground Granulated Blast Furnace Slag (GGBFS)	Partial replacement for cement	30-50%	Increases durability, Reduces permeability, Improves resistance to chemical attacks
Rice Husk Ash	Partial replacement for cement	5-15%	Improves strength, Enhances workability, Reduces environmental

Byproduct	Use in Concrete	Replacement Range	Potential Benefits
Wood Ash	Partial replacement for cement	5-15%	Improves workability, Enhances long-term strength, Reduces environmental impact

1.4 Coarse Aggregate Replacement Byproducts:

A range of byproducts can replace coarse aggregates, including Ceramic Waste, Construction and Demolition Waste, and Rubber Waste. These materials offer sustainability benefits by diverting waste from landfills while improving specific concrete properties, such as durability and shock absorption. Other alternatives like Recycled Concrete Aggregate (RCA) and Coal Ash can also improve the concrete’s mechanical properties, reduce environmental impact, and support circular economy initiatives. The replacement range for coarse aggregates is highly variable, from 0% to 100%, depending on the type of byproduct used and its impact on the final mix.

Table 2: Sand (Fine Aggregate) Replacement Byproducts

Byproduct	Use in Concrete	Replacement Range	Potential Benefits
Brick and Mortar Waste	Partial replacement for fine aggregates (sand)	0-50%	Reduces waste generation, Lowers reliance on natural sand, Enhances durability and resistance to cracking
Plastic Waste	Partial replacement for fine aggregates	0-10%	Reduces plastic waste, Improves workability, Lightweight concrete
Spent Foundry Sand	Partial replacement for fine aggregates	0-50%	Reduces waste from foundry industries, Lowers demand for natural sand, Improves durability
Crushed Glass	Partial replacement for fine aggregates	0-30%	Enhances workability, Improves resistance to chemical attacks, Recycles glass waste
Quarry Dust	Partial replacement	0-40%	Reduces dependence on

	for fine aggregates		natural sand, Enhances strength, Improves workability
Sea Shells	Partial replacement for fine aggregates	0-30%	Reduces environmental waste, Improves durability, Lightweight

			workability
Palm Kernel Shells	Partial replacement for coarse aggregates	0-50%	Lightweight, Improves thermal insulation, Reduces waste from palm oil production
Wood Waste (Chips/Sawdust)	Partial replacement for coarse aggregates	0-20%	Lightweight, Improves workability, Reduces waste from timber industries

One promising strategy to mitigate the environmental impact of concrete production is the incorporation of industrial byproducts as partial replacements for traditional concrete components. The use of waste materials, not only helps divert them from landfills but can also improve the sustainability of concrete by reducing the demand for natural resources.

The three tables presented above highlight various industrial byproducts that can be used as substitutes for cement, fine aggregates (sand), and coarse aggregates in concrete production.

Table 3: Coarse Aggregate Replacement Byproducts

Byproduct	Use in Concrete	Replacement Range	Potential Benefits
Ceramic Waste	Partial replacement for coarse aggregates	0-100%	Enhances concrete's durability, Reduces landfill waste, Improves workability
Construction and Demolition Waste	Partial replacement for coarse aggregates	0-50%	Reduces construction waste, Reduces demand for virgin aggregates, Increases sustainability
Rubber Waste (Tires)	Partial replacement for coarse aggregates	0-10%	Increases shock absorption, Lightweight, Reduces rubber waste in landfills
Recycled Concrete Aggregate (RCA)	Partial replacement for coarse aggregates	0-100%	Reduces construction waste, Enhances sustainability, Reduces demand for natural aggregates
Coal Ash	Partial replacement for coarse aggregates	0-30%	Increases durability, Reduces environmental impact, Improves

A wide range of industrial byproducts, such as fly ash, slag, rice husk ash, and other waste materials, have been explored in recent years. In this context, three specific industrial byproducts Iron Ore Sludge, Brick and Mortar Waste, and Ceramic Waste—are of particular interest for their potential to replace traditional concrete constituents.

- **Iron Ore Sludge** is a byproduct of the iron and steel manufacturing process, and its disposal poses environmental challenges. This sludge contains valuable minerals that can partially replace cement in concrete. Research has shown that iron ore sludge can improve the workability and strength of concrete when used as a partial substitute for cement.
- **Brick and Mortar Waste** is generated during the demolition of buildings and infrastructure. This waste consists of crushed bricks and mortar, which can be used as a substitute for fine aggregates (sand) in concrete. Reusing this waste helps reduce landfill usage and offers a more sustainable alternative to conventional sand.
- **Ceramic Waste** is the byproduct of ceramic manufacturing processes, including broken tiles, pottery, and bricks. When used as a partial replacement for coarse aggregates in concrete, ceramic waste can enhance concrete's durability and reduce environmental impact, as the ceramic materials are rich in silica and alumina.

The integration of these byproducts into concrete offers a significant opportunity to develop more sustainable construction practices by reducing the consumption of natural resources and minimizing waste. However, the properties of concrete made with these alternative materials need to be carefully evaluated to ensure that performance standards are met.

2 Literature Review

The use of industrial byproducts as replacements for conventional materials in concrete has garnered increasing

attention in recent years due to its potential to reduce environmental impact, lower production costs, and promote sustainability in the construction industry. With the global construction sector being one of the largest consumers of natural resources, there is a growing need to explore alternative materials that can reduce the dependence on non-renewable resources like cement, sand, and aggregates. These byproducts not only help mitigate environmental challenges but also offer practical solutions to waste management issues associated with industrial processes.

Adamu and Ibrahim (2024) explored the environmental sustainability and cost-benefit analysis of using Date Palm Ash (DPA) blended with Eggshell Powder (ESP) as supplementary cementitious materials (SCM) in concrete. The cement industry contributes significantly to global CO₂ emissions, and this study focused on reducing the embodied CO₂ in concrete. By blending 21.3% DPA and 2.3% ESP, the researchers achieved a substantial reduction in CO₂ emissions while enhancing the concrete's performance. The study used Response Surface Methodology (RSM) for experimental design and optimization of the mix, which showed a marked reduction in both the environmental impact and cost of the concrete. DPA proved to be a cost-effective, environmentally sustainable material that, when combined with ESP, further improved the eco-strength efficiency of the concrete. Mathematical models developed during the study accurately predicted both the concrete properties and the cost reductions. The results demonstrate the significant potential of DPA and ESP as sustainable alternatives to traditional concrete materials, offering both environmental and economic benefits ¹⁾.

Adamu et al. (2021) investigated the impact of plastic waste (PW) and graphene nanoplatelets (GNP) on the mechanical performance and optimization of high-volume fly ash (HVFA) concrete. The study employed response surface methodology for experimental design and mix optimization, focusing on the effects of these materials on concrete's compressive strength, tensile strength, flexural strength, and water absorption capacity. The findings revealed that while plastic waste and HVFA contributed to a reduction in concrete's strength and absorption, the addition of graphene nanoplatelets significantly enhanced its mechanical properties. Specifically, compressive strength showed a high correlation with experimental results, and splitting tensile strength improved with GNP inclusion. Flexural strength remained consistent across different curing ages, while water absorption capacity was reduced with the optimized mix. The workability of the concrete was found to increase with higher fly ash content, and higher plastic waste also enhanced the workability of the mixture. The optimized mix, which incorporated specific percentages of plastic waste, HVFA, and GNP, achieved a balanced performance, with models showing high correlation and low standard deviation, indicating the reliability of the optimization process. ²⁾

Adamu et al. (2024) explores the use of date palm ash (DPA) and eggshell powder (ESP) as sustainable alternatives in concrete production. The research utilizes Response Surface Methodology (RSM) to optimize the blend of these materials, aiming to enhance the mechanical properties of concrete while reducing water absorption. The study finds that substituting cement with DPA in various dosages, combined with ESP to promote pozzolanic reactions, significantly improves concrete properties. The optimal blend was found to be 14.77% DPA and 2.2% ESP, achieving a desirability value of 91.1%. The incorporation of DPA and ESP reduced water absorption and enhanced compressive strength, with a 28-day compressive strength model showing minimal error of 3.74%. However, the study also indicates that excessive DPA content negatively impacts the slump values and increases water absorption. The findings suggest that DPA and ESP are promising sustainable materials for concrete, offering improved mechanical properties and a lower environmental impact, making them suitable for future green construction practices. Additionally, the RSM models demonstrated high accuracy, with prediction errors below 6%, confirming the effectiveness of these materials in optimizing concrete performance ³⁾.

Aghajanzadeh et al. (2024) utilized the response surface method to optimize the mix design of alkali-activated slag concrete (AASC) by evaluating its mechanical, durability, economic, and environmental properties. The study aimed to find a balance between performance and sustainability by exploring the effects of recycled aggregates, including recycled coarse aggregates (RCA), recycled fine aggregates (RFA), and silica fume (SF) in various mixes. The optimum mix was identified as containing 0% RCA, 0% RFA, and 8.1% SF, which maximized mechanical properties such as strength and electrical resistivity while minimizing water absorption, weight, and strength loss in acidic environments. Notably, the inclusion of recycled aggregates did not significantly impact the final price of the concrete nor alter CO₂ emissions, suggesting that these materials could be used without compromising environmental or economic considerations. The desirability score for the optimal mix was 100 (D100), indicating its superior performance. Additionally, the study found that the relative price of alkali-activated concrete was lower than that of ordinary Portland cement (OPC) concrete. The study's findings, supported by a high coefficient of determination ($R^2 > 90$) for all equations, suggest that alkali-activated slag concrete with specific eco-friendly ingredients can be a viable alternative for sustainable construction without significant cost or environmental drawbacks ⁴⁾.

Ahmed et al. (2022) explores the use of waste glass and condensed milk can fiber (CMCF) as replacements for fine aggregate in concrete, aiming to address the depletion of natural sand. The study investigates the effects of these materials on the workability, density, compressive strength, and tensile strength of concrete. Using Response Surface Methodology (RSM), the researchers optimized the mix,

identifying the optimal replacement percentages for both glass and fiber reinforcement. The study found that workability deteriorated as the percentages of glass fine aggregate (GFA) and CMCF increased, while fresh density increased with CMCF but decreased with GFA. The compressive strength was maximized at 20% GFA and 1% CMCF, while splitting tensile strength decreased with higher content of both materials. The optimal mix was found to be 20.436% GFA and 0.843% CMCF, with the models closely matching experimental results and showing high R^2 values, indicating strong model accuracy. The study suggests that while the incorporation of waste materials in concrete can improve certain properties, future research should focus on enhancing workability and strength to further optimize the material's performance for practical applications ⁵⁾.

Amiri et al. (2022) investigates the potential of using coal waste as a partial replacement for cement in concrete production, aiming to enhance sustainability while optimizing the concrete's mechanical properties. The study employs response surface methodology (RSM) and desirability function to determine the optimal mix proportions for improving compressive strength and reducing water absorption. The results indicate that the optimal mix consists of a water-to-cement (W/C) ratio of 0.44, cement content of 304 kg/m³, and gravel volume of 954 kg/m³, leading to a compressive strength of 46.30 MPa and a water absorption of 7.41%. Additionally, coal waste can be used to replace up to 36.95 kg/m³ of cement in the mix, which significantly contributes to reducing the environmental impact of cement production. The study highlights the feasibility of incorporating coal waste into concrete formulations, suggesting that this approach not only improves the material properties of concrete but also addresses sustainability concerns in the construction industry. Overall, the research provides a promising method for utilizing coal waste in concrete, offering an eco-friendly alternative that could reduce reliance on traditional cement while improving the performance of the material ⁶⁾.

Awolusi et al. (2019) conducted a study on the use of waste tyre steel fibre in reinforced concrete and applied Response Surface Methodology (RSM) to predict various concrete properties. The study focused on three independent variables: aspect ratio, water-cement ratio, and cement content, with limestone powder kept constant at 5% by weight. RSM was used to develop predictive equations for key concrete properties, and the results demonstrated high predictive efficiency for most properties. The optimal conditions for concrete performance were identified through the model, with experimental and predicted values showing good correlation. Under the optimal mix conditions—an aspect ratio of 140, a water-cement ratio of 0.26, and cement content of 40%—the concrete achieved impressive results, including compressive strength of 42.69 N/mm², flexural strength of 7.97 N/mm², and split tensile strength of 5.23 N/mm². The slump value was recorded at 7.65 cm. The study

highlights the potential of waste tyre steel fibre as a reinforcement material in concrete, offering improved mechanical properties. Additionally, the RSM model's accuracy in predicting concrete behavior demonstrates its utility for optimizing mix designs, contributing to the sustainability of construction materials ⁷⁾.

Azeez et al. (2023) explored the use of steel slag (SS) and waste glass (WG) in concrete production to create cost-effective and environmentally sustainable materials. Their study assessed the effects of replacing conventional aggregates with steel slag and waste glass on concrete's workability, density, compressive strength, and splitting strength. The authors employed a design of experiments methodology to analyze various binary binder blends, revealing a strong correlation with a second-order polynomial model. The inclusion of waste glass notably improved the concrete's rheological properties and enhanced strength, with compressive strength increasing by 58% when 100% of the steel slag was used as a replacement. Additionally, splitting strength improved by 33% with the inclusion of waste glass. Higher water-to-binder ratios were found to reduce compressive strength and increase slump, while mixtures with more steel slag showed higher density and improved mechanical strength. The study demonstrated that steel slag and waste glass can significantly enhance concrete's mechanical properties, making them valuable for sustainable construction practices. It was also found that the control mixture exhibited the lowest compressive and splitting strengths, highlighting the benefits of using recycled materials for improving concrete's overall performance. These findings suggest that steel slag and waste glass are effective alternatives for optimizing concrete mixture design while promoting environmental sustainability ⁸⁾.

Chashm Khavari et al. (2023) investigated the mechanical properties and optimization of sulfur concrete (SC) reinforced with steel fibers. The study applied Response Surface Methodology (RSM) to optimize variables affecting compressive strength, finding that the addition of steel fibers increased compressive strength by approximately 15%. Notably, the SC with fiber reinforcement exhibited significant improvements, with strength increases of 70% at 7 days and 205% at 28 days. The recyclability of sulfur concrete was also explored, revealing a 19.2% decrease in strength when SC was recycled. The study further compared the performance of macro fibers versus micro fibers, with macro fibers showing superior strength enhancement. Factors such as sulfur content, plasticizer use, and fiber inclusion were found to influence compressive strength, with sulfur and the specific mix design having a greater impact than the fibers alone. The study demonstrated that mixing speed and temperature had no significant effect on SC properties. Statistical analysis confirmed the reliability of the optimization model, with an F-value of 13.83 and an R^2 value greater than 0.93, indicating high model accuracy ⁹⁾.

Dahish and Almutairi (2023) explore the impact of elevated temperatures on the compressive strength of nano-modified concrete, using nano-silica (NS) and nano-clay (NC) as cement substitutes. The study employs Response Surface Methodology (RSM) to develop predictive models and optimize the compressive strength of concrete exposed to high temperatures. The analysis of experimental data from 208 cubic specimens revealed significant correlations between compressive strength and the dosages of NS and NC. The optimal replacement levels for maximizing compressive strength were identified as 1% NS and 4% NC. The study shows that while the addition of nano-materials improves concrete strength, elevated temperatures tend to reduce its structural performance, highlighting the importance of material composition for temperature resilience. The models were assessed for significance and adequacy using ANOVA, with quadratic models demonstrating the highest predictive accuracy. The results align well with the experimental data, confirming the validity of the models. Notably, the study also emphasizes that high adequate precision values above four confirm the reliability of the predictive models, making RSM an effective tool for optimizing concrete strength outcomes under varying conditions. Overall, the research provides valuable insights into the potential of nano-modified concrete for improved performance in high-temperature environments, offering a path towards more resilient construction materials ¹⁰.

Divya and Praveenkumar (2024) conducted an integrated evaluation of graphene-based concrete mixtures incorporating copper slag (CS) and quarry dust (QD), utilizing Response Surface Methodology (RSM) to optimize concrete performance. The study aimed to explore the effects of Graphene Nanoplatelets (GNP) on concrete properties and how alternative aggregates like copper slag and quarry dust influence the material's behavior. Key findings showed that copper slag improved compressive strength, with a 40% replacement leading to enhanced performance, while quarry dust had a minimal impact. The slump value was influenced by surface texture and porosity, with copper slag reducing the slump and quarry dust increasing it. The interaction between GNP, copper slag, and quarry dust significantly enhanced the mechanical properties, particularly in terms of compressive strength. The optimized mix achieved high desirability values for concrete strength, with the optimal ratio of 0.2485 GNP, 59.98% copper slag, and 40.72% quarry dust yielding the best results. The study's response surface model successfully predicted the slump, compressive strength, split tensile strength, and flexural strength, demonstrating the accuracy and effectiveness of the optimization process. This research highlights the potential for improving concrete properties using innovative materials and sustainable aggregates ¹¹.

Hafiz et al. (2023) investigated the effects of graphene nanoplatelets (GNPs) on the engineering properties of geopolymer concrete (GPC) that also included crumb rubber

(CR) as an additive. A total of twenty mix designs were tested, varying the amounts of CR and GNPs, with experiments evaluating mechanical properties and microstructural characteristics. The study found that GNPs significantly enhanced the performance of the geopolymer concrete, despite the generally negative impact of CR on the properties. The optimal addition of GNPs was found to be 0.3%, which notably improved the compressive strength, elastic modulus, splitting tensile strength, and flexural strength of the concrete. Additionally, GNPs contributed to improved impact resistance, though it was less pronounced than the effects of CR. The study also noted a decrease in slump flow with the replacement of CR and the addition of GNPs, indicating a reduced workability. Furthermore, water absorption and porosity were minimized with the optimal GNP addition, enhancing the durability of the concrete. The microhardness tests indicated improved matrix compactness, which supports the improvement in the overall performance of GPC. These findings suggest that GNPs, particularly at 0.3%, can significantly enhance the mechanical and durability properties of geopolymer concrete, making it a promising material for sustainable construction ¹².

Haque et al. (2024) investigates the use of granite dust (GD) and scrapped copper wire (SCW) as sustainable alternatives to fine aggregates in concrete. The research employs Response Surface Methodology (RSM) to predict and optimize the hardened properties of concrete, focusing on the effects of varying percentages of GD and SCW in the mix. The study finds a strong correlation between the predicted and actual results, demonstrating that incorporating waste materials into concrete can significantly enhance its mechanical properties. The optimized mix, with 30% GD and 0.3% SCW, achieved a compressive strength of 16.90 MPa at 7 days and 25.37 MPa at 28 days, while the splitting tensile strength at 7 and 28 days reached 1.924 MPa and 3.321 MPa, respectively, with 20% GD and 0.5% SCW. However, the study also notes that while the compressive strength initially increases with higher GD and SCW content, it begins to decline after a certain point. The research highlights that the optimal mix for both compressive and tensile strength is achieved with 20% GD and 0.5% SCW. This study supports sustainable construction practices by demonstrating that waste materials can be effectively used in concrete production without compromising its strength, providing a promising alternative for urban growth and development ¹³.

Ja'e et al. (2024) investigates the use of Basalt Fibre Reinforced Concrete (BFRC) combined with silica fume (SF) to enhance the mechanical properties and impact resistance of concrete. The research demonstrates that BFRC significantly improves compressive strength, split tensile strength, flexural strength, and impact resistance. Specifically, the addition of basalt fibers resulted in an improvement in compressive strength by 28% to 65%, split tensile strength by 35% to 107%, and flexural strength by

11% to 46%. Moreover, the impact resistance increased by 117% to 150%. The optimal combination of basalt fiber and silica fume resulted in a concrete mix with superior mechanical performance, highlighting both materials as eco-friendly alternatives for reinforcing concrete. Silica fume was found to improve the flexural strength and energy absorption, while increasing the basalt fiber content further enhanced the ductility of the concrete. The study also noted that BFRC-1.0 exhibited a superior loading duration before microcracks appeared, making it more durable under stress. The use of regression models provided an effective prediction of the concrete's performance, aiding in the optimization of the BFRC and SF proportions. This research supports the potential of BFRC and SF as sustainable materials for improving concrete's mechanical and impact resistance properties in construction ¹⁴.

Kaliyavaradhan et al. (2022) explored the CO₂ uptake potential of waste concrete powder (WCP) using Response Surface Methodology (RSM) to optimize the carbonation process. The study examined the effects of carbonation time and water-to-solid (w/s) ratio on CO₂ absorption. The optimal CO₂ uptake, reaching 2.81%, was achieved with a carbonation time of 90 hours and a w/s ratio of 0.4. The carbonation process also led to a decrease in pH from 11.75 to below 9, suggesting a significant chemical transformation. The actual density of WCP increased from 2.527 g/cm³ to 2.535 g/cm³ after carbonation. The regression model used in the study showed strong significance (F-value = 33.29) and good model fit, with an adjusted R² of 0.88. The experimental results closely aligned with the predicted values from the model, confirming the accuracy of the optimization process. Furthermore, the carbonated WCP demonstrated a strength activity index of over 75, indicating its potential as a supplementary cementitious material. This research highlights the promising role of WCP in contributing to both CO₂ sequestration and sustainable construction practices, offering an innovative approach for utilizing waste materials in concrete production ¹⁵.

Kareem et al. (2025) investigated the use of waste steel and tyre rubber fibers as concrete reinforcement to enhance sustainability in construction. Using Response Surface Methodology (RSM), the study optimized concrete properties and evaluated the environmental impact of modified concrete. The results demonstrated significant improvements in mechanical properties, with a 48.85% increase in 28-day compressive strength and a 28.33% increase in split tensile strength. The maximum slump observed was 25 mm, and the maximum density was 2633 kg/m³, with a water absorption rate of 5%. The study also highlighted the benefits of using a lower water-cement ratio, which improved compressive strength. While the modified concrete showed slightly higher embodied energy and cost compared to conventional concrete, it exhibited lower embodied CO₂ emissions, making it more environmentally friendly. The research suggests that incorporating waste

steel and tyre rubber fibers in concrete not only enhances its mechanical properties but also contributes to sustainable construction practices by reducing carbon emissions. Additionally, the study explored how different mix ratios influenced concrete flowability, with increased waste steel fiber volume reducing slump, while a higher water-cement ratio improved flowability. This approach aligns with global efforts to incorporate waste materials into construction, promoting eco-friendly solutions ¹⁶.

Maaze and Shrivastava (2023) focus on optimizing the design of eco-friendly bricks made from recycled concrete waste. The study investigates three independent variables: NaOH molarity, activator material ratio (AMR), and curing temperature, using Response Surface Methodology (RSM) to develop a regression model for predicting brick performance. The research identifies optimal conditions for brick production: 12 M NaOH molarity, 2.32 AMR, and a curing temperature of 50°C. These conditions significantly enhance the bricks' physical and mechanical properties. The results show a compressive strength of 13.95 MPa, flexural strength of 3.45 MPa, and water absorption of 12.32%, indicating the bricks' durability and resistance to water penetration. Additionally, drying shrinkage was minimal at 0.105%, and efflorescence was slight to moderate. Microstructural analysis reveals the presence of zeolites and calcium-silicate-hydrate gels, which contribute to the enhanced strength and durability of the bricks. The study emphasizes the potential of recycled concrete waste in producing sustainable construction materials and highlights the importance of NaOH molarity in optimizing the performance of eco-friendly bricks. This research provides valuable insights into the use of recycled concrete waste for producing sustainable, high-performance bricks, contributing to the advancement of green building practices.

Mita et al. (2023) explores the use of Crushed Stone Dust (CSD) and Nylon Fiber (NF) in producing sustainable concrete. This research demonstrates the potential of using waste materials like CSD in concrete, while also highlighting the importance of optimizing fiber reinforcement to improve mechanical properties and achieve sustainable concrete solutions ¹⁷.

Panda and Panigrahi (2024) investigated the production of sustainable Self-Compacting Geopolymer Concrete (SCGC) using Ground Granulated Blast Furnace Slag (GGBFS) and e-waste materials as partial replacements for natural aggregates. The study aims to enhance the environmental friendliness of concrete by reducing the carbon footprint and promoting e-waste management. Eleven different mix designs, including a control mix, were prepared with varying levels of e-waste replacement. The results indicated that replacing natural fine aggregates (NFA) with 30% e-waste or natural coarse aggregates (NCA) with 10% e-waste offered optimal performance in terms of workability, mechanical strength, and durability. The SCGC mixes exhibited improved

chemical resistance compared to the control mixes, with higher e-waste content enhancing the concrete's resistance to acid attack. The study also examined the fresh concrete properties such as flow, passing ability, and segregation resistance, confirming that SCGC with e-waste replacements maintained favorable workability. Additionally, the incorporation of e-waste showed minimal loss in mass and strength during durability tests. This research highlights the potential of SCGC as a sustainable alternative to conventional concrete, offering a solution for both waste management and the reduction of environmental impact in the construction industry ¹⁸⁾.

Patil et al. (2024) evaluated sisal fiber-reinforced fly ash concrete, focusing on sustainable construction materials suitable for tropical regions. The study also explored the role of laterite as an aggregate to enhance concrete strength, employing Response Surface Methodology (RSM) for optimization. The results demonstrated that sisal fibers significantly enhanced tensile strength, with the optimal mix comprising 25% laterite, 10.52% fly ash, and 1% sisal fiber. This mix achieved a compressive strength of 47.35 MPa, split tensile strength of 4.76 MPa, and flexural strength of 5.19 MPa after 28 days of curing. The compressive strength model showed an R^2 value of 0.9893, indicating a high degree of accuracy in the predictions, and a significant F-value further confirmed the model's reliability. However, the workability of the concrete decreased as the proportion of laterite aggregate increased, and a similar reduction in workability was observed with higher sisal fiber content. Overall, the study highlighted the potential of using locally available materials like sisal fiber and laterite for producing sustainable, high-performance concrete, especially in tropical climates, offering a promising alternative for eco-friendly construction practices ¹⁹⁾.

Patil et al. (2024) focuses on optimizing the rheological and mechanical properties of sustainable lateritic self-compacting concrete (LSCC) using Response Surface Methodology (RSM). Thirteen different mixes were tested, with six responses evaluated, including rheological and strength characteristics. The study found that the optimal mix was achieved with 0.76% sisal fiber (SF) and 26.8% laterite (LA). The multi-objective optimization model provided accurate predictions of the concrete's fresh and hardened properties, with experimental validation showing less than 5% error. The optimized LSCC mix exhibited a viscosity time (VT) of 9.06 seconds, a T500 time of 2.26 seconds, and a slump flow (SF) of 795.63 mm for fresh properties. For hardened properties, the optimized mix showed compressive strength (CS) of 49.24 MPa, flexural strength (FS) of 5.21 MPa, and split tensile strength (STS) of 4.54 MPa, closely matching the experimental results. The research highlights that the addition of 26.8% laterite and 0.76% sisal fiber significantly improved the material's performance, achieving both strong rheological and mechanical characteristics. The results also indicated a

strong correlation between compressive and flexural strengths, making LSCC an effective and sustainable construction material with optimized properties for improved performance and durability ²⁰⁾.

Peng et al. (2023) investigated the use of steel-waste PET hybrid fibers in recycled aggregate concrete (RAC), aiming to improve its mechanical properties while offering a more sustainable alternative. The study employed hybrid fiber reinforced concrete (HFRAC) with varying fiber contents to analyze their effects on concrete properties. Response Surface Methodology (RSM) was used to examine the interactions between fiber content and performance indices. The results indicated that while workability decreased with increased fiber content, the mechanical strength of the concrete improved. Specifically, the inclusion of steel fibers increased compressive and flexural strengths, though the addition of PET fibers reduced flexural strength when they replaced steel fibers. Notably, the compressive strength remained largely unaffected by PET fiber content alone, suggesting that steel fibers were more impactful in enhancing mechanical properties. The optimal fiber contents, predicted by RSM, yielded the highest strength indices. This study highlights the potential of hybrid fibers, particularly steel-waste PET, as a sustainable and cost-effective reinforcement material for concrete, improving both its mechanical properties and environmental performance. The findings suggest that these hybrid fibers could offer an eco-friendly alternative to traditional reinforcement materials while maintaining or enhancing the structural integrity of concrete ²¹⁾.

Raveendran and Vasugi (2024) explored the synergistic effects of Nano Silica (NS) and Metakaolin (MK) on the mechanical properties of concrete, using Response Surface Methodology (RSM) to optimize the mix design. The study focused on the enhancement of compressive and split tensile strengths with varying proportions of NS and MK. The optimal mix was identified as 2% NS and 12.5% MK with a Water-to-Binder Ratio (WBR) of 0.4. Significant improvements in concrete strength were observed, with compressive strength increasing by 35.75% and split tensile strength improving by 26.56% on the 7th day of hydration. The study also highlighted that these enhancements continued over 90 days of hydration, with microstructural analysis revealing a dense structure and early hydration effects. The RSM technique demonstrated high predictive accuracy, with less than 5% mean error, confirming the validity of the optimization model. The results indicate that NS and MK significantly improve the mechanical properties of concrete, making it suitable for high-strength applications and promoting sustainable construction practices. This research provides valuable insights into how NS and MK can be combined to enhance concrete performance, contributing to more efficient and sustainable construction materials ²²⁾.

Ray et al. (2023) compare the performance of Artificial Neural Networks (ANN) and Response Surface Methodology

(RSM) in predicting concrete strength, focusing on the use of glass waste and tin can fiber as partial replacements in concrete mixes. The study evaluates compressive and splitting tensile strength at different curing ages, showing that both variables significantly affect the concrete's performance. Results indicate that the addition of glass fiber aggregate (GFA) and cellulose micro-fiber (CMCF) enhances the compressive strength, with peak strength achieved at 20% GFA and 1% CMCF. However, the splitting tensile strength decreased with higher levels of GFA and CMCF, reaching its maximum at 10% GFA and 0.5% CMCF. The study highlights that RSM models provided more accurate predictions of concrete strength than ANN models. Statistical analysis ($p < 0.01$) confirmed the significance of the models, further reinforcing RSM's superiority in this context. This research offers valuable insights into the use of waste materials in concrete and emphasizes the importance of selecting appropriate predictive models for optimizing concrete mix designs. Additionally, the study underscores the potential of using waste-derived materials in sustainable construction while improving concrete's mechanical properties ²³.

Sinkhonde (2022) focused on sustainable construction by utilizing waste materials, specifically waste clay brick powder (WCBP) and waste tire rubber (WTR), to optimize concrete properties and reduce CO₂ emissions. The study employed Response Surface Methodology (RSM) and central composite design to model the effects of these waste materials on concrete's properties, including CO₂ emissions, dry density, and compressive strength. The results indicated that the incorporation of waste materials significantly reduced CO₂ emissions without adversely affecting the mechanical properties of the concrete. The optimum mix design was identified with 5% WCBP and 0% WTR, where the waste materials showed a linear relationship with both wet and dry densities. The compressive strength was evaluated at both 7 and 28 days of curing, with high R² values (over 0.8) indicating the model's accuracy in predicting the concrete's response. Notably, WCBP had a lesser influence on dry density compared to WTR, and the linear models effectively predicted the concrete's performance. Overall, the study highlighted that the inclusion of waste materials not only improves concrete properties but also offers a sustainable solution to reduce CO₂ emissions in the construction industry, emphasizing the potential for eco-friendly concrete mixtures in reducing the environmental impact of construction activities ²⁴.

Sinkhonde et al. (2021) conducted a study on the optimization of cost and compressive strength of modified concrete using waste materials, specifically Burnt Clay Brick Powder (BCBP) and Waste Tire Rubber (WTR). The aim was to balance cost reduction with enhanced performance, using Response Surface Methodology (RSM) to determine the optimal contents for both strength and cost efficiency. The results showed that substituting BCBP for Ordinary Portland

Cement and WTR for natural coarse aggregates led to a significant reduction in production costs—up to 4.23% lower than conventional concrete. The study identified the optimal mix for compressive strength, achieving a maximum 7-day compressive strength of 27.607 MPa and a 28-day strength of 33.970 MPa. These strengths were reached with 5% BCBP and 6.875% WTR for 7 days, and 5% BCBP and 5.844% WTR for 28 days. The models developed in the study explained the variability of the results with coefficients of determination greater than 0.85, indicating strong model reliability. Experimental testing of six cubic samples confirmed the accuracy of the model's predictions. This research highlights the potential for using waste materials in concrete production, offering an eco-friendly and cost-effective alternative to traditional concrete ²⁵.

To-On et al. (2023) introduced a novel optimization approach combining the TOPSIS linear programming model with Response Surface Methodology (RSM) to improve the properties of lightweight concrete using sugarcane bagasse ash (SBA). The study aimed to enhance key concrete properties, including compressive strength, dry density, and water absorption, through the optimization of the mixture ratio. Experimental results demonstrated significant improvements in the concrete's performance, with compressive strength increasing by 7.22%, dry density rising by 9.19%, and water absorption decreasing by 16.83%. The optimal mixture ratio was determined to be 6:1:0.05 (SBA to cement to water by weight). The research also employed regression models for predicting concrete behavior, developed using Minitab software, which further validated the optimization process. This study contributes to sustainable construction materials by incorporating waste materials like SBA, offering both environmental and practical benefits in concrete production. The TOPSIS linear programming model, combined with RSM, proved effective in optimizing concrete properties and could be applied to other material optimization challenges, advancing both material performance and waste recycling solutions in the construction industry ²⁶.

Waghe et al. (2023) explored the potential of enhancing eco-concrete performance through the synergistic integration of sugarcane bagasse ash (SCBA), metakaolin (MK), and crumb rubber (CR) as alternative materials in concrete. The study aimed to reduce the carbon footprint of construction by incorporating industrial wastes and agricultural by-products. The research focused on evaluating the density, workability, and strength properties of the resulting eco-concrete. The results demonstrated that the integration of SCBA, MK, and CR significantly improved the compressive, flexural, and splitting tensile strengths compared to control concrete. Specifically, the compressive strength reached 45.44 MPa, and the flexural strength achieved 4.758 MPa with the optimal mix. The study also found that density decreased with the inclusion of crumb rubber, while workability was positively impacted by SCBA but negatively

affected by MK. The optimal mix, composed of 10% MK, SCBA, and CR, yielded the best performance. Response Surface Methodology (RSM) was employed for optimization, and the analysis showed a strong correlation with experimental results, further validated by ANOVA, which confirmed significant differences in the strength properties. The findings suggest that the combination of SCBA, MK, and CR offers a promising, sustainable approach to improving concrete performance²⁷⁾.

Waqar et al. (2023) explore the use of Coir Fibre Ash (CFA) as a supplementary cementitious material to reduce the environmental impact of concrete. The study investigates the effects of CFA on concrete's compressive, flexural, and tensile strengths, as well as its modulus of elasticity. CFA was tested at varying percentages from 3% to 18%, with a focus on optimizing its incorporation to enhance concrete properties. The research demonstrates that the addition of CFA up to 9% improves compressive strength, with the highest recorded strength of 35.89 MPa at this level. Similarly, both flexural and splitting tensile strengths showed positive results with CFA incorporation. The modulus of elasticity was also enhanced up to the 9% CFA threshold. Notably, the study highlights that increasing CFA content leads to a reduction in embodied carbon, making the concrete more sustainable. The research utilizes Response Surface Methodology (RSM) to develop predictive models for the concrete properties, which were validated with experimental data showing less than a 5% margin of error. Overall, this study provides valuable insights into CFA's potential as a sustainable alternative to conventional cement, contributing to both improved concrete performance and a reduction in environmental impact²⁸⁾.

3. CONCLUSIONS

The growing environmental concerns associated with traditional concrete production—particularly due to high CO₂ emissions and the depletion of natural resources—have intensified the need for sustainable alternatives. This study comprehensively reviewed the potential of industrial and agricultural byproducts such as Iron Ore Sludge, Fly Ash, GGBFS, Brick and Mortar Waste, and Ceramic Waste as partial replacements for cement, fine aggregates, and coarse aggregates in concrete. These materials not only mitigate waste disposal issues but also enhance key properties of concrete, including strength, durability, and workability. The incorporation of supplementary cementitious materials (SCMs), recycled aggregates, and fiber reinforcements has been shown across multiple studies to improve mechanical performance while supporting environmental sustainability. Response Surface Methodology (RSM) and advanced machine learning techniques have proven instrumental in optimizing mix designs and predicting concrete properties with high accuracy. However, challenges remain in standardizing mix proportions, ensuring long-term durability, and addressing variability in byproduct quality.

Future work should focus on developing composite mixes that exploit the synergistic effects of multiple waste materials, refining predictive modeling techniques, and promoting real-world application through policy support and industry collaboration. Overall, integrating waste-based materials into concrete production is a promising step toward greener and more resilient construction practices.

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