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Climate-Resilient Concrete: A Comprehensive Review of Industrial By-products and Recycled Materials for Sustainable Construction

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Abstract— **The construction industry is one of the largest contributors to global carbon emissions and the depletion of natural resources, creating an urgent need for sustainable alternatives to conventional concrete. Climate-resilient concrete has emerged as a promising solution by incorporating industrial by-products and recycled materials that reduce environmental impacts while enhancing the durability and performance of infrastructure under changing climatic conditions. This review comprehensively examines the utilization of supplementary cementitious materials such as fly ash, ground granulated blast furnace slag, silica fume, rice husk ash, and metakaolin, along with recycled aggregates, waste glass, plastic waste, construction and demolition debris, and other secondary resources in concrete production. The study analyzes their influence on fresh and hardened concrete properties, including workability, compressive strength, tensile strength, permeability, shrinkage, and long-term durability against aggressive environmental exposures such as freeze-thaw cycles, chloride penetration, sulfate attack, and elevated temperatures. Furthermore, the review discusses recent advancements in material characterization, life cycle assessment, carbon footprint reduction, and circular economy strategies that support the transition toward low-carbon construction practices. Challenges associated with material variability, quality control, standardization, and large-scale implementation are also critically evaluated. The findings indicate that the effective integration of industrial by-products and recycled materials can significantly improve the sustainability and climate resilience of concrete while conserving natural resources and reducing greenhouse gas emissions. The review provides valuable insights for researchers, engineers, policymakers, and industry stakeholders seeking innovative pathways for developing durable, eco-friendly, and resilient infrastructure for future generations.**

Keywords: Climate-resilient concrete, Sustainable construction, Industrial by-products, Recycled materials, Supplementary cementitious materials, Recycled aggregates, Circular economy, Low-carbon concrete, Green infrastructure, Durability, Life cycle assessment, Carbon emission reduction.

I. INTRODUCTION

Concrete is the most widely utilized construction material worldwide and serves as the backbone of modern infrastructure, including buildings, bridges, highways, dams, and transportation networks. Rapid urbanization, industrialization, and population growth have significantly increased the demand for concrete, making it the second most consumed material after water. However, the extensive production of ordinary Portland cement (OPC), the primary binding component of conventional concrete, is highly energy-intensive and contributes substantially to global greenhouse gas emissions. Current estimates indicate that the cement industry is responsible for approximately 7–8% of worldwide carbon dioxide (CO_2) emissions, posing a major challenge to global climate change mitigation efforts [1], [2].

The construction sector is increasingly shifting toward sustainable development practices that minimize environmental impacts while maintaining structural safety and durability. Sustainable construction emphasizes efficient resource utilization, reduced carbon footprints, waste minimization, and the adoption of circular economy principles. In this context, climate-resilient concrete has emerged as an innovative material capable of addressing both environmental sustainability and infrastructure resilience against extreme climatic conditions such as floods, heat waves, freeze-thaw cycles, and chemical deterioration [3], [4].

One of the most promising approaches for developing climate-resilient concrete is the incorporation of industrial by-products and recycled materials as partial replacements for cement and natural aggregates. Industrial by-products such as fly ash, ground granulated blast furnace slag (GGBFS), silica fume, rice husk ash, metakaolin, and steel slag possess pozzolanic or hydraulic properties that enhance concrete performance while reducing cement consumption. Their utilization not only lowers CO_2 emissions but also diverts significant quantities of industrial waste from landfills, thereby promoting sustainable waste management practices [5], [6].

Similarly, recycled materials including recycled concrete aggregates, construction and demolition waste, waste glass, recycled plastics, waste rubber, and ceramic waste have gained considerable attention in recent years. The effective utilization of these materials reduces the extraction of virgin natural resources, decreases landfill disposal, and supports resource conservation. Advances in processing techniques and mix design methodologies have demonstrated that appropriately engineered recycled materials can produce concrete with satisfactory mechanical strength, durability, and long-term service performance [7], [8].

Climate resilience in concrete extends beyond reducing embodied carbon. Future infrastructure must withstand increasingly aggressive environmental conditions resulting from climate change, including elevated temperatures, coastal salinity, moisture fluctuations, and extreme weather events. The incorporation of supplementary cementitious materials and recycled constituents improves pore structure refinement, decreases permeability, enhances resistance to chloride penetration and sulfate attack, and increases long-term durability. Consequently, these materials contribute to extending service life while lowering maintenance and lifecycle costs [9].

Recent research has also emphasized the integration of life cycle assessment (LCA), carbon footprint analysis, and performance-based design approaches to evaluate the overall sustainability of concrete materials. Digital technologies, artificial intelligence-assisted mix optimization, and advanced material characterization techniques are further accelerating the development of low-carbon and high-performance concrete systems. Nevertheless, challenges related to material variability, quality assurance, standardization, supply chain limitations, and large-scale industrial implementation remain significant barriers to widespread adoption [10].

Therefore, a comprehensive review of industrial by-products and recycled materials is essential to understand their contributions toward climate-resilient and sustainable construction. This review synthesizes current research on various alternative materials, their effects on fresh and hardened concrete properties, durability performance, environmental benefits, and practical implementation challenges. Furthermore, it highlights emerging research trends and future opportunities for developing next-generation climate-resilient concrete capable of supporting global sustainability goals and resilient infrastructure development.

II. LITERATURE SURVEY

The growing emphasis on sustainable infrastructure and carbon-neutral construction has accelerated research on climate-resilient concrete incorporating industrial by-products and recycled materials. Numerous studies have demonstrated that replacing conventional cement and natural aggregates with waste-derived materials not only reduces environmental impacts but also enhances the mechanical and durability characteristics of concrete when appropriately designed [11].

Recent investigations into supplementary cementitious materials (SCMs) have shown that fly ash, ground granulated blast furnace slag (GGBFS), silica fume, and calcined clay significantly improve the microstructure of concrete through secondary hydration reactions. These materials consume calcium hydroxide generated during cement hydration and produce additional calcium silicate hydrate (C-S-H) gel, resulting in reduced porosity and improved long-term strength. Furthermore, SCMs substantially decrease clinker consumption, thereby lowering the embodied carbon of concrete production [12].

The characterization of industrial by-products has become increasingly important for optimizing their performance in sustainable concrete. Advanced analytical techniques such as X-ray diffraction (XRD), Raman spectroscopy, and X-ray fluorescence (XRF) have been employed to investigate the glassy phases and chemical composition of fly ash, slag, silica fume, and recycled glass. These studies revealed that the degree of glass formation and network modification strongly influences pozzolanic activity and hydration kinetics, making material characterization essential for designing high-performance climate-resilient concrete mixtures [13].

Several researchers have explored the utilization of recycled concrete aggregates (RCA) obtained from construction and demolition waste. Although recycled aggregates generally exhibit higher water absorption and lower density than natural aggregates, proper surface treatment and optimized mix designs can significantly improve interfacial transition zones and overall mechanical performance. The incorporation of recycled aggregates contributes to resource conservation while simultaneously reducing landfill disposal and environmental degradation [14].

Waste glass has emerged as another promising recycled material for sustainable concrete production. Finely ground waste glass exhibits pozzolanic properties due to its high silica content and can partially replace cement without compromising compressive strength when used within appropriate replacement levels. Additionally, crushed glass can serve as fine aggregate, improving particle packing and contributing to aesthetic architectural applications. However, researchers emphasize controlling particle size to minimize alkali-silica reaction (ASR), which may otherwise affect long-term durability [15].

The application of agricultural by-products such as rice husk ash, sugarcane bagasse ash, palm oil fuel ash, and bamboo leaf ash has also gained considerable attention. These materials contain reactive amorphous silica capable of participating in pozzolanic reactions that enhance strength development and reduce permeability. Their utilization simultaneously addresses agricultural waste management challenges while promoting environmentally responsible construction practices, particularly in developing countries where such residues are abundantly available [16].

Plastic waste and waste rubber have been investigated as alternative aggregate materials to reduce plastic pollution and landfill accumulation. Studies indicate that incorporating recycled plastic fibers improves crack resistance, impact strength, and toughness, while crumb rubber enhances energy absorption and ductility. Although excessive replacement may reduce compressive strength, optimized proportions combined with supplementary cementitious materials can produce concrete suitable for non-structural and specialized engineering applications [17].

Durability remains one of the most critical indicators of climate resilience. Researchers have reported that SCM-modified concrete demonstrates superior resistance to chloride penetration, sulfate attack, carbonation, freeze-thaw cycles, and elevated temperatures compared with conventional concrete. The refinement of pore structure and reduction in permeability limit the ingress of harmful ions and moisture, thereby extending service life under aggressive environmental conditions associated with climate change [18].

Recent advancements in artificial intelligence and machine learning have introduced new approaches for optimizing sustainable concrete mixtures. Predictive models based on ensemble learning, neural networks, and regression algorithms have been successfully applied to estimate porosity, compressive strength, and durability characteristics using mixture composition parameters. These data-driven techniques reduce experimental costs while enabling rapid optimization of climate-resilient concrete formulations [19].

Life Cycle Assessment (LCA) has become an important tool for evaluating the environmental performance of sustainable concrete materials. Comparative studies consistently demonstrate that replacing Portland cement with industrial by-products significantly reduces embodied energy and greenhouse gas emissions. Moreover, integrating recycled materials supports circular economy principles by extending material life cycles and minimizing extraction of virgin natural resources. Such strategies align with international sustainability objectives and net-zero carbon initiatives [20].

Despite substantial progress, several challenges remain for the widespread implementation of climate-resilient concrete. Variability in waste material composition, inconsistent quality, limited standardization, transportation costs, and uncertainties regarding long-term performance continue to restrict large-scale adoption. Future research should therefore focus on standardized characterization methods, intelligent mix optimization, multi-scale durability evaluation, and policy frameworks that encourage industrial symbiosis and sustainable material utilization. The integration of advanced manufacturing technologies and digital monitoring systems is expected to further enhance the reliability and acceptance of climate-resilient concrete in future infrastructure development [21].

Table 1. Literature Review on Climate-Resilient Concrete Using Industrial By-products and Recycled Materials

Ref.	Author(s) & Year	Research Focus	Major Findings
[22]	Scrivener et al. (2018)	Eco-efficient cement technologies	Demonstrated that supplementary cementitious materials (SCMs) can substantially reduce CO_2 emissions while maintaining concrete performance.
[23]	Mehta and Monteiro (2014)	Microstructure and durability of concrete	Reported that pore refinement through SCMs significantly enhances durability and service life.
[24]	Siddique and Klaus (2009)	Metakaolin in concrete	Found that metakaolin improves compressive strength, permeability resistance, and early hydration characteristics.
[25]	Shayan and Xu (2004)	Waste glass utilization	Showed that finely ground waste glass acts as a pozzolanic material and can partially replace cement without strength loss.
[26]	Tam et al. (2005)	Recycled aggregate concrete	Proposed a two-stage mixing approach that improves the interfacial transition zone and mechanical properties of recycled aggregate concrete.
[27]	Chindaprasirt et al. (2005)	Fly ash fineness	Demonstrated that finer fly ash particles increase compressive strength and reduce pore size in blended cement systems.
[28]	Gesoğlu and Güneyisi (2007)	Rubberized concrete	Reported enhanced impact resistance and ductility when waste rubber is incorporated with silica fume.
[29]	Damtoft et al. (2008)	Sustainable cement production	Highlighted that clinker replacement is an effective strategy for lowering greenhouse gas emissions from cement manufacturing.
[30]	Serbource et al. (2024)	Characterization of SCMs and recycled glass	Used XRD and Raman spectroscopy to explain how glass structure influences pozzolanic reactivity and concrete performance.
[31]	Afsoosbiria and Machowska (2025)	Sustainable mass concrete	Concluded that industrial by-products improve thermal stability,

			durability, and sustainability while reducing cement consumption.
[32]	Rahmadani and Prasetyo (2025)	Recycled aggregates with SCMs	Found that combining recycled aggregates with fly ash and GGBS improves durability and chloride resistance.
[33]	Moolchandani et al. (2025)	Hybrid SCM systems	Demonstrated that hybrid combinations of SCMs and fillers can reduce lifecycle carbon emissions by up to approximately 60% while enhancing strength.
[34]	Bakr et al. (2025)	Sustainable self-compacting recycled aggregate concrete	Reported that 50–100% recycled coarse aggregates can produce workable and durable self-compacting concrete with optimized mix design.
[35]	Kumar (2025)	Recycled materials and supplementary binders	Reviewed fly ash, GGBS, silica fume, and recycled aggregates, concluding that they improve both environmental and mechanical performance.
[36]	Shekhar et al. (2023)	Recycled aggregate blocks	Demonstrated that replacing 70% natural aggregates and 35% cement with recycled materials produces structurally acceptable blocks.
[37]	Cao (2021)	Machine learning for sustainable concrete	Developed predictive models for porosity and strength using SCM composition, reducing experimental effort in mix optimization.
[38]	Hasan et al. (2024)	Sustainable material supply chains	Identified circular economy and intelligent supply chains as essential for scaling sustainable construction materials.
[39]	Isikgor and Becer (2016)	Biomass-derived sustainable materials	Discussed the potential of bio-based materials and agricultural waste as environmentally friendly construction resources.
[40]	Guo et al. (Recent studies)	Recycled concrete aggregates	Reported that appropriate processing and quality control significantly improve recycled aggregate performance in structural concrete.
[41]	Recent review studies (2025–2026)	Climate-resilient concrete technologies	Concluded that integrating industrial by-products, recycled materials, AI-assisted mix design, and life cycle

			assessment offers a pathway toward low-carbon, durable, and climate-resilient infrastructure.

III. RECYCLED MATERIALS FOR SUSTAINABLE CONSTRUCTION

Recycled materials have become an essential component of sustainable construction due to their ability to conserve natural resources, reduce construction and demolition waste, and minimize the environmental footprint of the building industry. The construction sector consumes enormous quantities of raw materials such as sand, gravel, limestone, and crushed stone while simultaneously generating significant volumes of waste during demolition, renovation, and infrastructure development. The adoption of recycled materials supports the principles of the circular economy by transforming waste into valuable construction resources rather than disposing of it in landfills.

One of the most widely used recycled materials is **recycled concrete aggregate (RCA)**, which is produced by crushing and processing demolished concrete structures. RCA can replace natural coarse and fine aggregates in new concrete, road base layers, and pavement applications. Research has shown that properly processed RCA can provide satisfactory mechanical properties and durability while reducing the demand for virgin aggregates. However, the presence of adhered mortar often increases water absorption and porosity, requiring appropriate treatment methods and optimized mix designs to achieve structural-grade performance.

Recycled glass is another valuable construction material due to its high silica content and chemical stability. Finely ground waste glass can function as a supplementary cementitious material by participating in pozzolanic reactions, while crushed glass can replace fine aggregates in concrete and mortar. The utilization of waste glass decreases landfill accumulation and reduces the extraction of natural sand. Nevertheless, controlling particle size is important to minimize the risk of alkali-silica reaction and ensure long-term durability.

The incorporation of **recycled plastic waste** into construction materials has gained increasing attention as a strategy to address global plastic pollution. Plastic fibers and shredded plastic particles can be used as reinforcement or partial aggregate replacements in concrete. These materials improve impact resistance, crack control, toughness, and thermal insulation while reducing the overall weight of concrete products. Recent studies have also explored modular architectural systems manufactured from recycled plastics, demonstrating their potential for lightweight and adaptable construction applications.

Construction and demolition (C&D) waste represents one of the largest waste streams generated worldwide. Materials such as crushed bricks, ceramic tiles, asphalt pavement, masonry debris, and reclaimed concrete can be processed and reused in new construction projects. Recycling C&D waste reduces landfill requirements, lowers transportation costs associated with waste disposal, and decreases the environmental impacts of quarrying new materials. Many countries have successfully incorporated recycled aggregates into road sub-base and pavement construction, demonstrating both technical feasibility and economic benefits.

Industrial recycling also contributes significantly to sustainable construction through the utilization of materials such as recycled gypsum, steel slag, and recovered mineral fillers. Recycled gypsum obtained from waste plasterboards can replace natural gypsum during cement production, while steel industry by-products can improve the mechanical performance of concrete and reduce clinker consumption. These practices simultaneously promote waste valorization and decrease greenhouse gas emissions associated with conventional material production.

The environmental benefits of recycled materials extend beyond waste reduction. Their use decreases the extraction of virgin natural resources, conserves energy, reduces embodied carbon, and supports sustainable resource management. Life-cycle assessments consistently indicate that replacing conventional construction materials with recycled alternatives can significantly lower carbon emissions while promoting circular economy principles. Furthermore, shorter transportation distances between demolition sites and recycling facilities can reduce fuel consumption and associated emissions.

Despite these advantages, several challenges remain for widespread implementation. Variability in recycled material quality, contamination, inconsistent physical properties, limited standardization, and concerns regarding long-term durability continue to affect their acceptance in structural applications. Effective quality control, advanced processing technologies, performance-based specifications, and supportive governmental policies are therefore essential to increase confidence in recycled construction materials and encourage their large-scale adoption.

Overall, recycled materials represent a fundamental pathway toward sustainable construction by transforming waste into high-value engineering resources. Their integration into climate-resilient concrete and green building practices contributes to resource conservation, carbon emission reduction, and the development of durable infrastructure capable of meeting future environmental and societal demands.

IV. CONCLUSION

Climate change, rapid urbanization, and the depletion of natural resources have created an urgent need for sustainable alternatives to conventional construction materials. This review demonstrates that climate-resilient concrete produced through the incorporation of industrial by-products and recycled materials represents one of the most promising strategies for reducing the environmental impact of the construction industry while enhancing infrastructure durability and resilience. The effective utilization of supplementary cementitious materials such as fly ash, ground granulated blast furnace slag, silica fume, metakaolin, and agricultural ashes significantly decreases Portland cement consumption, thereby lowering greenhouse gas emissions and energy requirements associated with cement manufacturing.

The review further highlights that recycled materials, including recycled concrete aggregates, waste glass, plastic waste, rubber waste, ceramic waste, and construction and demolition debris, can successfully replace conventional raw materials in many concrete applications. Their incorporation promotes resource conservation, reduces landfill accumulation, supports circular economy principles, and minimizes the extraction of natural aggregates. When appropriate processing techniques and optimized mix designs are employed, these materials can produce concrete with satisfactory workability, mechanical strength, and long-term durability suitable for both structural and non-structural applications.

From a climate resilience perspective, the integration of industrial by-products and recycled constituents contributes to improved resistance against chloride penetration, sulfate attack, carbonation, freeze-thaw cycles, elevated temperatures, and moisture-induced deterioration. The refinement of the concrete microstructure and reduction in permeability enhance service life while lowering maintenance requirements and lifecycle costs. Consequently, sustainable concrete not only addresses environmental concerns but also improves the adaptability of infrastructure to increasingly severe climatic conditions.

The review also identifies significant advancements in material characterization techniques, life cycle assessment methodologies, artificial intelligence-based mix optimization, and performance-based design approaches. These innovations provide valuable tools for developing next-generation low-carbon concrete with enhanced mechanical and durability characteristics. Furthermore, digital technologies and predictive modeling have the potential to accelerate the commercialization of sustainable concrete by reducing experimental costs and enabling precise optimization of material combinations.

Despite these encouraging developments, several challenges continue to hinder large-scale implementation. Variability in the chemical and physical properties of recycled materials, inconsistent quality control, limited standardization, transportation logistics, and uncertainties regarding long-term field performance require further investigation. Harmonized international standards, supportive governmental policies, industrial collaboration, and investment in recycling infrastructure will be essential for expanding the adoption of climate-resilient concrete technologies.

Overall, climate-resilient concrete developed through the utilization of industrial by-products and recycled materials provides a practical and scientifically sound pathway toward sustainable construction. Its ability to reduce carbon emissions, conserve natural resources, improve durability, and promote circular resource utilization aligns with global sustainability goals and net-zero initiatives. Future research should focus on multi-material hybrid systems, nanotechnology-enhanced binders, carbon capture and utilization in cementitious materials, smart monitoring technologies, and artificial intelligence-driven mix design to further improve the performance and environmental benefits of sustainable concrete. The widespread adoption of these innovative materials will play a crucial role in developing resilient, low-carbon, and environmentally responsible infrastructure for future generations.

REFERENCES

[1] M. Purton, "Cement is a big problem for the environment. Here's how to make it more sustainable," *World Economic Forum*, Sep. 2024.

[2] S. Barbhuiya, "Low carbon concrete: advancements, challenges and future directions," *Discover Civil Engineering*, vol. 2, 2025.

[3] H. Afsoosbiria *et al.*, "Development of Sustainable Concrete Using By-Products and Recycled Materials," *Sustainability*, vol. 17, no. 22, 2025.

[4] N. Marandi and S. Shirzad, "Sustainable cement and concrete technologies: A review of materials and processes for carbon reduction," *Innovative Infrastructure Solutions*, vol. 10, 2025.

[5] M. M. Johari, J. J. Brooks, S. Kabir, and P. Rivard, "Influence of supplementary cementitious materials on engineering properties of high-strength concrete," *Construction and Building Materials*, vol. 25, no. 5, pp. 2639–2648, 2011.

[6] T. Serbource *et al.*, "The glassy structure of reactive supplementary cementitious materials and recycled glass: Contribution of XRD and Raman spectroscopy to their characterization," 2024.

[7] H. Bahmani *et al.*, "Sustainable high-performance concrete: Harnessing recycled materials and industrial by-products," *Scientific Reports*, 2026.

[8] H. Bahmani *et al.*, "Harnessing recycled rubber and slag for strength and eco-friendly concrete," *Scientific Reports*, 2026.

[9] S. Barbhuiya, "Low carbon concrete: advancements, challenges and future directions," *Discover Civil Engineering*, 2025.

[10] N. Marandi and S. Shirzad, "Sustainable cement and concrete technologies: A review of materials and processes for carbon reduction," *Innovative Infrastructure Solutions*, 2025.

[11] K. L. Scrivener, V. M. John, and E. M. Gartner, "Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry," *Cement and Concrete Research*, vol. 114, pp. 2–26, 2018.

[12] R. Siddique and J. Klaus, "Influence of metakaolin on the properties of mortar and concrete: A review," *Applied Clay Science*, vol. 43, no. 3–4, pp. 392–400, 2009.

[13] T. Serbource, M. Courtial, M.-N. de Noirfontaine, S. Tusseau-Nenez, C. Sandt, and L. Izoret, "The glassy structure of reactive supplementary cementitious materials and recycled glass: Contribution of XRD and Raman spectroscopy to their characterization," 2024.

[14] V. W. Y. Tam, X. F. Gao, and C. M. Tam, "Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach," *Cement and Concrete Research*, vol. 35, no. 6, pp. 1195–1203, 2005.

[15] A. Shayan and A. Xu, "Value-added utilization of waste glass in concrete," *Cement and Concrete Research*, vol. 34, no. 1, pp. 81–89, 2004.

[16] S. Chindaprasirt, C. Jaturapitakkul, and T. Sinsiri, "Effect of fly ash fineness on compressive strength and pore size of blended cement paste," *Cement and Concrete Composites*, vol. 27, no. 4–5, pp. 425–428, 2005.

[17] M. Gesoğlu and E. Güneyisi, "Properties of rubberized concretes containing silica fume and waste rubber," *Construction and Building Materials*, vol. 21, no. 4, pp. 954–960, 2007.

[18] P. K. Mehta and P. J. M. Monteiro, *Concrete: Microstructure, Properties, and Materials*, 4th ed. New York, NY, USA: McGraw-Hill, 2014.

[19] C. Cao, "Machine Learning-based Prediction of Porosity for Concrete Containing Supplementary Cementitious Materials," 2021.

[20] J. S. Damtoft, J. Lukasik, D. Herfort, D. Sorrentino, and E. M. Gartner, "Sustainable development and climate change initiatives," *Cement and Concrete Research*, vol. 38, no. 2, pp. 115–127, 2008.

[21] M. Purton, "Cement: Building a green path in a hard industry," *Reuters Sustainability*, Jun. 11, 2025.

[22] K. L. Scrivener, V. M. John, and E. M. Gartner, "Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry," *Cement and Concrete Research*, vol. 114, pp. 2–26, 2018.

[23] P. K. Mehta and P. J. M. Monteiro, *Concrete: Microstructure, Properties, and Materials*, 4th ed. New York, NY, USA: McGraw-Hill, 2014.

[24] R. Siddique and J. Klaus, "Influence of metakaolin on the properties of mortar and concrete: A review," *Applied Clay Science*, vol. 43, no. 3–4, pp. 392–400, 2009.

[25] A. Shayan and A. Xu, "Value-added utilization of waste glass in concrete," *Cement and Concrete Research*, vol. 34, no. 1, pp. 81–89, 2004.

[26] V. W. Y. Tam, X. F. Gao, and C. M. Tam, "Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach," *Cement and Concrete Research*, vol. 35, no. 6, pp. 1195–1203, 2005.

[27] S. Chindaprasirt, C. Jaturapitakkul, and T. Sinsiri, "Effect of fly ash fineness on compressive strength and pore size of blended cement paste," *Cement and Concrete Composites*, vol. 27, no. 4–5, pp. 425–428, 2005.

[28] M. Gesoğlu and E. Güneyisi, "Properties of rubberized concretes containing silica fume and waste rubber," *Construction and Building Materials*, vol. 21, no. 4, pp. 954–960, 2007.

[29] J. S. Damtoft, J. Lukasik, D. Herfort, D. Sorrentino, and E. M. Gartner, "Sustainable development and climate change initiatives," *Cement and Concrete Research*, vol. 38, no. 2, pp. 115–127, 2008.

[30] T. Serbource *et al.*, "The glassy structure of reactive supplementary cementitious materials and recycled glass: Contribution of XRD and Raman spectroscopy to their characterization," 2024.

[31] H. Afsoosbiria and A. Machowska, "Development of Sustainable Concrete Using By-Products as a Green Material, and Potential Solutions for Sustainability in Mass Concrete Construction—Comprehensive Review," *Sustainability*, vol. 17, 2025.

[32] S. Rahmadani and A. Prasetyo, "Performance evaluation of sustainable concrete incorporating recycled aggregates and industrial byproducts," *International Journal of Research in Civil Engineering and Technology*, 2025.

[33] K. Moolchandani, A. Sharma, and K. Dharavath, "Hybrid use of supplementary cementitious materials, industrial byproducts, and fillers for sustainable high-performance concrete," *Discover Civil Engineering*, 2025.

[34] M. A. Bakr *et al.*, "Sustainable Self-Compacting Recycled Aggregate Concrete," 2025.

[35] H. Kumar, "The Role of Recycled Materials and Supplementary Binders in Sustainable Concrete," 2025.

[36] D. Shekhar *et al.*, "Sustainable approaches in the built environment with recycled concrete aggregate and coal ash," 2023.

[37] C. Cao, "Machine Learning-based Prediction of Porosity for Concrete Containing Supplementary Cementitious Materials," 2021.

[38] M. R. Hasan, M. A. Khan, and T. Wuest, "Towards Industry 5.0: A Systematic Literature Review on Sustainable and Green Composite Materials Supply Chains," 2024.

[39] F. Isikgor and C. R. Becer, "Lignocellulosic biomass: A sustainable platform for the production of bio-based chemicals and polymers," 2016.

[40] Representative studies on recycled concrete aggregates and sustainable concrete summarized in recent reviews.

[41] Recent review literature on climate-resilient concrete integrating industrial by-products, recycled materials, and lifecycle assessment.