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Revolutionizing Concrete: A Review of Sustainable Innovations with Recycled Materials and Advanced Additives

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Abstract Cement continues to be the most used construction material globally, but its manufacture contributes substantially to the environment, mainly due to a high carbon footprint and resource depletion. Sustainable innovations in concrete are highlighted through the use of recycled materials and innovative additives, which aim to improve performance and minimize ecological footprint. Recycled materials like Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Recycled Aggregates (RAs), and by-products of industries are discussed in the replacement of conventional ingredients. In contrast, nano-scale additives like nano-silica, graphene oxide, and carbon nanotubes are discussed for their role in enhancing mechanical and durability characteristics. The review utilizes the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach to systematically examine research conducted between the years 2020 and 2025 from databases such as Scopus, basing the comparison of the variables like Compressive Strength (CS), Tensile Strength (TS), Durability, and environmental performance. Some of the studies have claimed the improvement of the strength by up to 25%. At the same time, issues like the difficulty of workability, the cost implication, and long-term performance uncertainty persist. The study concludes by stating that the sustainable development of concrete involves the enhancement of material combinations and the adoption of innovative methodologies to satisfy the twin targets of the performance of the material and environmental sustainability. The conclusion indicates that the use of supplementary cementitious resources and nano-additives minimizes the permeability, improves the strength, and increases the service life of concrete.

Keywords Sustainable Concrete, Recycled Materials, Advanced Additives, Mechanical Properties, Recycled Course Aggregate

1. Introduction

Infrastructural construction has relied on concrete, a composite material, for centuries [1]. The four primary ingredients that go into its production are water, Fine Aggregates (FAs), Coarse Aggregates (CAs), and cement. Cement, most commonly Portland cement, is the binding component; it creates calcium hydroxide and Calcium Silicate Hydrate (C-S-H) gel through a chemical reaction with water known as hydration [2]. The constituents fill the void spaces between the aggregates, and after some time, these voids become replete, enhancing the rigidity and strength of the concrete. The FAs, which might include sands sourced from the banks of a river or manufactured sands, provide the matrix between the coarse aggregates, thus augmenting the volume and reducing the voids in the concrete. The coarse aggregates, which might include gravels or crushed rocks, contribute bulk, strength, and stability in the mix [3]. The constituents of the blend undergo a hydration reaction. The addition of water to the mix activates the hydration reaction and renders the mix workable so that it can be shaped and placed before setting. The amount of each constituent might be varied with respect to the desired properties of the concrete, which might include strength, workability, and durability. In addition to the principal constituents, it is also possible to include admixtures to alter particular properties like the setting time, water retention, or resistance to the freeze–thaw cycle. The flexibility of the mix allows it to be utilized in various construction works like masonry, structural elements of buildings, roads, bridges, dams, and marine structures [4].

1.1. Conventional Concrete Composition

Concrete is primarily composed of water, cement, coarse aggregates (gravel or crushed stone), fine aggregates (sand), and, most critically, cement, which binds these elements to form and harden. The uses of concrete are widespread owing to its malleability, ability to assume complex shapes, and high compressive strength. However, its environmental shortcomings are grave. The cement industry is among the highest producers of energy and greenhouse gases. At the same time, the extraction of aggregates (sand and gravel) causes severe environmental issues, including the destruction of habitats and erosion [5]. Furthermore, conventional concrete contains no recycled material, meaning it both uses virgin resources and produces a large volume of construction and demolition waste. High durability in aggressive conditions further increases the environmental cost due to the large amount of material and energy required to repair and replace the components. The basic materials of concrete composition are shown in Figure 1.

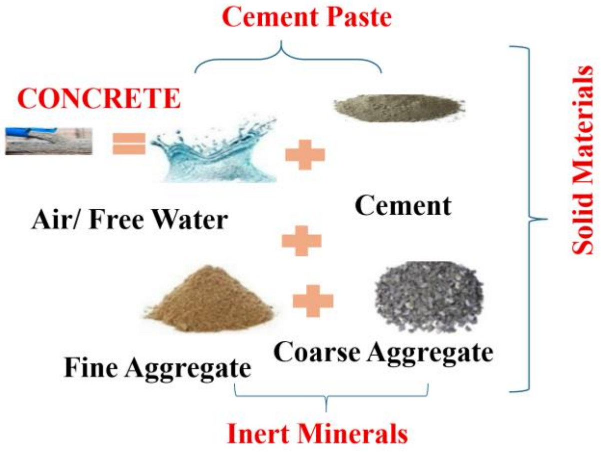

Figure 1. Basic materials of concrete composition [6]

Despite its advantages, traditional concrete construction has some considerable drawbacks that have led to the search for sustainable alternatives. Production of cement results in the calcination of limestone, which releases large amounts of Carbon Dioxide (CO_2), in addition to the considerable burning of non-renewable energy sources within kiddle, which is one of the fossil fuels and a major contributor to greenhouse gases [7]. Also, the process of Naturally Available (NAs) resource extraction from rivers, quarries, and the coastal belt not only leads to resource depletion but also contributes to degradation in the form of habitat loss, erosion and waterway sedimentation [8]. From a performance aspect, traditional concrete exhibits low TS, which leads to the necessity of steel reinforcements in the structure, and is prone to cracking and fractures from changes in temperature or shrinkage. Other than that, concrete suffers from issues of durability, such as the penetration of chloride, the sulfate attack, and carbonation that compromise reinforcements and structural strength over time, especially in the marine or industrial aggressive zones [9].

Moreover, concrete has limited TS, rendering it prone to sudden and unanticipated failure. Its enormous mass also increases shipping expenses and diminishes its utility in particular engineering configurations. These are precisely the issues that justify the need for the use of innovative technology, like the use of recycled and sophisticated additives to enhance performance while mitigating environmental footprints.

1.2. Recycled Materials in Sustainable Concrete

Recycled materials in sustainable concrete refer to waste products or industrial by-products that are processed and incorporated into concrete mixes as partial or full replacements for traditional ingredients like cement, FAs, and CAs [10]. Examples include RA from demolished concrete, ceramic waste, brick rubble, and industrial residues such as FA, as shown in Figure 2.

The rising demand for new materials for construction stems from the increasing depletion of natural resources and the adverse effects of traditional concrete, such as significant emission of carbon dioxide during the production of cement and the excessive mining of aggregates from quarries and riverbeds [11]. Sustainable concrete addresses the resource inadequacies of conventional mixes through the use of Supplementary Cementitious Materials (SCMs) to minimize carbon emissions and the utilization of RAs to conserve natural raw materials. Some construction by-products enhance concrete's durability through denser pore structure and aggressive agent resistance [12]. The responsible diversion of waste from landfills also promotes effective waste management systems, as materials themselves often provide the benefits of reduced costs coupled with adequate performance. Sustainably developed plastic concrete enables the construction industry to minimize the impact of concrete and construction on the environment by upholding the principles of the circular economy [13]. Figure 3 shows the utilization of Recycled Concrete Aggregates (RCAs) in sustainable construction.

Figure 2. Typical Recycled Materials [6]

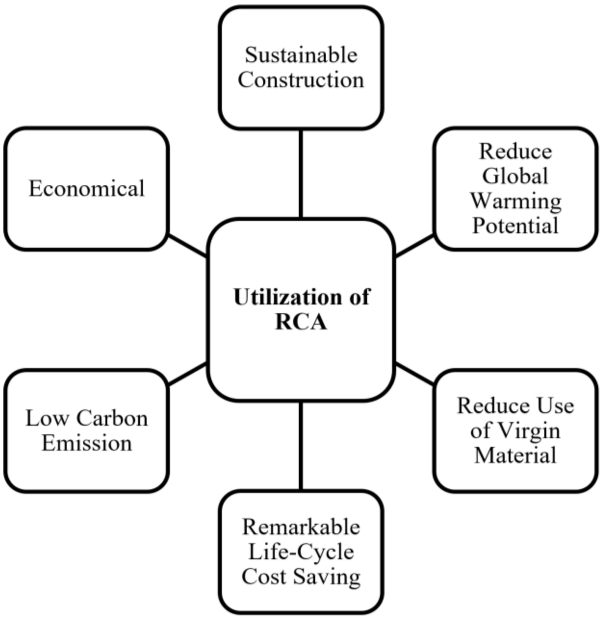

Figure 3. Utilization of RCA [11]

1.3. Advanced Additives for Performance Enhancement

Advanced additives in sustainable concrete are high-precision engineered materials added in minimal amounts to achieve significant improvement in mechanical durability and environmental performance [14]. They operate at the micro and nano scale to improve concrete internal structure, hydration and bonding between cement paste and aggregates. One of the most widely studied additives is nano silica, which is an excellent pozzolanic material with particles smaller than cement grains. Its high surface area and the ability to fill micro pores within the cement matrix contribute to the packing density of the pore structure, which decreases permeability and strengthens during the early and long-term curing stages, enhanced and refined. Nano silica also accelerates the hydration of tricalcium silicate, resulting in higher CS and TS with reduced shrinkage cracking [15]. Carbon nanotubes yield very high TS and stiffness while being very light. They provide cementitious matrix nano reinforcement and, when dispersed, improve microcrack bridging and crack propagation, resulting in increased tensile and flexural strength, toughness, and ductility. These properties make the concrete super ductile and resistant to sudden failure [16].

Graphene oxide improves impermeability and flexural strength and increases fracture toughness due to strong bonding with the cement matrix and the layered structure, which helps to suspend discrete particles during mixing, control crack propagation, and preserve microstructural integrity. Superplasticizers are high-range water-reducing admixtures that enhance the workability of a mix without increasing the water-cement ratio, resulting in low-porosity, high-strength, and dense concrete, which improves pumpability, segregation, and bleeding [17]. These improvements, along with the additive's effects, lower compressive tensile and flexural strength, stiffness, and load-bearing capacity while improving durability by reducing porosity, limiting chloride ingress, improving sulfate resistance, and enhancing resilience against freeze-thaw cycles. Their performance increases while reducing the cost of cement and embodied carbon emissions. When used with RA or industrial by-products, these additives create high-performance, sustainable concrete, which lengthens service life, decreases maintenance, and promotes the circular economy [18].

The novelty of this work is the application of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach to perform the review on recent developments in sustainable concrete using recycled materials and additive technology. As opposed to the common narrative review or the purely bibliometric evaluation that uses literature selection & descriptive summaries or conclusions, the methodological use of the PRISMA allows the work to use transparent, reproducible, and unbiased screening from pre-defined inclusion & exclusion criteria. This is particularly important in sustainable concrete studies due to the interdisciplinary nature and the quickly accumulating number of experimental studies using different methodologies & findings. As applied in the review using the PRISMA principles, the review allows the screening & evaluation to focus on the systematic assessment of material content rates, strength properties, durability factors & interaction effects; simultaneously searching for contradictions & research gaps. Consequently, the PRISMA-based methodology strengthens the reliability of the conclusions and provides a more rigorous and decision-oriented synthesis for both researchers and practitioners.

Section 2 of the paper details the study's methodology for doing the review, and Section 3 uses the PRISMA model to show how the papers were chosen.

2. Literature Review

The following are the previous studies done by various authors based on the Recycled Materials and Advanced Additives used in concrete.

Youssf et al. [19] produced High-Strength Geopolymer Mortar (HSGM) from Construction and Demolition (C&D) waste. The results showed that the use of Brick Waste (BW) offered excellent resistance to sulfate attack and freezing/thawing. Half of the water absorption of HSGM came from Ceramic Tile Waste (CTW), which increased by 57.8 percent, and the other half came from Glass Waste (GW), which decreased by 26.5 percent. Using 50% CTW fine aggregate resulted in the maximum water sorption of HSGM.

Girish et al. [20] developed a novel geopolymer concrete blend that could be used for paving, called Paving Quality Geopolymer Concrete (PQGC), by replacing river sand with Slag Sand (SS). Multiple loadings at stress levels between 0.9 and 0.6 were applied to PQGC beam specimens to assess fatigue performance. Results showed that PQGC with SS was a greener and more efficient approach to building rigid pavements, allowing roads to be opened to traffic earlier, and being very resilient to cyclic stresses.

Ziada et al. [21] produced underwater geopolymer mortar with different percentages of Polypropylene (PP) fiber to investigate the usability of geopolymers in water structures like seas and rivers. In the first stage, the effect of PP fiber on fresh underwater geopolymer mortar was investigated by performing slump and pH tests. In the next stage, mechanical tests were performed on the hardened mortars, and microstructural analyses were carried out to verify the mechanical experiments. As a result of this study, after 28 days, the compressive and flexural strengths of underwater geopolymer specimens containing 0.5% PP fiber were boosted by 3.90% and 210.75%, respectively, compared to the fiber-free underwater geopolymer specimens.

Minh et al. [22] investigated the influence of three different curing methods on the CS of FA-based geopolymer concrete. The maximum CS values were evaluated by testing five mixes with different curing circumstances and an Alkaline Liquid (AL) to FA ratio ranging from 0.6 to 1.0. In a 16-hour oven-curing experiment, the highest CS was 30.2 MPa, in a 10-minute microwave-curing experiment, it was 13.7 MPa, and in a hybrid-curing experiment, it was 33.1 MPa (microwave-curing for 10 minutes followed by 8 hours in an oven at 80 ℃).

Tseng et al. [23] conducted research into 3D-printed concrete's (3DPC) printing and hardened properties. To make 3DPC, various ratios of FA to GGBFS were utilized as cement substitutes. Unit weight, CS, and flexural strength were all increased in specimens with a greater percentage of GGBFS, while water absorption and drying shrinkage were decreased. By day 28, 3DPC had surpassed the cast specimens in flexural and CS along the printing direction. Based on the findings, it is possible to substitute half of the cement in 3DPC with FA and GGBFS.

Vigneshkumar et al. [24] investigated hardened properties of Self-Compacting Geopolymer Concrete (SCGC) with NaOH Molarities (M) ranging from 8 to 16; a mixture of 50% FA along with 50% GGBS was used. According to research on SCGC workability, the optimal molarity was 14 M, and as the Sodium Hydroxide (NaOH) concentration rose, the slump flow fell. At the 28-day mark, the CS was 39.4 MPa, the split TS was 4.72 MPa, and the flexural strength was 5.91 MPa. Therefore, the optimal NaOH concentration was 14 M with 50% FA and 50% GGBS as binder ingredients, according to workability.

Gebremariam et al. [25] prioritized the Development of environmentally friendly concrete by utilizing aggregates made of recycled concrete and other materials salvaged from C&D projects. The initial step in making concrete using recycled materials was to substitute the natural coarse and FAs entirely. Following this, the glass powder, from glass recycling, added mineral fibers obtained from the construction and demolition waste, and the cementing ultra-fines, as well as other components, were incorporated as cement replacements or additional blending materials in a gradual manner. The end product, which constitutes more than 75% of the total weight as recycled materials, was assumed to be the most ecological and sustainable concrete mix available.

Qin et al. [26] performed an extensive study and scientometric assessment on the incorporation of Waste Glass (WG) into concrete in relation to green building construction. The influence of WG on the performance of Cement-Based Materials (CBMs) was analyzed, and the use of WG in construction materials was discussed in consideration of ecology. Specifically, the workability and durability of composites with WG were examined as well. When it came to mechanical qualities, finer WG particles were better than coarser ones. Cement replacement levels of up to 25% and aggregate replacement levels of up to 20% were determined to improve microstructure and durability, with a slight decrease in carbonation resistance.

Hossiney et al. [27] demonstrated the creation of paver blocks for a pedestrian facility with various types of garbage. To create paver blocks, geopolymer concrete was mixed with recycled asphalt pavement aggregates and FA. The laboratory investigation demonstrated that its application in pedestrian facilities also opened new possibilities for recycling and reusing the trash that would otherwise end up in landfills, costing the paving sector money.

Edwin et al. [28] created a range of concrete mixes by substituting varying amounts of copper slag for cement, starting at 0% and working up to 40% by weight. Using a ball mill, the copper slag was ground to two different fineness levels. Compared to the control mixture, concrete containing copper slag had a weaker early strength (7 days) across all water-to-cement ratios. At replacement levels up to 20% for two-level fineness, concrete's CS was either comparable to or slightly greater than the reference mixture for extended curing durations (28 days).

3. Review Methodology

Researchers use the PRISMA declaration to screen and improve their studies. Searches in the SCOPUS database covering the years 2020–2025 were used to compile a comprehensive literature review on the subject. The Scopus data reviewed here comprises articles, journals, and publications. Table 1 shows all the keywords that were used to find relevant papers in Scopus.

Table 1. Searching Keywords

Databases	Keyword used
Scopus	TITLE-ABS-KEY ("concrete" OR "mortar" OR "cementitious composite*") AND ("recycled aggregate*" OR "RCA" OR "RFA" OR "waste glass" OR "glass powder" OR "waste plastic" OR "crumb rubber" OR "construction and demolition waste" OR "CDW" OR "fly ash" OR "ground granulated blast furnace slag" OR "GGBS" OR "slag" OR "metakaolin" OR "calcined clay" OR "red mud" OR "quarry dust") AND ("nano silica" OR "nanosilica" OR "nano-silica" OR "graphene" OR "carbon nanotube*" OR "CNT" OR " TiO_2" OR "photocatalytic concrete" OR "self-healing concrete" OR "bacteria*" OR "microcapsule*" OR "basalt fiber*" OR "polypropylene fiber*" OR "superplasticizer*" OR "crystalline admixture*" OR "CO_2 curing" OR "3D printed concrete" OR "alkali-activated" OR "geopolymer") AND ("compressive strength" OR "tensile strength" OR "flexural strength" OR "modulus" OR "durability" OR "chloride penetration" OR "RCPT " OR "water absorption" OR "sorptivity" OR "carbonation" OR "sulfate" OR "freeze-thaw" OR "ASR" OR "shrinkage" OR "creep" OR "life cycle assessment" OR "LCA" OR "carbon footprint" OR "CO_2" OR "embodied energy" OR "cost" "))

Table 2. The criteria for determining what is included and excluded

Criterion	Inclusion	Exclusion	Reasons for Exclusion
Keywords	Records discussing the use of recycled materials (e.g., FA, GGBS, slag, RA, ceramic waste, plastic waste) and advanced additives (e.g., nano-silica, carbon nanotubes, graphene oxide, superplasticizers) in sustainable concrete.	Records that do not address recycled materials or advanced additives in concrete.	Exclusion based on irrelevant or mismatched keywords that do not align with the study's focus on sustainable concrete innovations.
Type of Literature	Peer-reviewed journals, review articles.	Books, book series, book chapters.	Non-article formats that are not peer-reviewed or do not provide current research contributions.
Language	English	Other than English	Non-English publications are excluded due to language barriers and limited accessibility for a wider audience.
Timeframe	Publications from 2020–2025	Publications before 2020	Older studies might not reflect current trends, technological advancements, or recent sustainability standards.
Category	Open Access	Paid Access	Papers inaccessible due to paywalls are excluded to ensure free availability for review and dissemination.

The evaluation process in literature reviews only records that are classified as articles, so only such records are thoroughly examined. Only records that met both the inclusion and exclusion criteria were included in the analysis, as indicated in Table 2.

3.1. Prisma Model

The PRISMA Statement lays down the standards used to conduct meta-analyses and systematic reviews. Figure 4 shows the detailed and organized procedure for data extraction. Several processes are involved in this process, such as finding appropriate sources, extracting research articles from them, analyzing those sources, and finally, analyzing the research papers' substance. Researchers have set aside six years (2019–2024) to locate significant documents in the field by performing a comprehensive systematic literature review. In order to find relevant papers, researchers examine a number of databases, including IEEE, Web of Science, Scopus, Research Gate, Science Direct, and Springer.

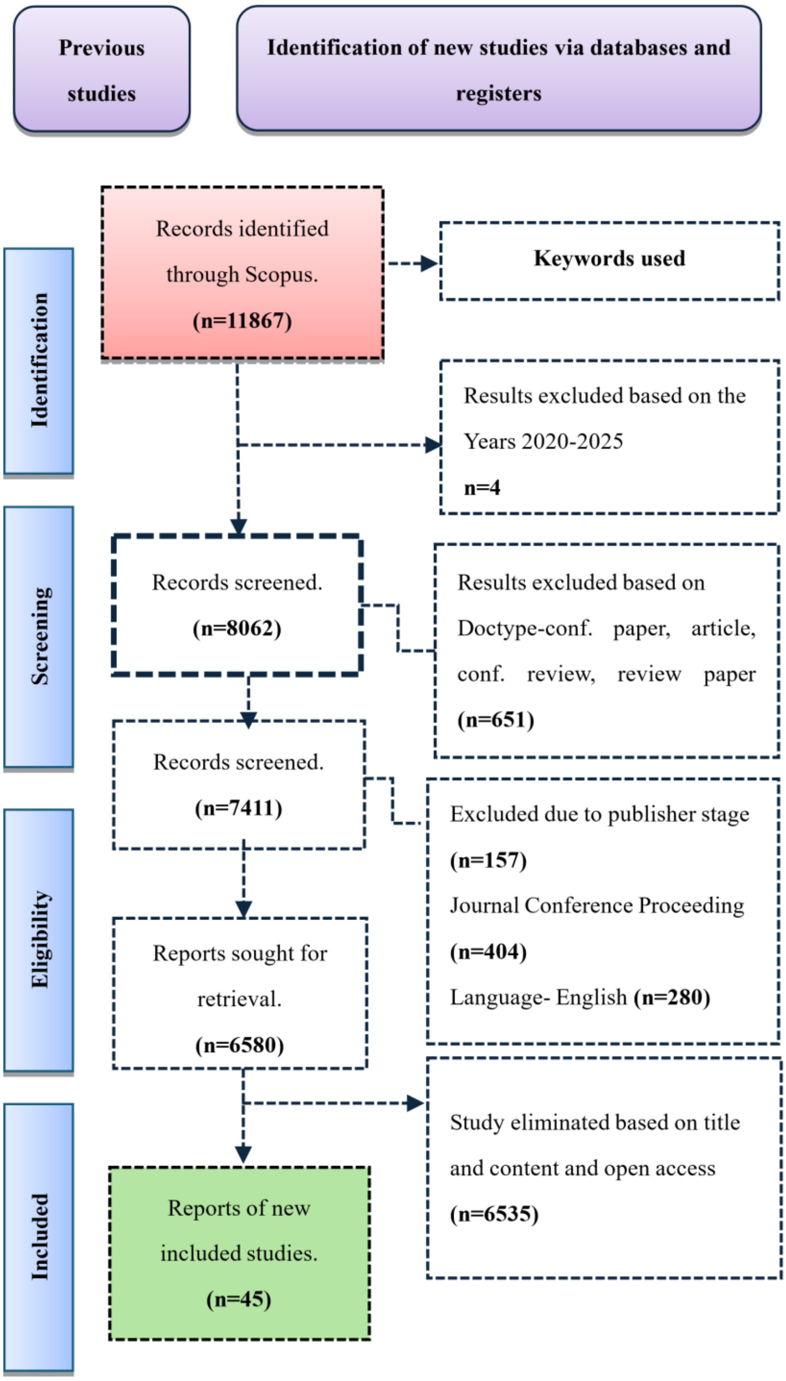

Figure 4. Prisma Model

Based on the criteria set by Scopus, a total of 101 records were obtained from the collection of data. There are 97 results excluded due to the year of publication, the document type (conference paper, article, conference review, review paper), and the language, which leaves 87 records after the screening. After the screening, the total number of publications that satisfy the inclusion criteria is 45. These retrieved papers are further screened for language and duplicate records. Only papers published in the English language are considered, which, after the completion of the filtering, results in 45 publications.

Figure 5 illustrates the spread of literature among the top five subject areas. Engineering is the top area with 4,228 papers, showing how much attention is given to research in its infrastructure, materials, and construction systems. Material science is the second most cited field, scoring 3,606 papers, proving the need for novel materials, especially composite recycled construction materials and various special concrete additives. The 1,089 papers for environmental science show the need for research in the field, which is focused on sustainability, environmental impact assessment, and green construction. The 799 papers in physics and astronomy depict fundamental aspects of the materials and techniques of characterization and performance analysis of materials. Lastly, the 496 papers in Earth and planetary science represent the study of geo materials with special reference to the environmental aspects of the materials' extraction. In general, Figure 5 describes the multidisciplinary approach of the research, which integrates engineering, materials science, and ecology.

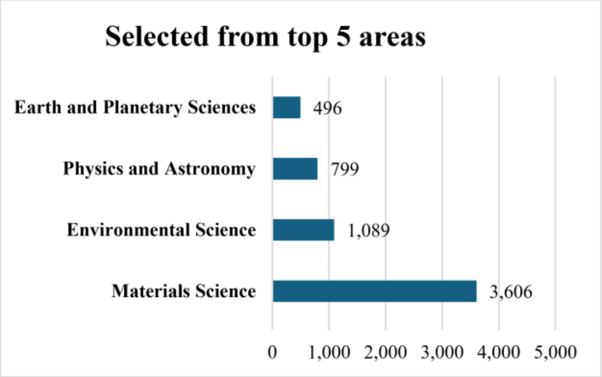

Figure 5. Selected papers from the top 5 Areas

Figure 6 depicts the distribution schemas of the literature associated with the keywords in the sustainable concrete research domain. CS has the most papers with 3,763, highlighting the relevance of studying the structural performance of concrete with recycled materials and advanced additives. FA has the second most papers with 2,610, highlighting its application as a supplementary cementitious material for promoting concrete durability and reducing its carbon footprint. Slags have 2,054 papers, demonstrating the interest in the research in the use of the industrial by-products of steel manufacturing for concrete. The rising interest in sustainable construction is reflected in the 1,597 papers on Geopolymers and 1,459 documents on Inorganic Polymers.

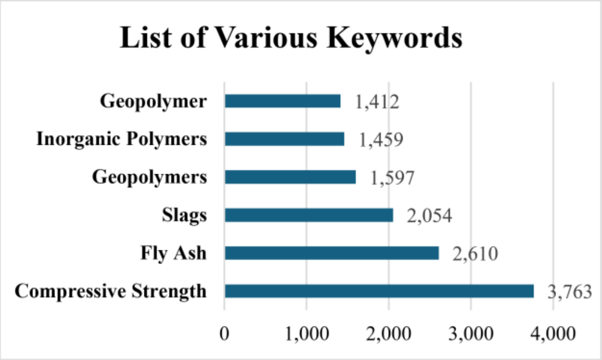

Figure 6. List of various Keywords

The Geopolymer also has a significant number of records, 1,412, pointing towards the research interest in alkali-activated binders and their remarkable performance and environmental benefits. The conclusions derived from the data sets are very indicative of the focus areas in the concrete and its sustainable innovations research, showing a broad interest in its mechanical performance, industrial by-products, and eco-friendly binders.

Considerable data about the publication years of the papers are presented in Figure 7. The search terms used in this systematic literature review were chosen with the specific purpose of exploring innovations in sustainable concrete incorporating recycled materials and advanced additives.

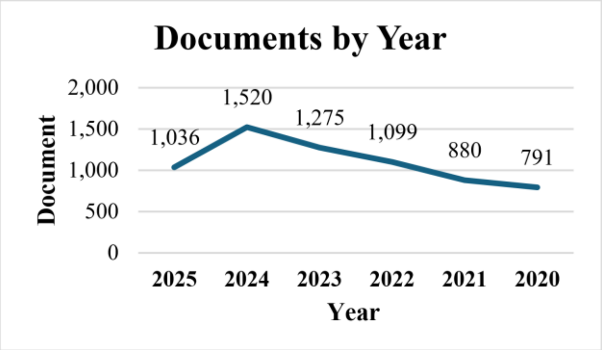

Figure 7. Trend in published papers

Figure 8 presents the author co-citation network highlighting dominant Western contributions to bibliometric and sustainability studies. However, the sparse presence of regional scholars indicates a gap in localized perspectives on sustainable concrete innovations with recycled materials and advanced additives.

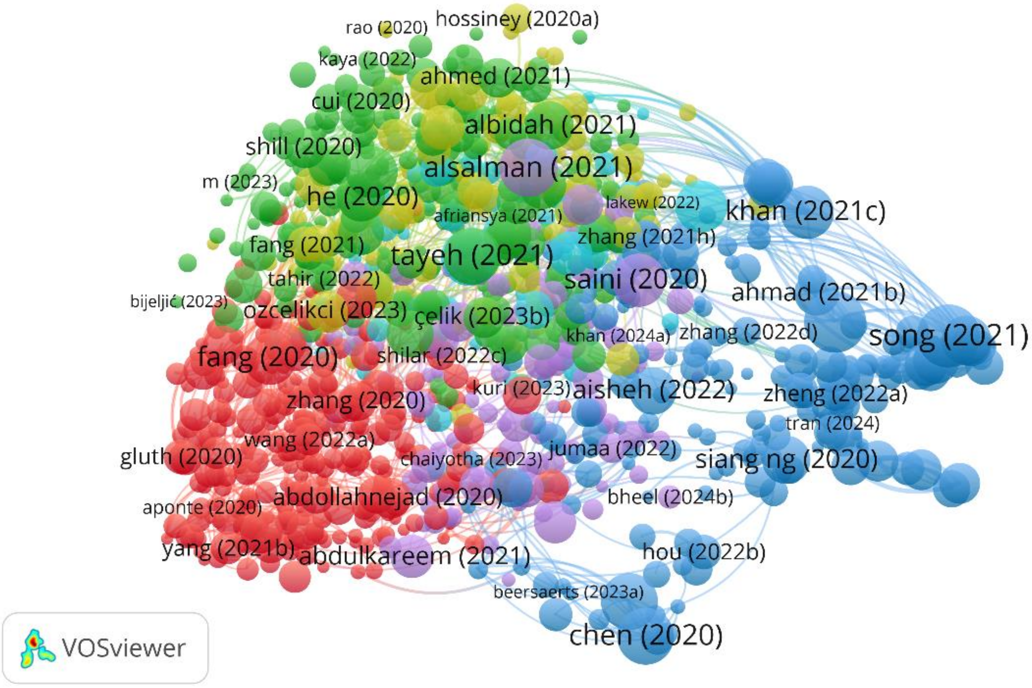

Figure 8. Author co-citation network

4. Supplementary Materials

Supplementary materials refer to industrial by-products or additional components incorporated into concrete mixtures to enhance performance, sustainability, and durability while reducing environmental impact.

4.1. Fly-Ash

One of the waste products of thermal power plants is FA, which is made when coal is burned. It enhances the fluidity of newly mixed cement paste and is mainly composed of spherical particles and a substantial amount of aluminum phase. Raghav et al. [29] noted that FA requires activation for two reasons. Firstly, the dense, chemically stable glass surface of the glass beads retains the porous, spongy, and amorphous interior constituents. Second, the stable silica-alumina glassy chain, which contains mainly silicon and aluminum and very little calcium, must be broken down before it can react with the free lime in cement. More finely ground FA requires more free lime. To increase its reactivity, mechanical grinding, thermal activation, and chemical activation are essential processes.

In addition, cement composites' mechanical and durability qualities are improved when FA is partially substituted for regular Portland cement. This outcome aligns with the findings, which indicate that incorporating 5–30% FA enhances the strength of cementitious materials. Lekhya and Kumar [30] demonstrated a more significant increase in CS at 28 days for the mixtures containing 10% FA, 15% FA combined with 10% SF, and 10% FA with 15% SF, respectively. A mere 3–11% gain in strength was noted between 56 and 90 days. Hossain et al. [31] noticed that after adding jute fiber, the mixes with 5% FA and 0.2% JF, 10% FA and 0.2% JF, and 15% FA and 0.2% JF showed markedly enhanced strength. At 7 days, the mixture containing 10% FA and 0.2% JF reached 25.37 MPa, and at 28 days, it reached 33.91 MPa, showing the most significant strength improvement among all of them.

The CS of Saudi-FA-based concrete with a high percentage of Class C FA declined from 10% to 50% FA at all ages up to 365 days, according to research by Amran et al. [32]. Due to the continuous hydration of Ordinary Portland Cement (OPC) and the higher pozzolanic activity of the FA, the authors observed that the CS improved with age in both reference concrete and FA concrete. In particular, at 3, 14, 28, 56, and 91 days, as well as after one year, the CS decreased by 57.34%, 41.61%, 37.50%, 29.42%, 28.32%, and 35.52%, respectively, when FA was used in place of half of the OPC. Xu et al. [33] found that adding more FA to pavement concrete decreased its 7-day CS. The 7-day CS of the control sample was higher than that of the FA-admixed sample. Concrete with 5% type I FA had a 14-day CS that was lower than that of concrete with slag, but similar to the control concrete. As compared to the 5% type I FA concrete and the control specimen, the 15% type I FA concrete showed the best strength at 28 days in the tests. It should be noted that type II FA, with a particular surface area of 3100 cm^2/g, performed poorly in terms of CS during the whole testing process compared to the other samples. The admixtures' efficacy was mainly associated with how quickly they hydrated. Type II FA required a longer hydration interval and had the lowest activity compared to slag and type I FA in this study. Some mechanical qualities and durability are affected by FA, as shown in Table 3.

4.2. Coconut Fibers

Researchers have extensively explored the use of natural and synthetic fibers, as well as industrial by-products, to improve the flexural response of concrete. Abbass et al. [35] developed geopolymer concrete using three by-product components, i.e., Rice Husk Ash (RHA), FA, and GGBFS, along with coconut fibres to promote sustainable Development. Results showed that a 0.2% coconut fiber binder material increased CS by 5.13 percent, while a 0.4% coconut fiber binder material increased it by 5.6 percent. Similarly, Srinivas et al. [36] used Polypropylene fiber in various proportions (0.5%, 1%, and 1.5%) to enhance the mechanical properties of the concrete. Results from the durability tests showed that at 1%, there was a lower percentage of weight loss and strength loss. Moreover,

Kumar et al. [37] utilized fiber material obtained from coconut and coconut fiber ash in an M20 grade mix. Both the coconut fibers and their ash were added to the concrete mixture at a rate of 5% and 15%, respectively. It appears that the mix's base strength qualities have been optimistically increased, and the structural property of the building material has been strengthened with the inclusion of this coconut fiber and ash component.

Khan et al. [38] evaluated the Silica-Fume Plain concrete (S-PC) and Silica-Fume Coconut Fiber Reinforced Concrete (S-CFRC). Compared to their corresponding S-PC, S-CFRCs with a 15% content exhibited superior mechanical characteristics. In the same manner, Das et al. [39] studied the mechanical properties of Hybrid Fiber Reinforced Concrete (HFRC) with steel and coconut (coir) fibre and its comparison with control concrete. From the trial results, the CS was found to be 18.36% higher than the control mix, and flexural strength was 24.87% higher. Further, Raj et al. [40] investigated the mechanical, durability, and functional characteristics of Hybrid Fiber Reinforced Foam Concrete (HFRFC). It was determined from the research that the ideal fiber percentage to achieve maximum strength was 0.3%. The hybrid combinations achieved a satisfactory level of strength with minimal reduction. Lastly, Wongsa et al. [41] investigated the properties of high calcium FA geopolymer mortars containing natural fibers. According to the results, natural fibers (coconut and sisal) significantly improved tensile and flexural strength to levels comparable to those of glass fiber. The flexibility of concrete with varying amounts of coconut fibers is summarized in Table 4.

Table 3. Effect of FA on mechanical properties

FA Replacement	W/C	Curing duration	Optimum CS		Optimum TS		Optimum Flexural Strength		Durability of replacing FA with OPC compared with CM		Reference
			% Replacement	Age (days)	% Replacement	Age (days)	% Replacement	Age (days)	% Replacement	Age (days)	
10	0.28	28	10	28	--	--	--	--	10	28	Lekhya and Kumar [30]
10	0.41	28	10	28	10	28	--	--	--	--	Hossain et al. [31]
0-50	0.286	28	20	28	10	28	10	28	10	28	Amran et al. [32]
0-25	0.42	28	15	28	--	--	15	28	15	28	Xu et al., 2020 [33]
0-20	0.469	28	20	56	--	--	--	--	20	56	Zahedi et al. 2020 [34]

Table 4. Evaluation of coconut-fiber-infused Concrete

Materials	Percentage of Replacement	CS (MPa)	Flexure Strength (MPa)	Split TS (MPa)
Geopolymer Concrete [35]	0.2	38.0	5.4	3.90
Polypropylene fiber concrete [36]	1.0	9.03	3.00	0.87
M20 Concrete [37]	CF%:5 CF ASH%:15	19.53	5.27	2.93
S-CFRC [38]	10:2	28.5	6.3	3.6
HFRC [39]	1:2	20.42	4.92	4.12
HFRFC [40]	0.3	11.5	1.7	3.8
FA geopolymer [41]	1.0	25.0	6.7	2.4

Figures 9,10 show a comparative analysis of various research based on the compression strength and Tensile Strength.

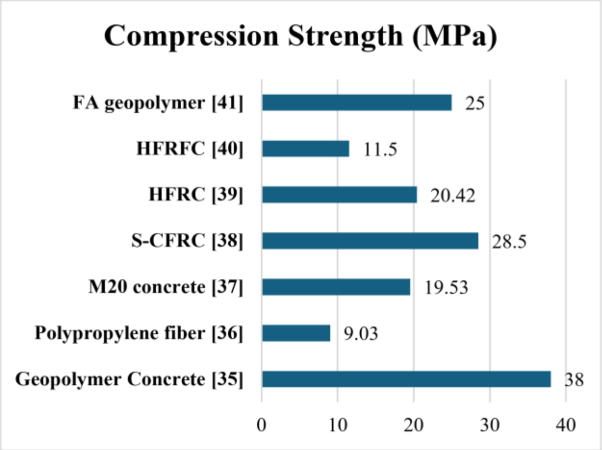

Figure 9. Compression strength

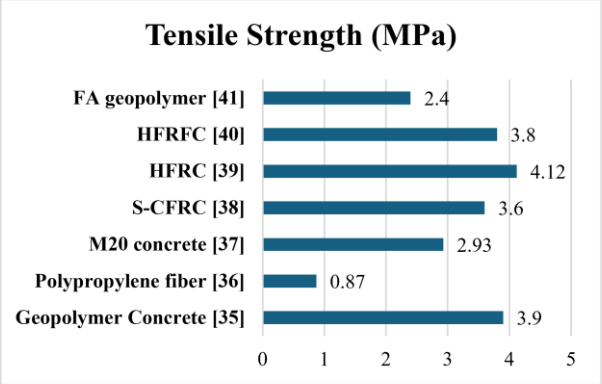

Figure 10. Tensile Strength

5. Aggregate

The majority of India's solid waste in landfills is made up of building waste, which is generated daily. Materials such as concrete, bricks, slabs, dirt, dust, wood, metals, paper, plastic, and cardboard are standard components of construction debris. A serious environmental and social problem has emerged in the nation over the disposal of this garbage. Global urbanization has been further accelerated by the widespread use of concrete in construction. But there are environmental problems and resource depletion because of the cement production and the high demand for Natural Aggregates (NAs). One promising strategy for accomplishing long-term sustainability objectives is the production of RCA from used concrete ingredients. The building sector is making a beneficial impact by reducing environmental impacts, increasing the need for naturally occurring aggregate reserves, and reusing waste by adding RCAs to concrete mixes [42].

RCA optimization usually considers the partial substitution of NAs. Studies show that the concrete properties can be maintained or improved when 25 to 30 percent of CAs are replaced with RCA [43]. For FAs, replacement rates of 50 to 60 percent have been promising. However, it should be noted that a high percentage of recycled FAs often corresponds to a drop in CS. Depending on the application and desired properties of concrete, the replacement rate of recycled FAs might differ. There is a lack of research that determines the long-term durability and performance of concrete containing high volumes of recycled FAs. Also, the incorporation of additional cementitious materials or chemical admixtures might partially mitigate the adverse effects of high RCA content.

The optimization of FA is aimed at identifying the optimal percentage ratio of replacement cement to be used, including its fineness. Noted, up to 35 to 50% High Volume Fly Ash (HVFA) showed improvements on slump retention and CS of the RCA [44]. It is interesting to point out that the blend of RCA plus FA, and in particular the latter, results in some synergies. For instance, a concrete mix with 25% RCA and 20% (a subtype of FA) coal bottom ash in HVFA self-compacting concrete shows an exceptional increase in multi-dimensional strengthening properties after 120 days [45]. The FA and the RCA improve the flow and the chloride penetration. The pozzolanic FA and RCA synergistic effects are due to improved particle packing densification in the concrete matrix. Further, FA also tends to conceal some of the typical disadvantages of the RCA, which are high water absorption and low density. The combination also contributes to the more sustainable concrete formulation by minimizing the extraction of new aggregates and cement, as well as incorporating industrial by-products.

5.1. Mechanical Properties

This section highlights the fundamental characteristics that determine the performance and structural integrity of concrete, focusing on strength and long-term durability.

- **Compressive Strength (CS)**

The use of RA in geopolymer concrete does not seem to compromise mechanical performance, as some studies suggest. The CS depends on the particular mix design and curing conditions and can range between 14 and 35 MPa. For example, geopolymer concrete containing RA achieves compressive strengths comparable to, or greater than, ordinary portland cement mixes, provided the geopolymer concrete is cured at elevated temperatures (60 ℃ for 24 hours) [46]. The modulus of elasticity and TS, however, were slightly lower than those of natural aggregate geopolymer concrete.

Wenzhuo et al. [47] observed that increasing the RA content reduced the CS of RAC, but the addition of RHA mitigated the strength loss, especially with a 10-20% Rice Husk Ash (RHA) replacement. The study found that adding Metakaolin (MK) significantly improved the CS of RCA under sulfate attack conditions. Nanoparticles, particularly Silicon Dioxide (SiO_2) and Calcium Carbonate ($CaCO_3$), improved both compressive and flexural strength. However, these benefits were observed only up to an optimal concentration (typically between 1-4% of cement weight), beyond which strength began to decrease due to particle agglomeration. Paving blocks' CS rose with curing time and fell as the proportion of Processed Tea Waste Ash (PWTA) used to replace cement rose; nevertheless, flexural strength was lowered when cement was partially replaced with PWTA [48]. Using SiO_2 nanoparticles in concrete might increase its CS, according to several experimental investigations. CS was achieved at an early age when 2% nano-sized silica was added to a high-volume FA-modified concrete system.

- **Tensile Strength (TS)**

The use of hybrid fibers, macro-Basalt Fiber (BF), and macro-Polypropylene Fiber (PF) in RA concrete. It significantly improves the splitting TS by 34%–78% due to better crack bridging capabilities. However, the CS remains similar to single fiber systems due to the low workability of BF. There was a decline of 8.54% and an increase of 18.13% in ultimate tensile strain. This suggests that while Reinforced Autoclaved Aerated Concrete Aggregates (RAACA)'s self-cementing property helps with matrix-fiber bonding, using too much of it leads to more noticeable defective effects and the addition of more water, which interferes with interfacial densification and reduces tensile properties [49].

- **Durability**

Durability of concrete is its ability to withstand environmental and chemical attacks, mechanical wear, and time-related deterioration without significant loss of performance. Chauhan et al. [50] have assessed durability through tests like sorptivity and electrical resistivity, with RAC-AF showing lower permeability due to the formation of Si-rich C-S-H gels. Durability of the Concrete-Filled Double-Skin Steel Tube (CFDST) beams was inherent through effective confinement between the steel tubes and RCA, improving the overall performance of RCA in structural applications. The paving block's CS following 56 days of curing in an air-conditioned laboratory with a 3% H_2SO_4 solution. Paving blocks of different sizes (M0, M10, M20, M30, M40, and M60) showed an increase in CS of 20.55%, 17.7%, 12.89%, 10.64%, 11.72%, and 11.13%, respectively, when stored in an air-conditioned laboratory compared to the CS at 28 days. Most likely, this is because of the constant hydration caused by the impact of the laboratory's accessible moisture [47,48]. Table 5 and Figure 11 show the durability improvement of RCA concrete from the reviewed research papers, measured as the percentage reduction in water absorption or porosity at optimum dosage.

Table 5. Durability Improvement

Durability Improvement (%)	Remarks	Reference
18%	Polyolefin fiber reduced absorption	Gorji et al. [51]
12%	Steel slag + seawater decreased porosity	Lardhi and Mukhtar [52]
22%	CNS improved compactness	Hussein and Ghalehnovi [53]
20%	Ultrafine ceria densified matrix	Hashim et al. [54]
16%	Basalt fiber improved matrix	Zhang et al. [55]
17%	PVA fibers reduced permeability	Chen et al. [56]
10%	PP fiber reduced water uptake	Ye et al. [57]
15%	SCMs lowered permeability	Ahmad et al. [58]
14%	Steel fibers slightly reduced cracking	Pereiro-Barceló et al. [59]

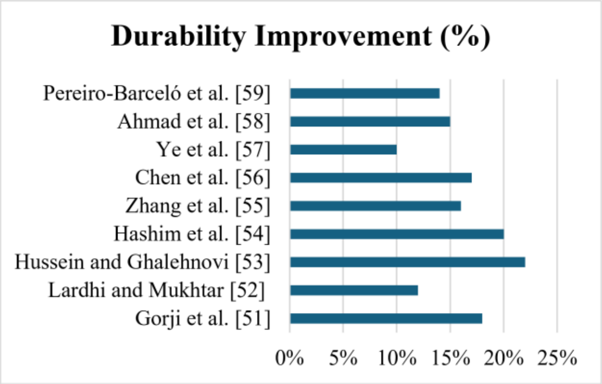

Figure 11. Comparative Analysis

Figure 11 shows the comparative analysis of various studies based on the durability Improvement.

6. Discussion

The studies reviewed show that the use of advanced additives along with recycled materials improves the mechanical properties of concrete and contributes to sustainability. The results summarized in Table 6 demonstrate that optimal performance is generally achieved at moderate replacement levels. Excessive substitution or additive dosage beyond these ranges might lead to workability reduction or early-age strength loss, highlighting the importance of balanced mix design in sustainable concrete applications.

Among the most common supplementary cementitious materials, FA enhances concrete microstructure by pore refinement and permeability diminution, resulting in increased CS for later curing ages. Based on the study, the following key findings are noted:

- FA (10–30% replacement): Refines pore structure, reduces permeability, and improves CS at later curing ages; excessive use (>40%) lowers strength due to delayed pozzolanic reaction.
- GGBS: Enhances long-term strength and durability by forming additional C-S-H gel; improves resistance against sulfate attack and chloride penetration.
- Fibers (coconut, polypropylene, basalt): Increase tensile and flexural strength through crack-bridging, reduce brittleness, and enhance ductility.
- Hybrid Fiber Reinforcement: Boosts splitting TS by up to 78% by restricting crack propagation under tensile stresses.
- Nano-Silica: Accelerates hydration, fills micro-voids, and improves early compressive and flexural strength; 2% inclusion in high-volume FA mixes offsets strength loss.
- Graphene Oxide: Improves fracture toughness and overall structural integrity.
- Recycled CAs (25–30% replacement): When combined with supplementary materials like FA, they maintain satisfactory strength while reducing environmental impact.
- Collective Impact: These innovations restore or enhance mechanical properties, improve durability, and make sustainable concrete suitable for high-performance structural applications.

Although the reviewed literature shows a common trend of improvement in performance, significant discrepancies and contradictions exist based on material properties, types, and test conditions. In spite of the overall encouraging results in the literature, some contradictions exist in the performance evaluation between recycled material, advanced additive, and concrete. These include, for instance, the improvement in compressive strength, durability, and other properties by replacing 10-30% by weight of concrete by fly ash, compared to other studies where a substantial reduction in early age strengths is noticed for replacement ratios above 40%. These discrepancies are primarily due to their fineness, calcium content, and curing conditions, which in most instances involve a lack of high-temperature curing for activation of pozzolanic action. concrete using Recycled Aggregates, in their studies, also face some discrepancies regarding their strength properties. While some researchers record fair to better performance for replacement ratios in between 25-30%, others infer a loss in strengths due to their higher water absorption, poor interfacial transition zones, and adhered mortar in the recycled aggregates.

There also exist contradictions in the application of nanomaterials. Nano-silica has been reported to increase the early age strength and pore densification at lower dosages (around 2% of cement weight), but high dosages can result in agglomeration and lower workability and strength properties. Such discrepancies can also be noticed in the results for graphene oxide, where fracture toughness can be improved depending heavily on dispersion efficiency and dosage. Such contradictions clearly convey that it is not appropriate to derive performance solely on the basis of material in sustainable concrete systems. Material properties, optimized dosage, curing factors, and interactions would play an integral role in determining concrete performance. There is an increasing need for standardized testing procedures for future studies to overcome these contradictions and derive performance factors or benchmarks.

Besides the individual material effects, it is evident from the literature review that a synergistic combination of recycled material, additive, or both, offers higher performance than a single material approach. Evidence in the form of quantified results in various studies reveals the synergy between 10-20% replacement of fly ash and 2% nano-silica by the weight of cement, where it helps in the resistance against early age strength loss, in addition to the overall improvement in the compressive strength by up to 20-25% for later ages. Similar synergy is reported in fiber-reinforced concretes. Combinations involving polypropylene, basalt, or natural fibers offer multiscale bridging, which helps in improving the splitting tensile strength by up to 78% compared to natural fibers, besides significant improvements in the flexibility properties. These present a strong case suggesting that a combination, rather than a replacement, is the optimal material goal for high-performance concrete. Recycled coarse aggregate concrete Addition of supplementary cementitious material like fly ash, GGBS, or both, leads to a higher interfacial transition zone, which resists similar strength losses in concretes containing recycled aggregates by 25-30%. The improved durable properties in these mixtures include water absorption cutbacks by 15-22%, which indicates resistance against hostile environment exposure.

Table 6. Optimal dosages of materials and their performance effects

Material	Optimal Dosage Range	Key Performance Effects
Fly ash (FA) [30, 32]	10–30% cement replacement	Refined pore structure, reduced permeability, improved later-age compressive strength
GGBS [23, 24]	30–50% cement replacement	Enhanced long-term strength, improved sulfate and chloride resistance
Coconut fiber [35, 41]	0.2–0.5% volume fraction	Improved tensile and flexural strength, enhanced ductility
Polypropylene fiber [36, 49]	0.5–1.0% volume fraction	Crack-bridging, reduced brittleness, improved splitting tensile strength
Hybrid fiber systems [39, 49]	0.3–1.0% volume fraction	Splitting tensile strength improvement up to ~78%, enhanced crack control
Nano-silica [15, 53]	≈2% cement weight	Accelerated hydration, improved early-age strength, pore densification
Graphene oxide [16, 18]	≤0.05% cement weight	Improved fracture toughness and microstructural integrity
Recycled coarse aggregate (RCA) [42, 43]	25–30% aggregate replacement	Acceptable strength retention, reduced environmental impact

7. Economic and Logistical Challenges

Although concrete's sustainability and performance are significantly improved by the incorporation of these recycled materials, advanced additives are not yet widely adopted for practical construction because of a number of economic and logistical obstacles. Advanced additives like nano-silica, graphene oxide, and carbon nanotubes definitely increase the cost of concrete. Generally, these materials necessitate specialized production and dispersion techniques, which bring about significantly higher material and processing costs when compared with conventional concrete. Recycled materials, mainly recycled coarse aggregates and industrial by-products like fly ash and slag, can be of inconsistent quality and unavailable at all times. Indeed, differences in source material, contamination levels, and processing methods might yield the erratic and unstable mechanical and durability performance of such materials, which might call for additional quality control measures. Extra costs are due to recycling treatment and transportation of the material that might decrease viability, especially for those developing remote or resource-constrained regions.

Further, the applicability process of Geopolymer concrete and nano-modified concrete is hindered by a lack of standardized design, codes, and data related to the long-term performance in the field. Contractors might require different training, different batch mixing, and different curing conditions, which might not be feasible in a typical construction site. These obstacles need the following Development related to cost-effective process development, material standardization, and pilot-scale field testing as a precursor for the advent of new technologies in the industry.

8. Conclusion and Future Scope

All over the world, concrete remains the most widely used construction material and plays a critical role in infrastructure development. However, its extensive use poses serious environmental challenges, primarily due to high carbon emissions associated with cement production and the large-scale extraction of natural aggregates. To address these concerns, this review systematically examined recent advances in sustainable concrete through the incorporation of recycled materials and advanced additives. The PRISMA-based methodology ensured a rigorous and transparent selection of peer-reviewed studies published between 2020 and 2025 from the Scopus database, enabling a reliable synthesis of experimental evidence. The review focused on industrial by-products such as FA and GGBS, construction and demolition waste in the form of RA, and nano-scale additives including nano-silica, graphene oxide, and carbon nanotubes, with particular emphasis on their effects on mechanical performance and durability. The findings reveal the following key points:

- Concrete remains essential for infrastructure, but its conventional production causes high CO_2 emissions and depletion of natural aggregates.
- Supplementary cementitious materials such as fly ash (10–30%) and GGBS (30–50%) reduce cement usage and enhance later-age compressive strength by up to 20–25%, while improving sulfate and chloride resistance.
- Recycled coarse aggregates at 25–30% replacement maintain acceptable strength and improve durability, with 15–22% reductions in water absorption and permeability.
- Nano-silica at about 2% by cement weight accelerates hydration and significantly improves early-age strength, offsetting strength loss in high-volume fly ash systems.
- Fiber reinforcement, particularly hybrid fiber systems, markedly enhances tensile performance, achieving up to 78% improvement in splitting tensile strength.
- Synergistic combinations of recycled materials and advanced additives consistently outperform single-material systems in terms of strength, durability, and service life.

- Key challenges remain, including the high cost and dispersion issues of nanomaterials, variability in recycled aggregate quality, and the lack of standardized design guidelines for large-scale applications.

Future research should emphasize the following key points:

- Develop cost-effective activation methods for industrial development of cost-effective activation and processing techniques for industrial by-products to improve their reactivity and large-scale usability.
- Exploration of emerging technologies such as self-healing concrete, carbon-sequestering binders, and low-clinker cement systems to reduce environmental impact further.
- Application of artificial intelligence and machine learning tools for optimized mix design, performance prediction, and durability modeling of multi-material concrete systems.
- Execution of large-scale field trials and long-term monitoring programs to validate laboratory-scale findings under real construction and exposure conditions.
- Comprehensive life-cycle assessments integrating mechanical performance, durability, economic cost, and environmental impact to support data-driven decision-making for sustainable infrastructure development.

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