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Advancing Concreting Practices: A Comprehensive Review of Modern Methods, Materials, and Sustainability Strategies

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Abstract: The most used construction material in the world, concrete faces an environmental issue due to its environmental impact from cement production. A global perspective on contemporary concreting practices in India is explored through a systematized framework focused specifically on progress in materials, practices, and sustainability efforts for India. Notably, it provides a research focused evaluation on its performance by incorporating Supplementary Cementitious Materials (SCMs), recycled aggregates, and nano-admixtures with large-scale CO_2 emission reductions over the horizon of up to 35% with no loss to structural compliance standards such as IS 456:2000. Innovations in batching, mixing, curing, non-destructive testing (NDT), and lifecycle assessment (LCA) are analyzed from various perspectives. In addition to the traditional methods, novel technologies are provided such as 3D concrete printing, self-compacting concrete (SCC) and sensor-enabled smart concreting. A synthesis of empirical field data and academic literature reveals gaps in research and on-site practices and a solution approach. Recommendations are made for improving the quality of construction work, expanding workforce training and changing government policies as appropriate. While providing a pragmatic approach to the transition to low-carbon infrastructure, this review adds to the contemporary dialogue regarding sustainable, high-performance concrete systems.

Keywords: Concrete technology; Supplementary Cementitious Materials (SCMs); sustainable construction; nano-admixtures; lifecycle assessment (LCA); self-compacting concrete; batchi

1.Introduction

Concrete continues to be the most widely used construction material in the world for the construction of highways, bridges, residential towers, and industrial complexes. With annual production reaching over 30 billion tonnes worldwide, the demand for them and many other materials continues to expand due to rapid urbanization and infrastructure growth in developed and developing countries. But the widespread employment of cement and concrete is associated with serious environmental problems. Concrete and its primary binding agent, Ordinary Portland Cement (OPC) contribute approximately 7–8% to global carbon dioxide (CO_2) emissions and positions the concrete industry to be one of the largest contributors to climate change. In the context of the concrete industry in India, the demand for concrete has experienced a sharp increase across the world: in 2023, the cement produced in the country stood at more than 380 million tonnes, making India the second-largest producer in the world (Statista, 2024). At that scale itself, however, the sector faces problems of environmental sustainability and variable quality control (Sharma et al., 2019). Raw materials of differing quality, manual-batching problems, lack of protocol testing, and staff shortage are some of the reasons why urban and semi-urban areas experience very general variation in concrete performance (Raj & Das, 2020). As a result, the challenge has further exacerbated the need for a sustainability-oriented concrete and for strong QA systems in concrete manufacturing. The use of Supplementary Cementitious Materials (SCMs): fly ash, GGBS and silica fume in concrete has been proposed as good potential towards reducing CO_2 emissions of concrete with observed reductions of 23–35% at an energy saving value not to mention strength and durability (Kumar & Singh, 2020). The use of recycled and nano aggregates may also increase the mechanical properties of cement especially in the areas of city development and precast cement industry. Also the application of NDT procedures and lifecycle assessment (LCA) techniques is contributing to a more comprehensive assessment of material performance and the quality of the environment. The aim of this study is to explore what works and where the concreting in the major regions of India needs to be improved. Focusing on empirical field data, available academic literature and current industry trends, we have drawn up strategic recommendations for the promotion of sustainability and durability of concrete in the context of India's climate goals and IS 456:2000 as embodied in the construction industry research agenda.

2.Literature Review

The development of research in concrete technology in the last twenty years emphasizes the optimization of mix design, the increase in durability, and the reduction in environmental impacts. The optimization of mix design is a fundamental concern, with the adoption of multifactorial approaches like Response Surface Methodology, genetic algorithm, and machine learning (ML) to optimize mechanical strength/functioning as a function of performance/workability and sustainability performance. For instance, Kumar et al. (2024) used ML to forecast hydration behaviour of SCM-enriched concrete mixture reducing cement content by 40% without compromising on performance (Kumar, 2024). Similarly, Golafshani et al. (2024) have used a dataset of more than 3,500 concrete samples to train AI models on sustainable recycled aggregate concrete (RAC), showing significant gains in strength and carbon efficiency Golafshani et al., 2024, Chemical and mineral admixtures were incorporated, which resulted in greater concrete performance. Superplasticizers, viscosity-modifying agents, nano-silica, and metakaolin have been well established to increase workability, early-age strength, and longer durability, particularly in challenging conditions. For example, Tipu et al. (2023) reported that the combination of nano-admixtures with GGBS has been found to lead to better chloride resistance and microstructural integrity of high-performance concrete (Tipu et al., 2023). Concrete production, mostly for OPC production, has another priority in relation with environment. Life cycle assessments (LCA) repeatedly find that the binder phase contributes to up to 90% of the embodied CO_2 in concrete. In these conditions, partial cement replacement through the use of industrial by-products such as fly ash and GGBS has been repeatedly recommended to decrease Global Warming Potential (GWP), energy intensity and water demand (Anand et al., 2025; Golafshani et al., 2024). From a dedicated concreting point of view, studies have also been conducted on large concrete mass and underwater concreting. Dasgupta et al. (2018) illustrated the effective control of the temperature differential and durability in Indian dam projects using thermal blankets and anti-washout admixtures for mass concrete pours. Techniques like placing tremie with respect to placement for underwater concreting are refined with rheology-optimized mixes—and the result can now be better cohesion and placement success. Innovative technologies are redefining the concept of concrete construction. 3D Concrete Printing (3DCP) has made the leap from laboratory practice to full scale, allowing efficient and formwork-free digitally constructed materials (Bos et al., 2016). Likewise, self-healing concrete which is made by using microbiology or microcapsules has indicated some promising results in improving service life and lifecycle maintenance (Wang et al., 2022). AI-based curing predicting behavior and strength prediction tools can be used, with work by Nadgouda et al. (2024) providing real-time control using sensor data as a big breakthrough in smart building technologies (Nadgouda et al., 2024). These developments, together, signify a transition in focus away from strength-focused methods towards performance-driven and sustainability-driven frameworks, reinforcing the challenge for India's field-level concreting practices to respond to global trends.

3.Concreting Workflow: A Comprehensive Review.

3.1 Material Selection

3.1.1 Types of Cement : There is the use of cement which has a remarkable influence on determining mechanical performance and durability of concrete. Different kinds of cement are appropriate for specific structural and environmental requirements. According to Indian Standards:

- Ordinary Portland Cement (OPC) is regulated by IS 269:2015.
- IS 1489 (Part 1 & 2):1991 encompasses Portland Pozzolana Cement (PPC).
- Rapid Hardening Cement (RHC) IS 8041:1990.
- Low Heat Cement (LHC) is defined in IS 6452:1989.

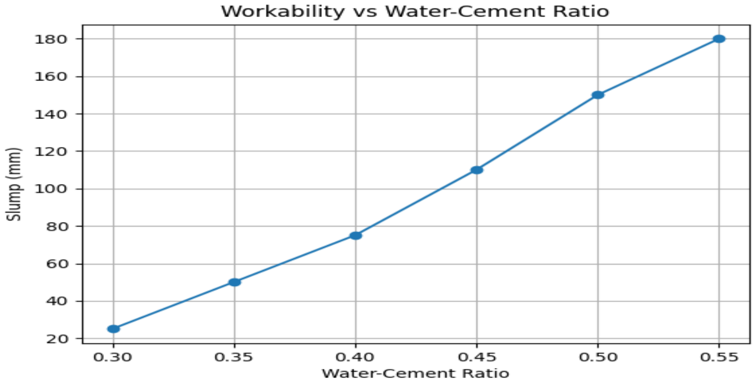
Blended cements (PPC and LHC) are particularly favoured in infrastructural projects due to their better long-term durability and lower heat of hydration, as well as improved longevity compatibility on long-span or mass concreting (IS 1489; IS 6452; Young Civil Engineering, 2017).

3.1.2 Aggregate Classification : Aggregates in concrete mix will comprise 70–80% of aggregate volume therefore significantly affecting workability, strength and durability is a major factor in the final good. Classification and quality control of aggregates are given in:

- IS 383:2016 – Specifications for Coarse and Fine Aggregates.
- IS 2386 (Parts I–VIII):1963 – Methods of Test for Aggregates.

Concrete's strength (with its structure and surface area) is closely controlled by fine and coarse aggregates which in turn influence the fresh and hardened state of the concrete. Lightweight aggregates provide thermal insulation and heavyweight aggregates serve nuclear and radiation-shielded structures (ACI, 2002; Concrete.org, 2023).

3.2 Batching Methods



Graph1:Workability vs Water-Cement Ratio

3.2.1 Volume vs. Weight Batching. Mixing accuracy and ability to predict strength depend heavily on the batch method used. IS 4925:2004 emphasizes the need for precision in batching process, in particular for weight-based systems. Weight batching has been documented to result in higher precision and consistency, which can reduce errors and wastage of material (NRMCA, 2020).

3.2.2 Indian vs. Global Practices :International trends have embraced digital and automated systems to achieve accurate and up to date control on ingredient proportions, while the current baseline model of batching operations in India is still in the primitive form (IS 456:2000). More than ever worldwide, the use of precision batching is ensuring greater quality control and operational excellence (Aimix Group, 2023).

3.3 Mixing Techniques

3.3.1 Manual vs. Machine Mixing : Machine blending is also recommended in all concrete constructors since the IS 456:2000 provides that one shall use only machine mixing in all concrete productions due to uniformity and quality. In a most industrial context, manual mixing is confined to minor works. It is open to human error and due to that uneven dispersion of materials leads to incorrect strength development. However when mixing by hand, the product is not homogeneous and therefore more likely not to hold to a stable surface area.

Table 1: Types of Cement and Their Applications

Cement Type	IS Code	Key Properties	Typical Applications
OPC	IS 269:2015	High early strength	General construction
PPC	IS 1489	Low heat, durable	Mass concreting
LHC	IS 6452	Reduced heat of hydration	Dams
RHC	IS 8041	Rapid strength gain	Pavements

3.3.2 Mixing Duration : IS 4926:2003: Proper mixing time is essential for the uniform distribution of materials. For transit mixers, a mixing process will usually require at least 60 revolutions at no less than 7 RPM to establish a standard mixing time. If under-/over-mixing increases the strength of a specimen is not very great, this will yield only an inferior solution whereas over-mixing results in the lack of segregation and less workability (Scribd, 2021).

3.4 Transportation and Placement

3.4.1 Methods by Terrain and Scale : Transportation of concrete including truck mixers, belts or buckets should be determined based upon the land and project size as well as volume of concrete. IS 456:2000 offers measures for avoiding delays and segregation during transport. Effective logistics keep the desired properties of the mix maintained at place (SE Cement, 2019).

3.4.2 Segregation and Time Management : IS 1199:1959 lays down guidelines for preserving concrete quality in handling. This results in significant delays during placement that can compromise workability and cause segregation. When place is quickly and continuously supported with appropriate planning, homogeneity is maintained in the work (NRMCA, 2020).

3.5 Compaction and Finishing

3.5.1 Mechanical vs. Hand Compaction: IS 456:2000 underlines the need for compaction removal by means of entrapped air and material bonding. Vibrator-based mechanical compaction results in denser concrete structures of higher strength. Compaction by hand can also be labour-intensive and not be as effective to dig deeper into the cement (Cement.org, 2023).

3.5.2 Use of Finishing Tools : Appropriate surface finishing requires the use of trowels, screeds and floats. IS 9103:1999 is a system that governs admixtures, which are the factors which affect the time of setting and surface finish of concrete. The more precise the finish is the better the wear resistance of the concrete and its appearance is appreciated (SE Cement, 2019).

3.6 Curing Methods

3.6.1 Water, Membrane and Steam Curing : Curing is key to both enhancing both strength gain and crack prevention. IS 456:2000 mentions water, membrane, and steam curing methods. Steam curing is particularly applicable to precast parts because, in particular, the strength builds very quickly in steam curing and there is a preference for membrane curing in water-scarce communities (Cement.org, 2023).

3.6.2 Duration and Temperature Control. The hydration rate is directly affected by temperature and curing duration. Under normal conditions, IS 456:2000, is for OPC, 7 days of curing is recommended with OPC. Sustained, well-controlled curing, extended curing reduces cracking and complete strength development can take in full strength development if maintained in a prolonged time (SE Cement, 2019).

4. Innovations in Concreting

4.1. Self-Compacting and High-Performance Concrete : Self-Compacting Concrete. SCC is a non-segregating, highly flowable concrete that spreads into formwork beneath its own weight where mechanical vibration may be unnecessary. Because of this, SCC particularly works well in dense reinforcement structures or complex type of formworks where regular vibrational means are limiting. It improves surface finish, adds higher durability and cuts up on both labour and noise at construction sites with SCC. Design of SCC mixes includes variations to mix proportions which may increase fines and/or use of superplasticizers to obtain the desirable flow capability. An applicable codal guideline for SCC mix design is IS 10262:2019 – Concrete Mix Proportioning. High-Performance Concrete (HPC). High-Performance Concrete (HPC) is designed for superior mechanical and durability capabilities to traditional concrete. Commonly, they consist of adding cementitious materials like silica fume, fly ash and ground granulated blast furnace slag to enhance workability, lessen permeability and improve long-term strength. HPC is widely used in critical infrastructure, such as high-rise buildings, long-span bridges or marine or aggressive chemical-exposed buildings. It follows general principles as provided in IS 456:2000 – Code of Practice for Plain and Reinforced Concrete.

4.2 Smart Sensors and 3D Printing Applications : Smart Sensors. The inclusion of smart sensors in concrete structures is a major breakthrough in construction monitoring and durability assessment. Real time measurement of key factors including interior temperature, dampness, and strain evolution is possible because these sensors are embedded. Such features enable an engineer to make rational decisions on curing, load application, and structural health evaluation. In particular, advancements in electronic textiles (e-textiles) embedded with cementitious materials have evidenced high sensitivity and robustness for long-term monitoring. Such recent developments are increasingly becoming mainstream practices within intelligent infrastructure systems, and have been documented in recent structural health monitoring studies (e.g., [arXiv:2101.00140]). 3D printing in the building of concrete. 3D printing or 3D-printing (additive manufacturing) helps us to generate structures, layer by layer, with automated construction, thereby minimising the need for formwork and handcraft. This technology offers a superior system for design flexibility, low wasted material, and a more rapid construction time. Housing units, custom façade panels and complex architectural elements are some applications of 3D printed concrete. Scalability for large-scale structures has been demonstrated by research and pilot projects, further accelerating the adoption and widespread acceptance of the technology in the worldwide construction industry.

4.3 Techniques of Underwater and Hot/Cold Weather Concreting. Underwater Concreting. Marine structures, foundations, bridge piers, and the like require underwater concreting. Techniques such as tremie pipe, pumping or anti-washout admixtures use to avoid segregation during subaqueous depositions are some common practice. Proper mix design control on top of high cohesiveness and appropriate techniques is needed to guarantee monolithic integrity and bond strength. Special conditions are also covered in the IS 456:2000 material for concrete. Hot Weather Concreting. If ambient temperatures are high, the setting time, workability and long-life of concrete can be affected. Rapid hydration in a warm-weather environment also increases the likelihood of plastic shrinkage, thermal cracking, and rapid moisture loss. The recommended mitigations are the use of cooled materials, set-retarding admixtures, wind barriers, and placement in mild or cooler conditions. The relevant guidelines are detailed in IS 7861 (Part 1):1975 – Hot Weather Concreting. Cold Weather Concreting. Lack of hydration means slower gain in strength and frost damage. In cold climates, pre-heated water and aggregates, thermal insulation, and accelerating admixtures are used to ensure proper curing. These methods will be described in IS 7861 (Part 2):1981 – Cold Weather Concreting, which outlines the processes for concreting below 5°C.

5.Quality Control and Testing

Table 2: Quality Control Tests

Test	IS Code	Purpose
Slump Test	IS 1199	Workability
Compressive Strength	IS 516	Strength
Split Tensile Test	IS 5816	Crack resistance
Permeability Test	IS 3085	Durability

A good concrete quality is necessary for strong structural performance and durability. Fresh/hardened concrete testing is part of QMS testing. Standard test practices in compliance with Indian Standards(IS) and global best practices are described in this part.

5.1 Workability Assessment. Slump Test. The slump test is one of the most common tests used in the field to assess the workability of a fresh concrete. The method is set in the process of the application IS 1199:1959 and consists in inserting new concrete to a standard slump cone which has been cast three layers and tamped with rods. From there, the cone is raised in a vertical direction, and a measure of reduction in height (slump) is provided (Civil Allied Gyan, 2023; BIS, 1959). The degree of workability is divided into:

- Very Low: 0–25 mm.
- Low: 25–50 mm. • Medium: 50–100 mm.
- High: 100–175 mm.

A good test is the simple one. Good results will happen quickly for medium and high workability blends like this and it avoids mistakes that might cause the product to fail. Compacting Factor Test. IS 1199:1959 also describes the compacting factor test, used for concrete with poor workability. It determines the ratio between the weight of partially compacted and fully compacted concrete. This approach generates higher precision for harder concretes, particularly when slump testing is less effective (Scribd, 2023).

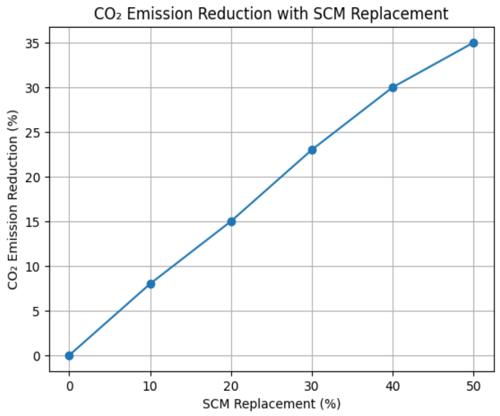
5.2 Strength Evaluation : Compressive Strength Test. A main indication of the strength of concrete is its strength of compression. IS 516:1959 requires the use of cube (150 mm) or cylinder (150 mm × 300 mm) specimens which are cured based on requirement and tested at 7, 28 or 90 days. Strength improvement is tracked over time to guarantee compliance with design standards (Testbook, 2023; BIS, 1959). Split Tensile Strength Test. IS 5816:1999 describes the split tensile test, in which the cylindrical concrete sample is subjected to a diametral compressive force. Due to the necessity to study the tensile behaviour of concrete and its crack resistance.

5.3 Durability Testing

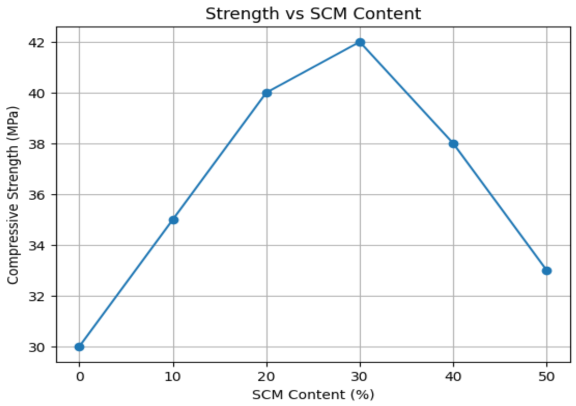
5.3.1 Permeability Test : Fluid ingress resistance of concrete is essential for durability. IS 3085:1965 sets down a measurement test, the water permeability test under pressure. Low permeability provides improved resistance to chloride ingress, freeze-thaw cycles, and sulfate attack, resulting in a longer service life (BIS, 1965). The Rapid Chloride Permeability Test (RCPT). The RCPT (as per ASTM C1202 and AASHTO T277) is used for assessing chloride ion penetration, despite not being part of Indian Standards. A voltage is imposed on the specimen, which causes a change in the charge passed (coulombs) and is an indication of the susceptibility of concrete in marine or chloride rich environments (ASTM, 2019).

5.4.Validation in Laboratory vs Field :Field Testing. Slump, temperature and air content in the mixing and the placing are on-site tested and provide instant feedback. These will enable immediate remediation and will assist in maintaining quality across disparate field environments. Laboratory Testing. The long-term performance is proven in laboratory tests under controlled circumstances. Compressive strength, shrinkage and permeability assessments form the basis for compliance and durability evaluation.

6.Integrated Assessment : Field and laboratory data is combined together to develop a rich system of quality and concrete performance in our concrete system. Laboratory- or field-cured specimens are compared to detect at-site anomalies (Scribd, 2023), aligning with design expectations. Sustainable Concreting. Sustainable concreting incorporates sustainable building materials and procedures to minimize environmental harm while preserving structural strength. Key Elements of Sustainable Concrete Production This subsection outlines the critical ingredients of sustainable concrete construction.



Graph2:CO_2 Emission Reduction with SCM Replacement



Graph3: Strength vs SCM Content

6.1 The Role of Supplementary Cementitious Materials (SCMs)

Table 3: Properties of SCMs

SCM Type	Source	Benefits	Environmental Impact
Fly Ash	Coal plants	Improves workability	Reduces CO_2
GGBS	Steel industry	Enhances durability	Lowers clinker use
Silica Fume	Silicon industry	High strength	Improves impermeability

SCMs are made up of industrial by-products that serve in part for Portland cement while cementing (the concrete is the clinker) by removing small-scale CO_2 emissions. And they all help increase efficiency in workability, strength and durability. • Fly ash: A residual from coal burning that makes the new concrete more workable and takes longer to set. This fine grain-grained material's packing density, permeability and resistance to sulphate and chloride pressure, both of which support it being used for massive concreting and heat-releasing applications.

Ground Granulated Blast-Furnace Slag (GGBS): This steel industry by-product improves toughness in the long term, decreases hydration heat and increases the resistance to chemical attack. It is applied in marine and industrial concrete works owing to its sulphate resistance and the fact that it decreases the level of thermal cracking.

Silica Fume: A very fine byproduct of production of silicon and ferrosilicon alloy products, silica fume is a solid material which enhances concrete compressive strength and its impermeability substantially. It serves as a very good durability in extreme weather conditions with high resistance against an acidic and sulphurous environment.

6.2 Recycled Aggregates and Industrial By-products. Recycled aggregates: These are taken from construction and demolition waste. They not only lower the need for virgin aggregates and contribute to landfilling reductions but also enable a circular economy of materials in the construction industry. Properly processed, they can serve structural end-use in low- to medium-strength concrete applications.

Industrial by-products: fly ash, GGBS and silica fume are recycled in cement for better ecological performance. Not only do they keep the recyclables out of landfills, but they also improve the durability of concrete to complement a circular economy approach.

6.3 Low-Carbon Binders and Lower Water-Cement Ratios. Low-Carbon Binders: The partial replacement of cement with SCMs significantly reduces the need for energy-intensive clinker, thus resulting in a decrease in carbon footprint of concrete. This action is believed to be an important step toward decarbonization of the cement and construction industries.Water-Cement ratio lowering: Reduced water-cement ratio for better strength and impermeability of concrete. In addition, chemical admixtures, like superplasticizers, make it possible to reduce the size of material without loss of workability, leading to a more durable and sustainable structure.

6.4 Policy Implications and Implementation Challenges in India: Policy framework: National Action Plan on Climate Change (NAPCC) encourages sustainable projects in India through various stakeholders, including construction. We want to explore energy efficiency materials and how infrastructure development can support sustainable practices.

Implementation Challenges: o Quality Variability: Inconsistent properties of SCMs due to varying production sources prevent standardization and control of quality. o Lack of Awareness: Lack of technical proficiency among engineers, contractors, and policy makers means that sustainable methods of concreting are not readily accepted and limited technical progress. o Regulatory Barriers: Poor enforcement of sustainability codes and no financial inducements act as hurdles to green construction tech adoption in the mainstream.

7. Challenges and Recommendations

Table 4: Challenges and Solutions

Challenge	Impact	Suggested Solution
Material variability	Inconsistent quality	Standardization
Lack of training	Poor implementation	Certification programs
Limited field validation	Low adoption	Pilot projects

Even with tremendous progress in concrete technology and sustainability, some important gaps exist in practice.

Filling these gaps will depend on targeted interventions, workforce development, and a stronger evidence base in terms of research. Laboratory research and field implementation are still far removed from one another. Although research has shown that supplementary cementitious materials (SCMs), recycled aggregates and low carbon binders offer advantages, lack of general application on site is hampered by:

•Material quality variations (e.g. recycled aggregates with variable gradation or contamination).

•Absence of real-time quality control tools on sites.

•Contractor resistance (to consider or use sustainable materials). Closing this gap will necessitate better on-the-ground testing, real-time tracking and material traceability structures.

7.1 Need for Training and Certification of Workers

Construction workforce skill levels are often inadequate for handling advanced concreting techniques or sustainable materials. Most laborers are not formally trained to:

1) Mix or place SCC or high-performance concrete.
2) Work with recycled materials or waste-derived binders.
3) Implement curing or placement best practices under extreme conditions.

To address this, the following steps are recommended:

1) Develop national certification schemes for concrete laborers and supervisors.
2) Integrate sustainability modules into vocational training programs.
3) Promote industry-academia collaboration for hands-on skill development.

7.2 The role of harmonization of sustainable practices. Without a standardized sustainability approach, projects and regions do not uniformly apply the standards. Many of these contractors work without proper standards regarding:Clear guidelines are needed to specify the minimum amount of supplementary cementitious materials (SCMs) required for different structural components to maintain performance. Limits should also be set on how much recycled aggregate can be used without affecting strength and safety. Additionally, proper criteria must be established to assess durability in harsh or unusual environmental conditions, ensuring structures remain reliable over time.

Recommendations include: Revising IS codes to better correlate with environmental conditions by aligning them with local and national government regulations as well as international standards is essential for improving sustainability in construction practices. Alongside this, there is a need to develop and release simple, clear, and actionable sustainability guidelines that practitioners can easily implement in real-world projects. Furthermore, incorporating mandatory requirements for Life Cycle Assessment (LCA) frameworks in government infrastructure tenders would ensure that environmental impacts are systematically evaluated, promoting more sustainable and responsible decision-making throughout the project lifecycle

7.3 Recommendations for Future Experiment: Empirical studies are urgently required to inform practical decisions. Some suggested directions for research include: The performance of reclaimed aggregates in hot and arid regions needs closer study, as high temperatures and rapid moisture loss can increase the risk of cracking due to shrinkage and thermal stresses. It is also important to evaluate the durability of blended concretes, such as those containing GGBS and silica fume, especially in harsh marine environments where long-term exposure can affect strength and resistance. Understanding how concrete behaves under repeated and dynamic loading, particularly when industrial by-products are incorporated, is another key area of focus. In addition, smart sensors should be tested under real project conditions with limited resources to check their practicality and reliability. To confirm the applicability of these approaches, real-world pilot studies and partnerships with construction companies are necessary.

8. Conclusion

The growth from conventional to high-performance, sustainable forms of concreting reflects the challenge of balancing structural integrity with environmental stewardship. In this paper, we have presented an in-depth examination of the complete concreting system including the fundamental processes in material selection, batching, mixing, placement, curing, and testing of solid concrete and the development of new methods in smart concreting and green technologies.

Addition of SCMs, such as fly ash, GGBS and silica fume, have been found to reduce demand for clinker and enhance durability. Incorporating recycled aggregates and low-carbon binders is a big step in the right direction for a more circular economy, and testing protocols have advanced and brought quality control benefits to the field-laboratory integration. Moreover, 3D printing and embedded sensors are changing how concrete is tracked and built on the fly. However, although advances have been made recently concerning the physical structures and performance of concrete structures, standardized guidelines for the physical aspects, training for labour practices and material compliance remains needed to address this issue.

Solving these issues is a matter of policy intervention; skill upgrading of workers and pragmatic research based on real situations (for example in extreme climates and tight environments). Concrete science will become more innovative, digital monitoring will be much more effective in monitoring progress, and regulatory harmonisation shall be another driving force for the future of this technology. As long as we focus on sustainably sourced, sustainable construction, and practical use, concrete will continue to be not only the underpinnings of infrastructure, but a paradigm for low-carbon engineering advancements

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