

RESEARCH CONTRIBUTIONS OF NATIONAL COUNCIL FOR CEMENT AND BUILDING MATERIALS IN THE RESEARCH-DRIVEN EVOLUTION OF INDIAN STANDARDS

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Abstract

This manuscript presents the fundamental and blue-sky research contributions of the Construction Development and Research Group at the National Council for Cement and Building Materials (NCCBM). The research spans the development of alternative aggregates from construction and demolition (C&D) waste and industrial by-products such as bottom ash, ferrochrome slag, electric arc furnace slag, conarc slag, air cooled blast furnace slag, granulated blast furnace slag etc.; advances in low-carbon binders such as fly ash-slag composite cement, Portland limestone cement, high volume fly ash cement, PSC blended with granulated blast furnace slag (GBFS) and LD slag, and fly ash-limestone composite cements etc.; characterization of high-performance concretes (HPC), ultra high performance concrete (UHPC), geopolymers concrete, roller compacted concrete, sintered fly ash lightweight concrete, pervious concrete, plastic concrete and controlled low strength materials and pioneering work in chemical admixture and reinforcement corrosion inhibitor evaluation, thermal studies and temperature control of mass concrete, cathodic protection, 3D printable concrete, etc. The group's scientific outputs have directly contributed to revisions and formulation of major Indian Standards such as IS: 456, IS: 383, IS: 516, IS: 1199, IS: 9103, IS: 2386^[1-6] etc. This article synthesizes the principal research findings, methodologies, and theoretical advancements developed over the last 10 years of research.

1. INTRODUCTION

Concrete research in India is undergoing a critical shift driven by demands for sustainability, durability, and resource efficiency. With increasing pressure on natural aggregates and cement production, the need for low-carbon materials and innovative construction technologies has intensified. The Construction Development and Research Group at NCCBM has responded to this national challenge through sustained scientific research

into materials, structural behaviour, and durability engineering. This manuscript captures the fundamental research outcomes of the group, focusing on developments that not only address immediate industry needs but also provide foundational knowledge for next-generation concrete technologies. As indicated in the abstract, it is pertinent to outline at the outset the specific technological contributions of the NCCBM over the past decade that underpin the subsequent technical discussions. During this period, NCCBM has undertaken a series of coordinated, long-term research programmes aimed at advancing concrete technology through scientifically rigorous investigations, multi-institutional collaborations, and direct linkage of research outputs with national standardization activities. These initiatives have addressed critical challenges related to sustainable material utilization, durability-driven design, and performance-based specification of concrete materials under Indian environmental and exposure conditions. A key area of contribution has been the systematic research on construction and demolition (C&D) waste^[7-8] and industrial by-products, including bottom ash^[9-10], blast furnace slag^[11], electric arc furnace slag, Conarc slag, ferrochrome slag^[12], and copper slag^[11]. Through comprehensive material characterization, microstructural analysis, mechanical and durability evaluation, and field-scale validation, NCCBM has generated robust datasets and performance criteria that enabled the safe and standardized use of these materials as alternatives to natural aggregates.

These research outcomes have directly influenced revisions to aggregate specifications and test methods, thereby translating laboratory findings into nationally applicable standards and facilitating large-scale industrial adoption. Concurrently, NCCBM has made significant advances in the development and assessment of low-carbon binders^[8, 13], such as composite cements^[14], Portland limestone cement, high-volume fly ash cement^[15, 16], slag-rich binders, and fly ash-limestone composite systems^[16, 17]. Detailed investigations into hydration mechanisms, carbonation resistance, chloride ingress, and reinforcement

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corrosion behaviour have resulted in scientifically justified limits for clinker reduction and optimized blend proportions. The outcomes of these studies have provided a technical basis for new and revised cement standards aimed at reducing the carbon footprint of cementitious materials while ensuring durability and long-term performance. In addition to material innovations, NCCBM has contributed to the advancement of characterization techniques and performance-based evaluation methodologies for emerging concretes, including high-performance concrete [18-19], ultra-high-performance concrete [20], geopolymer concrete, lightweight concrete, roller-compacted concrete, and rheology-controlled 3D-printable concrete.

These efforts have led to improved understanding of mechanical behaviour, durability indices, rheological control, thermal response, and corrosion mitigation, supporting a shift from prescriptive requirements to performance-oriented design and quality control. The generated knowledge has been systematically integrated into revisions of major Indian Standards such as IS: 456, IS: 516, IS: 1199, IS: 9103, IS: 383, and IS: 2386 [1-6] given below in Table 1. The broader impact of these contributions extends to industry practice, academic research, and community outreach. Collaborative projects with academic institutions such as IITs, infrastructure agencies, and industry stakeholders such as Ultratech, JSW, Tata Steel, SAIL, AMNS etc. have facilitated technology transfer, pilot-scale demonstrations, and capacity building. The research outputs have informed academic studies through validated experimental evidence and constitutive models, strengthened industry confidence in sustainable materials, and supported the development of national policies and standards.

As summarized in Table 1, these contributions collectively demonstrate NCCBM’s pivotal role in advancing concrete

technology in India over the past decade and provide the framework for the detailed technical discussions presented in the subsequent sections of this manuscript. Anchored in research-driven principles, the group has systematically translated sustainability, durability, and resource efficiency into national standards, notably through the introduction of multi-source aggregates in IS: 383 [2] and the formulation of a dedicated standard for geopolymer concrete (IS: 17452). The circular utilization of industrial by-products, recycled aggregates, and construction and demolition (C&D) waste supports a circular economy by reducing clinker consumption, conserving natural aggregates, and lowering embodied carbon. Simultaneously, rigorous scientific evaluation of transport properties, permeability, cracking behaviour, and long-term deformation ensures durability under diverse exposure conditions. By explicitly linking material composition and microstructure with exposure-specific performance, these standards facilitate performance-based and service-life-oriented design while mitigating common infrastructure failures such as premature reinforcement corrosion and excessive deflections. Collectively, this approach reframes sustainability from mere material substitution to a reliability-driven engineering paradigm.

2. RESEARCH VISION AND PHILOSOPHY

The group follows a research philosophy centered on (i) circular use of materials, (ii) scientific characterization of concrete properties across scales, (iii) multi-mechanism durability studies, and (iv) translation of research into national standards. Emphasis is placed on blue-sky research that explores fundamental mechanisms governing hydration, microstructure evolution, aggregate-paste interaction, fracture processes, rheology, and corrosion mitigation.

Table 1: Indian standards impacted by NCCBM's research work

| IS CODE | RESEARCH THEME(S) | NATURE OF IMPACT ON INDIAN STANDARDS |
|---------------------------------|--|--|
| IS: 383 (Parts 1 & 2) | C&D waste, industrial by-product aggregates | Transition from natural aggregates to multi-source aggregates; quantified utilization limits; durability-linked acceptance |
| IS: 2386 (Parts 1-5) & IS: 2430 | Aggregate testing & sampling | Introduction of durability, chemical, hazardous, and petrographic testing protocols |
| IS: 456 (under revision) | Low-carbon binders, HPC/HSC, durability design | Shift to performance- and service-life-based design; durability limit states; revised stress-strain and creep models |
| IS: 516 (multiple parts) | HPC, UHPC, FRC, durability testing | Expansion into advanced mechanical and durability testing (permeability, resistivity, creep, tensile response) |
| IS: 1199 (7 parts) | Fresh concrete rheology | Inclusion of SCC, rheology-based workability and setting characterization |
| IS: 9103 (proposed Parts 1-7) | Chemical admixtures | Transformation into performance-based, multi-part admixture standard |
| IS: 17452 | Geopolymer concrete | First national framework for alkali-activated concrete |
| IS: 9142 | Lightweight concrete | Revised constitutive relationships specific to lightweight aggregates |

3. FUNDAMENTAL RESEARCH CONTRIBUTIONS

3.1 Alternate Aggregates

Research on alternate aggregates included systematic evaluation of C&D waste, ferrochrome slag, EAF slag, LD/BOF slag, Conarc slag, bottom ash^[10-11], blast furnace slag and copper slag. Studies established fundamental relationships between mineralogical composition, microstructure, surface roughness, and interfacial transition zone (ITZ) behaviour. The research work has led to the revision of IS: 383^[2]. The current revision will now be published in two parts-Part 1 catering to specifications of aggregates for use in concrete and Part 2 catering to specifications of fine aggregates for use in masonry and plaster. Extensive research conducted by the National Council for Cement and Building Materials (NCCBM) has demonstrated the potential of various industrial by-products and recycled materials as sustainable alternatives to natural aggregates in concrete^[7, 9-12, 18-22].

NCCBM has undertaken systematic investigations on alternative aggregates derived from industrial by-products and C&D waste to reduce dependence on natural aggregates. The studies covered over 150 concrete mixes across strength grades M20-M60, with durability exposure extending up to years. Bottom ash was found suitable as a fine aggregate replacement up to 50 % in OPC-based concretes, maintaining compressive strength above 95 % of control mixes and chloride diffusion coefficients below $12 \times 10^{-12} \text{ m}^2/\text{s}$ ^[9]. Granulated and air-cooled blast furnace slag enabled 100 % replacement of natural sand and up to 50 % replacement of coarse aggregates, achieving compressive strengths exceeding 60 MPa. Processed EAF and CONARC slags demonstrated stable volumetric behavior, permitting full replacement of natural aggregates under defined limits. Recycled concrete aggregates from C&D waste were validated for 40 % replacement in M30 concrete^[8-10]. These findings directly informed the expansion and restructuring of IS: 383, along with revisions to IS: 2386 and IS: 2430, enabling performance-based acceptance of alternative aggregates.

Bottom ash, constituting approximately 20 % of ash generated in thermal power plants, was found suitable for partial replacement of fine aggregates, and the corresponding recommendations have been incorporated into the revised IS: 383^[9-10]. Studies on granulated blast furnace slag (GBFS) revealed that it can effectively replace natural fine aggregates up to 100 % for producing concrete of grades up to M60^[11]. Similarly, air-cooled blast furnace slag (ACBFS) exhibited favorable characteristics, enabling complete (100 %) replacement of natural sand^[10]. Investigations on basic oxygen furnace (BOF/LD) slag established its suitability as fine aggregate in reinforced cement concrete, provided that appropriate weathering treatments are applied to reduce free lime and magnesia content. Electric

arc furnace (EAF) slag and CONARC slag (Figure 1) were both shown to be viable for complete replacement of natural fine and coarse aggregates while maintaining satisfactory fresh, hardened, and durability properties of concrete. Ferrochrome slag demonstrated application-specific potential, wherein water-cooled slag could replace up to 60 % of natural fine aggregates, and air-cooled slag could replace up to 60 % of natural coarse aggregates^[12]. Copper slag was found suitable for replacing natural fine aggregates up to 50 % without compromising performance^[11]. Additionally, the use of recycled concrete aggregates derived from construction and demolition (C&D) waste was found feasible up to 40 % in reinforced cement concrete of M30 grade, marking a significant step toward enhancing resource efficiency and sustainability in the construction sector^[7, 20, 22]. Further to establish correspondence with the specification standard. *i.e.*, IS: 383, the standards on testing of aggregates, *i.e.*, IS: 2386 and the standard on methods of sampling of aggregates, *i.e.*, IS: 2430 are also currently under revision.

3.2 Low-carbon cement systems and cementitious materials

The group developed multiple low-carbon binders including composite cement, Portland limestone cement (PLC), High Volume fly ash cement, PSC blended with granulated blast furnace slag (GBFS) and LD slag, and fly ash-limestone composite cements. Research focused on hydration kinetics, particle packing, synergistic effects of multi-mineral fillers, and durability in sulfate, carbonation, and chloride environments. For the formulation of new standards for low carbon cement extensive study has been carried out in terms of its durability under various aggressive environment (Figure 2).

To address carbon intensity in cement production, NCCBM conducted extensive research on blended and low-clinker binders, including Portland limestone cement, high-volume fly ash cement, and fly ash-slag composites. More than 120 concrete mixtures were evaluated, with clinker substitution levels ranging from 30 to 60 %. Long-term carbonation and chloride exposure long term studies showed that optimized composite binders achieved carbonation depths comparable to OPC and

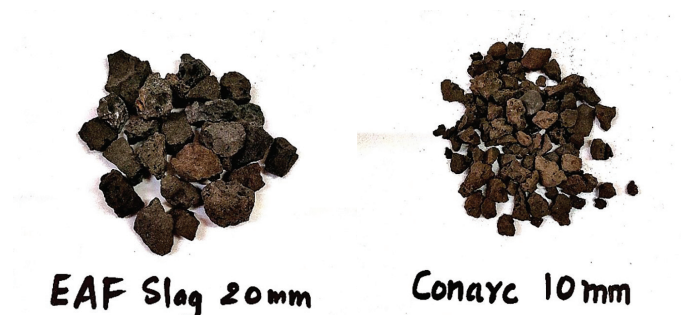


Figure 1: EAF slag and conarc slag aggregates



Figure 2: RCC samples in field environment for durability study

chloride ingress values below 1,000 coulombs in RCPT tests. Reinforcement corrosion studies confirmed passive behavior in moderate exposure environments when mix design and curing were adequately controlled. These results demonstrated that substantial clinker reduction is feasible without compromising durability, provided performance-based criteria are applied. The generated data have contributed to durability-linked provisions and clinker substitution limits in the ongoing revision of IS: 456 and draft low-carbon cement standards, supporting a transition from prescriptive cement composition requirements to exposure-based performance specifications.

The extensive evaluations on various composite cement systems-including fly ash-slag composite cement, Portland limestone cement (PLC), high-volume fly ash cement (HVFA), fly ash-limestone composite cement, helps to establish optimal blend proportions ensuring mechanical and durability performance comparable to or exceeding that of PPC^[8, 13-17, 23-27]. Studies on fly ash-slag composites, comprising 20 mortar and 72 concrete mixes, indicated that maintaining a minimum OPC content of 50 % (or clinker \geq 45 %), fly ash between 10-25 %, and GGBS between 25-40 % yields favourable strength,

carbonation resistance, and corrosion performance^[14]. For PLC, assessment of eight concrete mixes showed that limestone fineness \geq 600 m²/kg and overall cement fineness \geq 425 m²/kg ensure performance parity with OPC at limestone contents up to 15 %^[26,27]. Investigations on HVFA demonstrated that blends incorporating 40 % fly ash with a Blaine fineness of 400-410 m²/kg achieve carbonation and corrosion performance comparable to PPC containing 35 % fly ash at 300 m²/kg fineness^[16]. In fly ash-limestone composite cements (24 mixes), optimal performance was achieved with minimum OPC content of 65 % (clinker \geq 60 %), fly ash 15-30 %, and limestone 5-10 % for achieving durability and mechanical properties equivalent or superior to PPC^[23-27]. Based upon the mechanical and durability study carried out on concrete designed at various combinations, following proportions were suggested and drafts were prepared that are submitted to Bureau of Indian standards for discussion as well as deliberations.

The findings of the study will support the development of new cement standards that promote sustainability and achieve a significantly lower carbon footprint-approximately 30-60 % lower than that of ordinary Portland cement. Furthermore, the research confirms that low-carbon cementitious systems offer a dual advantage: they not only ensure the durability and long-term performance of concrete but also contribute substantially to both national and global decarbonization goals. To promote indigenous cementitious materials as potential replacements for imported additives such as silica fume, comprehensive studies have been undertaken on the use of ultrafine cementitious materials specifically ultrafine fly ash and ultrafine GGBS in concrete production. These materials have now been standardized in terms of their physical and chemical characteristics through IS: 19058 (Ultrafine Fly Ash) and IS: 16715 (Ultrafine GGBS). Additionally, ongoing research is exploring the application of ultrafine and nanomaterials, including nanosilica and graphene, for the development of high-performance and ultra-high-performance concrete.

3.3 High performance concrete (HPC) and ultra high performance concrete (UHPC)

Fundamental studies on high-performance concrete (HPC) and ultra-high performance concrete (UHPC) addressed

Table 2: Low carbon cementitious systems

| TYPE OF LOW CARBON CEMENTITIOUS SYSTEM | MINIMUM CLINKER CONTENT, PERCENT | TYPE OF SCM OR ALTERNATIVE MATERIALS, PERCENT | | | |
|--|----------------------------------|---|-------|-----------|----------|
| | | FLY ASH | GGBS | LIMESTONE | LD SLAG |
| Fly ash - slag composite cement | 45 | 10-25 | 25-40 | - | - |
| Portland limestone cement (PLC) | 80 | - | - | 10-15 | - |
| LD slag-based Portland slag cement | 40 | - | 51 | - | \leq 9 |
| Fly ash-limestone composite | 60 | 15-30 | - | 10-15 | - |
| High volume fly ash cement | 55 | 40-45 | - | - | - |

creep, shrinkage, fracture energy, micro cracking patterns, and rate-dependent behavior^[28-33]. Experimental work was supported by advanced characterization, including SEM-EDS, TGA-DTG, MIP, etc. NCCBM's research on HPC and UHPC focused on mechanical behavior, creep, shrinkage, and durability under Indian conditions. Experimental programs included compressive strengths from 60 to 150 MPa, with creep and shrinkage monitoring extending up to 365 days. UHPC mixes incorporating steel fibres achieved tensile strengths exceeding 8 MPa and exhibited post-cracking ductility with fracture energy values more than five times that of conventional concrete. Durability indicators such as water permeability and chloride diffusion were an order of magnitude lower than OPC concretes. Mechanistic insights into creep of blended cements informed revisions to creep models included in IS: 456 (under revision)^[29-30]. IS: 456 (under revision) introduces HPC defined through engineered characteristics such as reduced permeability, abrasion and erosion resistance, shrinkage control, and enhanced ductility, moving beyond strength-based classification. Provisions for UHPC and ultra-high-performance fibre-reinforced concrete (UHFR) enable the adoption of advanced composites with superior tensile capacity, crack control, and impact resistance^[31].

Steel-fibre-reinforced concrete gains formal recognition, with performance classification based on residual tensile strengths and post-cracking behaviour determined through standardized testing aligned with IS: 516-1 (2021) and EN 14651. Design treatment of SFRC predominantly as a strain-softening material ensures structural safety consistent with fib Model Code 2010 practice. Special provisions for high-strength concrete (HSC) address explosive spalling risks during fire exposure, suggesting the use of polypropylene fibres for concrete grades above M60. M60^[32-33]. UHPC represents an advancement over conventional and HPC due to its exceptional mechanical strength, durability, and dense microstructure, enabling more efficient, long lasting structural systems with reduced member sizes and enhanced service life. However, UHPC's low water to binder ratio and dense matrix, while beneficial for strength, result in higher autogenous shrinkage and complex creep behaviour, which can induce internal tensile stresses, microcracking, and serviceability issues if not accurately predicted and managed. Conventional creep and shrinkage prediction models (e.g., B3, B4)^[29-30] tend to overestimate or misrepresent time dependent strains in UHPC because they do not fully capture mechanisms such as self desiccation, chemical shrinkage, pore humidity reduction, and the influence of diverse admixtures and microstructural features inherent to UHPC. The development of a specific coefficient calibrated for UHPC in mix optimisation research provides a more accurate representation of its time dependent deformation characteristics by incorporating parameters directly linked to microstructure, binder interactions, and early age behaviour. Such a coefficient improves predictive accuracy for shrinkage and creep strains, enabling better structural design, reduced

risk of cracking, and enhanced reliability in performance based specifications. By embedding this coefficient into analytical and design frameworks, researchers and practitioners can more effectively bridge the gap between experimental observations and predictive models, addressing key uncertainties in long term performance of UHPC components.

A major advancement is the adoption of a hybrid creep modelling framework, combining creep coefficients for conventional structures in line with fib Model Code 2010 practice for precision-based and long-life design. The model expresses creep as $\varphi(t, t_0) = \varphi_0 \cdot \beta(t, t_0)$, where φ_0 accounts for humidity, member size, concrete strength and age at loading, while $\beta(t, t_0)$ governs time evolution, improving the accuracy of long-term deflection and prestress loss predictions for advanced concrete systems. Research work of NCCBM on fire behaviour of HPC shows that elevated temperatures significantly reduce strength and stiffness. Dense matrices are prone to explosive spalling, which can be mitigated by polypropylene fibres that provide vapour release paths. Thermal gradients and microcracking further compromise post-fire performance. Heat of hydration, thermal diffusivity, and conductivity govern the material's response, emphasizing the need for performance-based evaluation. In the IS: 456 under revision methods to improve the fire resistance of high strength concrete has been included based on limited research done and guidance taken from European standard EN-1992.

3.4 Geopolymer concrete

Geopolymer concrete (GPC), an emerging class of alkali-activated, low-carbon binders, offers a sustainable alternative to ordinary Portland cement (OPC) by utilizing industrial by-products such as fly ash and GGBS and significantly reducing CO₂ emissions. Laboratory and field studies covered over 80 mixes with compressive strengths ranging from 30 to 80 MPa, using fly ash-slag based alkali-activated systems. Durability tests demonstrated chloride diffusion coefficients below $8 \times 10^{-12} \text{ m}^2/\text{s}$ and excellent resistance to sulfate attack. Full-scale precast elements and ready-mix trials confirmed consistency, workability retention, and early-age strength development suitable for precast applications. Based on these validated datasets, geopolymer concrete was standardized in IS: 17452, providing mix design guidance, material specifications, and acceptance criteria. For structural applications, despite strong laboratory evidence of its mechanical and durability performance, its widespread adoption has been limited by the lack of field-scale validation and standardized guidelines. NCCBM's study addresses that gap by developing an M35-grade reinforced geopolymer concrete (RGC) mix suitable for ready-mix production, evaluating its mechanical and durability properties, and constructing and load-testing a full-scale demonstration structure^[34-36]. Activated using sodium hydroxide and sodium silicate, the developed mix achieved high workability,

ambient-curing capability, and stable slump retention-critical requirements for RMC operations. Laboratory investigations confirmed strong performance across strength, modulus, permeability, resistivity, chloride diffusion, and corrosion resistance metrics, matching or exceeding OPC concrete. The geopolymer mix was then used to cast a single-room RGC structure equipped with embedded and surface strain gauges for performance monitoring. Load testing conducted as per IS: 456 (2000)^[1] showed deflection and strain responses well within permissible limits, with substantial recovery after unloading, demonstrating reliable structural behavior. Overall, this study successfully bridges the transition from laboratory development to practical field application, providing essential evidence and quality-assurance practices to support the standardization and broader adoption of geopolymer concrete as a durable, high-performance, and low-carbon construction material.

3.5 Sintered fly ash lightweight concrete

Sintered fly ash lightweight concrete nowadays is getting used in construction industry because of its reduced dead load, improved durability performance, better thermal and sound insulation along with improved fire resistance. Apart from this lower water permeability, lower chloride ion penetration and better corrosion resistance of lightweight concrete makes it more durable as compared to normal concrete. NCCBM has carried out comprehensive investigations on the production and performance of sintered fly ash lightweight aggregates as a sustainable alternative to natural coarse aggregates in concrete^[37-41]. Experimental evaluation of concrete produced

using these aggregates demonstrated that structural-grade strength levels up to M35 can be achieved. Fresh property assessments indicated adequate workability, while mechanical testing lead to the development of various constitutive relationship between properties like flexural strength^[38], Modulus of elasticity^[39, 41-42] with the compressive strength as the conventional relationship between normal weight concrete does not stand valid for light weight concrete and same has been incorporated in revised IS: 9142. Durability studies revealed favorable performance with respect to permeability, shrinkage, and resistance to aggressive environmental exposure. Overall, NCCBM's work establishes sintered fly ash lightweight concrete as a technically viable and environmentally responsible material that enables large-scale utilization of fly ash and reduces dependence on natural aggregates, contributing to resource conservation and improved sustainability in the construction sector.

3.6 Rheology controlled 3D printable concrete

3D-printable concrete is an emerging class of digitally placed, formwork-free materials engineered to flow through a nozzle, retain shape upon deposition, and build structurally stable layers. Unlike conventional concrete, it requires a carefully tuned balance of pumpability, extrudability, and buildability governed by rheology rather than slump. NCCBM's study includes, optimization of cement, fly ash, silica fume, fine aggregate, water, and chemical admixture like PC-based superplasticizer along with VMA for 3D printable concrete mixes. Various tests related to fresh properties were performed to develop a robust 3D-printable mix. Superplasticizer demand increased with rising aggregate to binder (a/b) ratio, while increasing a/b from 0.75 to 0.90 elevated plastic viscosity by ~35%. Flow values of 160-225 mm reflected sensitivity to material type and packing density. Yield stress emerged as critical for structural stability, as low yield stress caused layer collapse and inadequate buildability. An optimum polypropylene fibre content of 0.1% ensured smooth extrusion with no clogging or shrinkage cracking, and the system exhibited an open time of 12-15 minutes^[42]. Overall, the findings underscore that precise mix design-particularly binder composition and admixture dosage-is essential for achieving reliable, high-performance 3D-printable concrete. Based upon the extensive work carried out, design guidelines on 3D printable concrete mixes has been submitted to CED32 committee of BIS.

3.7 Plastic concrete, pervious concrete and controlled low strength material (CLSM)

NCCBM carried out an extensive investigation into three specialized concretes-Pervious Concrete, Plastic Concrete, and Controlled Low Strength Material (CLSM) to develop high-performance, application-specific materials using locally available constituents. The study established clear relationships between mix parameters and functional properties: pervious

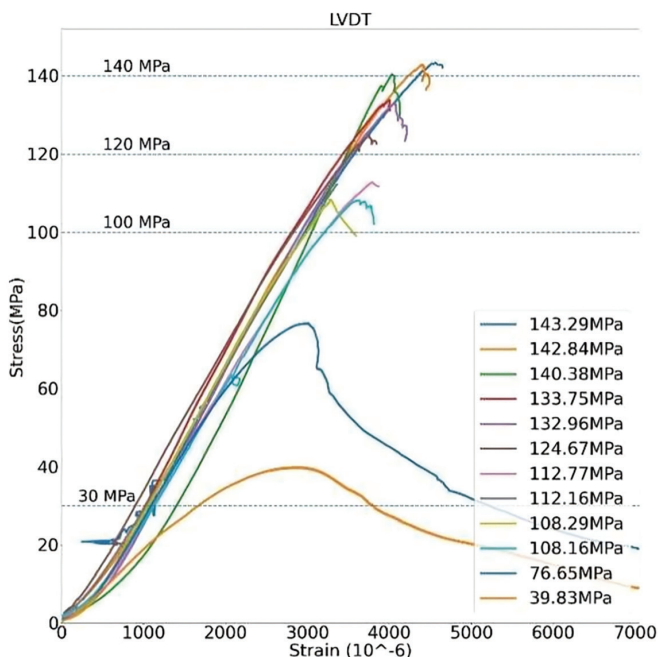


Figure 3: Graphs for strain vs stress

concrete demonstrated optimized strength-permeability balance through controlled porosity and limited fine content; plastic concrete exhibited enhanced ductility and ultra-low permeability with increasing bentonite incorporation, supporting its use in cut-off walls and seepage control; and CLSM mixes, formulated with exceptionally high fly ash volumes, delivered self-compacting, low-strength, low-permeability performance ideal for sustainable backfilling and utility bedding^[35]. Mix Design philosophy and methodology for pervious concrete was adopted in IRC44 based upon the research work done at NCCBM.

3.8 Roller compacted concrete

Roller Compacted Concrete (RCC) refers to a special class of concrete, which is compacted by the vibratory rollers. RCC, which uses the same basic ingredients as conventional concrete but in different proportions, commonly incorporates high volumes of fly ash to replace Portland cement (PC), while the use of limestone remains limited despite its role as both an inert filler and a minor reactive component. Studies carried out at NCCBM^[27, 28] evaluate optimal PC replacement levels using fly ash and limestone to develop high-volume fly ash RCC mixes suitable for dam construction in India. Seventeen mixes were prepared with up to 72 % PC replacement using two fly ash types and two limestone sources, and their fresh properties (Vee-Bee time, density, setting time) and compressive strengths (7-180 days) were assessed. Ternary mixes containing OPC, fly ash, and limestone showed setting times intermediate to those of binary mixes and exhibited superior strength at all ages due to synergistic effects. Results indicate that 365-day strength is nearly double the 28-day strength, admixtures have negligible influence on compressive strength, and finer fly ash enhances long-term strength, with all mechanical and thermal properties aligning with Indian Standards and international data.

3.9 Thermal Properties on concrete and temperature control of mass concrete

NCCBM has conducted extensive studies on the thermal properties of mass concrete for several hydroelectric projects, including the Dhaulasidh, Arun-3, and Luhri H.E. Projects. It has also carried out temperature-control investigations for projects such as the Tanahu and Dibang H.E. Projects. The thermal studies involved evaluating concrete mixes for key parameters like coefficient of thermal expansion, specific heat, thermal conductivity, and thermal diffusivity using the Transient Plane Source (TPS) method, while the temperature-control studies included semi-adiabatic temperature-rise measurements on various concrete mixes. However, based on these studies, it has been found that there is need to revise standards on thermal properties of concrete and temperature control of mass concrete as mentioned in section 4.5

3.10 Test methods of fresh and hardened concrete

There was a pressing need to develop and standardize test methods for fresh and hardened concrete that capture the unique rheology, mechanical behaviour, and durability performance of self-compacting, 3D-printable concrete, HPC, UHPC, and other next-generation concretes. Novel rheological frameworks were developed to characterize flow, setting, and early-age stiffness evolution. These studies supported revision of IS: 1199 to revised test procedures for workability, setting characteristics. The studies also lead to the revision of IS: 516, with inclusion of new standards associated with mechanical properties of concrete such as flexure, compression, direct tensile strength and durability assessment of concrete through tests like depth of water penetration, oxygen permeability, carbonation resistance etc. As an outcome of NCCBM's research work, IS: 1199 has been revised and published in 7 Parts as (a) Part 1-Sampling of Fresh Concrete, (b) Part 2-Determination of Consistency of Fresh Concrete, (c) Part 3-Determination of Density of Fresh Concrete, (d) Part 4-Determination of Air content of Fresh Concrete, (e) Part 5-Making and Curing of Test Specimens, (f) Part 6-Tests on Self Compacting Concrete, and (g) Part 7-Determination of Setting Time of Concrete by Penetration Resistance. Additional guidance has been incorporated in Part 5 to specify preferred methods of compaction based on slump requirements, with particular emphasis on Self-Compacting Concrete (SCC) and Fiber-Reinforced Concrete (FRC). Furthermore, Part 6 introduces standardized test methods applicable to SCC, ensuring uniform evaluation of its fresh and hardened properties. Some of the revised IS: 516 standards are (a) IS: 516 Part 1/Section 1-Testing of Strength of Hardened Concrete-Compressive, Flexural and Split Tensile Strength, (b) IS: 516 Part 4-Sampling, Preparing and Testing of Concrete Cores, (c) IS: 516 Part 6-Drying Shrinkage and Moisture Movement, (d) IS: 516 Part 8/Section 1-Modulus of Elasticity and Poisson's Ratio (Static), (e) IS: 516 Part 11-Determination of Portland Cement Content of Hardened Concrete, (f) IS: 516 Part 5/Section 1-Ultrasonic Pulse Velocity (UPV) Test, (g) IS: 516 Part 5/Section 3-Carbonation Depth Test, (h) IS: 516 Part 5/Section 4-Rebound Hammer Test. To facilitate comprehensive assessment of concrete durability, several standardized test methods have been incorporated into IS: 516 for evaluating key performance parameters, they are as (a) Water permeability test-IS: 516 Part 2/Section 1, (b) Initial Surface Absorption test-IS: 516 Part 2/Section 2, (c) Oxygen permeability index-IS: 516 Part 2/Section 3, (d) Carbonation resistance of hardened concrete by accelerated carbonation method-IS: 516 Part 2/Section 4, (e) Half-cell Potential Test-IS: 516 Part 5/Section 2. This breakthrough in the standardization now makes it possible to explore the impact of innovative cementitious materials and alternative aggregates on concrete rheology, and to fine-tune concrete mix proportions for

designing stronger and durable concrete. Furthermore, many more standards are also under formulation to cater the needs of various engineering and durability properties of the concrete as mentioned in section 4.3.

3.11 Chemical admixture evaluation

The evolution of chemical admixtures has arguably been the single most transformative development in the modernization of concrete. Originally conceived as workability aids or setting modifiers, admixtures are now precision tools for microstructure tailoring, enabling control over hydration kinetics, particle dispersion, shrinkage, and pore structure formation. Admixtures such as polycarboxylate ether (PCE) based superplasticizers, Viscosity Modifying Admixtures (VMAs), modern retarders and accelerators which fine-tune the induction period of hydration, offering precise control over setting and early strength development in case of self-compacting concrete and rheology controlled 3D printable concrete mixes.

Fundamental evaluations of permeability-reducing admixtures for hydrostatic (PRAH) and non-hydrostatic (PRAN) applications were conducted. The group also pioneered research on organic and inorganic corrosion inhibitors^[44], establishing mechanistic pathways of inhibitor-steel interaction, adsorption thermodynamics, and long-term performance under chloride and carbonation exposure. Over the past decade, the group has rigorously evaluated a diverse spectrum of chemical admixtures such as low, high and mid-range water reducing admixtures, retarders, extended set retarders, anti washout admixtures, viscosity modifiers, permeability reducing admixtures, corrosion inhibitors etc. while simultaneously pioneering advanced techniques and methodologies for their performance assessment. These breakthroughs have paved the way for a transformative revision of IS: 9103 as mentioned in Section 4.4. The proposed paradigm shifts positions the standard to encompass comprehensive general requirements, clearly defined performance benchmarks, compatibility evaluation protocols, and robust testing methodologies. Adopting this forward-looking framework will catalyze innovation, accelerate research, and foster the development of next-generation chemical admixtures, ultimately elevating the technological landscape of concrete science in India.

3.12 Corrosion mitigation, cathodic protection and concrete surface coatings

A significant line of research involved electrochemical characterization of steel in concrete exposed to chloride and carbonation environments. Studies developed correlations between concrete chemistry, pore solution properties, corrosion rate, and protection mechanisms. The group advanced cathodic protection (CP) methodologies for Indian conditions, including sacrificial anode based CP systems and performance monitoring frameworks. NCCBM carried out experimental

investigations on the effectiveness of sacrificial anodes in different cementitious systems for both corrosion control and corrosion prevention under carbonation induced and chloride induced corrosion environments. This research evaluates the effectiveness of cathodic protection-specifically sacrificial zinc anodes-in extending the service life of reinforced concrete structures exposed to corrosion from chlorides and carbonation. Recognizing that conventional patch repairs often fail due to electrochemical incompatibility, the study compares sacrificial anodes across different cementitious systems (OPC, OPC-Fly Ash, PSC, OPC-GGBS, and ternary blends) through laboratory and field investigations. Laboratory tests show that sacrificial anodes significantly reduce corrosion rates in both corrosion-control and corrosion-prevention applications, with greater gains in chloride-induced corrosion and higher effectiveness when corrosion has not yet initiated. Performance also depends on the initial corrosion rate, with lower initial deterioration yielding larger service-life improvements. A field study on a residential building in Delhi confirmed that the installed anode system delivered current outputs consistent with ISO 12696 criteria, demonstrating effective cathodic prevention when combined with complementary repair measures. Overall, the study establishes sacrificial anodes as a practical, cost-effective means to enhance durability in new and existing concrete structures and provides a basis for developing Indian guidelines and best-practice specifications. The formulation of guidelines and specifications for adoption of CP for RCC is also under discussion at the level of BIS.

Another study on the Evaluation of Concrete Surface Coatings for their effectiveness in service life enhancement of RCC elements was taken up. This study evaluates commercially available surface coatings for concrete to identify those most effective in extending the service life of reinforced concrete structures under typical Indian exposure conditions, especially chloride-induced and carbonation-induced corrosion. Four coating types (acrylic, epoxy, polyurethane, and cementitious polymer modified) along with silane-siloxane and methyl methacrylate treatments were tested through standardized assessments of water permeability, chloride diffusion, carbonation resistance, adhesion, moisture control, and chemical durability. Results show that epoxy and polyurethane coatings consistently offer the highest protection, outperforming acrylic and cementitious coatings in most durability criteria, while also providing better cost-to-performance balance. The study proposes threshold values and selection guidelines for coating performance to support inclusion in BIS standards, enabling more informed, exposure-specific coating selection for improved longevity of reinforced concrete structures in India.

3.13 Stress-strain characteristics of high strength concrete

In the IS: 456 under revision, provisions are being proposed for inclusion that specifically address the stress-strain behaviour

Table 3: Extent of utilization of manufactured coarse aggregate

| SL. NO. | TYPE OF AGGREGATE | MAXIMUM UTILIZATION AS A PERCENTAGE OF TOTAL MASS OF COARSE AGGREGATE | | |
|---------|---|---|------------------------------|--|
| | | PLAIN CONCRETE, PERCENT | REINFORCED CONCRETE, PERCENT | LEAN CONCRETE (LESS THAN M15 GRADE), PERCENT |
| a) | Processed Air cooled Blast Furnace slag (ACBFS) aggregate | 50 | 25 | 100 |
| b) | Processed Electric arc furnace slag (EAFs) aggregate | 100 | 100 | 100 |
| c) | Processed Conarc slag aggregate | 100 | 100 | 100 |
| d) | Recycled concrete aggregate (RCA) | 40 | 40 (upto M30 grade) | 100 |

Table 4: Extent of utilization of manufactured fine aggregate

| SL. NO. | TYPE OF AGGREGATE | MAXIMUM UTILIZATION AS A PERCENTAGE OF TOTAL MASS OF FINE AGGREGATE | | |
|---------|---|---|------------------------------|--|
| | | PLAIN CONCRETE, PERCENT | REINFORCED CONCRETE, PERCENT | LEAN CONCRETE (LESS THAN M15 GRADE), PERCENT |
| a) | Processed Air cooled Blast Furnace slag (ACBFS) aggregate | 100 | 100 | 100 |
| b) | Processed Granulated Blast Furnace slag (GBFS) aggregate | 100 | 100 (up to M60 grade) | 100 |
| c) | Processed Electric arc furnace slag (EAFs) aggregate | 100 | 100 | 100 |
| d) | Processed Conarc slag aggregate | 100 | 100 | 100 |
| e) | Processed Copper slag aggregate | 40 | 35 | 50 |
| f) | Recycled concrete aggregate (RCA) | 25 | 20 (upto M25) | 100 |
| g) | Bottom ash from Thermal Power Plants | 50 | 50* / 25** | 50 |

* For concrete made with OPC

** For concrete made with PPC or OPC with fly ash, PSC or OPC with GGBS, and composite cement.

and stress block parameters for high-strength concrete (HSC), recognizing that the current code provisions are insufficient beyond M55. Experimental research at NCCBM has shown that HSC exhibits a more linear and steeper ascending stress-strain curve (Figure 3) with a significantly reduced ultimate strain, unlike the constant 0.0035 strain value presently used in IS: 456.

Consequently, revised values of the strength reduction factor (K) and lever arm factor (k_2) which reduce progressively with increasing concrete grade-are being proposed to prevent overestimation of flexural strength and compression capacity. Typical values being recommended for higher grades are K in the range of 0.25-0.31 and k_2 between 0.33-0.36, compared to existing IS: 456 values of 0.36 and 0.42 [32-33]. The proposed revisions will enable more realistic modelling of flexural behaviour, reduce neutral axis depth for balanced sections, and enhance ductility and safety margins in structural design involving high-strength concrete, particularly in high-rise, prestressed and seismic-resistant structures. These inclusions aim to align IS: 456 with global design practices such as Eurocode-2 and ACI, ensuring reliability and performance-based design using modern high-strength concrete.

3.14 Limit state of durability design for resistance against corrosion

Durability-based limit state design for resistance against corrosion proposed in the revision of IS: 456 shifts from the

traditional deemed-to-satisfy approach toward a performance-based, service-life-oriented methodology, where deterioration mechanisms like carbonation and chloride-induced corrosion are explicitly modelled. The revised framework is aligned with ISO 16204 and fib Model Code principles, intending to use quantifiable durability limit states rebar depassivation, cracking due to corrosion, and cover spalling to ensure that the initiation plus propagation period of corrosion exceeds the design service life. For carbonation, ingress is expressed as a square-root-of-time model to determine when the carbonation depth equals the concrete cover, while chloride ingress is evaluated using Fick's second law, where chloride concentration at reinforcement depth $C(x, t)$ is compared with the critical chloride threshold required to trigger corrosion. The apparent diffusion coefficient D_{app} decreases over time due to ageing, enabling prediction of chloride penetration and cover design [16,25]. Under the upcoming IS: 456 revisions, concrete cover, material specifications, crack control and quality control parameters are expected to be determined based on these predictive durability models, supporting a rational and reliability-based service life design rather than prescriptive minimum values.

4. CONTRIBUTIONS TO INDIAN STANDARDS

Research outputs have led to the revisions of several BIS standards including IS: 456, IS: 383, IS: 9103, IS: 1199, IS:

516, and IS: 2386⁽¹⁻⁶⁾. Contributions include classification of alternative aggregates, incorporation of new exposure classes for durability, updated testing protocols, performance-based criteria for admixtures, and harmonization of mechanical and durability requirements with global best practices.

4.1 Revision of IS: 456 structural concrete-code of practice

IS: 456, the Indian Standard Code of Practice for Plain and Reinforced Concrete, was first published in 1953 and subsequent revised in 1957 and 1964 to provide basic guidance on concrete materials, design and construction. A major scientific shift took place in 1978 with the introduction of Limit State Design. A comprehensive revision came in 2000, incorporating advances in concrete materials, durability provisions, workmanship, testing, and alignment with structural engineering practices. Since then, IS: 456 (2000) has been reaffirmed several times. BIS is currently working on a new revision to incorporate modern durability and sustainability concepts, advanced materials such as blended cements and SCMs, and performance-based design principles, although it has not yet been released. Currently, IS: 456⁽⁴⁵⁾ is under revision with the titled "Structural Concrete-Code of Practice", its incorporates a transformational upgrade from the 2000 edition, moving from prescriptive specifications to a modern performance-based design philosophy aligned with ACI 318, Eurocode 2, fib Model Code 2010 and EN 206. The new provisions integrate advanced concrete technologies, high-performance materials, durability modelling and structural fire engineering to support long-life and resilient infrastructure. The key changes and additions based on work done by the research group for revision of IS: 456 are as under:

1. Broadened acceptance of Supplementary Cementitious Materials (SCMs) such as ultrafine GGBS, processed fly ash, silica fume, metakaolin, rice husk ash, LC³ components, and calcined clays
2. Expanded coverage of modern chemical admixtures, including HRWR/polycarboxylate ether (PCE), shrinkage-reducing admixtures, viscosity-modifying admixtures, corrosion inhibitors, and self-compacting concrete admixtures.
3. High-strength concrete (HSC) upgraded with provisions addressing explosive spalling and suggesting polypropylene fibres above M60 for fire safety.
4. Introduction of high-performance concrete (HPC) based on performance criteria such as permeability, abrasion resistance, shrinkage control and enhanced ductility. Formal coverage of fibre-reinforced concrete for superior tensile performance and crack control.

5. Adoption of structural lightweight concrete using sintered fly ash aggregates.
6. Introduction of a hybrid creep model for accurate long-term deflection and prestress-loss prediction.
7. Comprehensive limit-state durability design with exposure-class-based requirements such as 4 classes of exposure conditions for carbonation induced corrosion environment, 7 classes of exposure conditions for chloride induced corrosion environment, 3 classes of exposure conditions for sulphate environment and 3 classes of exposure conditions for freeze and thaw environment has been proposed in IS 456 in line with EN 206 environmental conditions. Additionally, predictive carbonation/chloride modelling and electrical resistivity performance testing was also introduced.
8. Integration of performance-based structural fire design, including temperature-dependent material degradation curves and advanced thermal-structural analysis options.
9. Introduction of Construction Quality Control Classes (QC1, QC2, QC3) based on project scale, risk level, and durability requirements, defining mandatory testing frequency and acceptance criteria

4.2 Revision of IS: 10262 concrete mix design guidelines

IS: 10262 was first published in 1982 and substantially revised in 2009 to become the Indian guideline for concrete mix proportioning. Based on the research work done by this group, IS: 10262 (2019) revision significantly expands the scope of concrete mix design. While the 2009 code mainly covered normal strength concrete, the 2019 version introduces detailed procedures for high-strength concrete (above M60), Self-Compacting Concrete (SCC), and mass concrete, making it more comprehensive. It also includes updated guidelines for the use of mineral admixtures and chemical admixtures, revised approaches for determining target mean strength, and improved methods for adjusting workability, water-cement ratio, air content and aggregate proportions. To align with the ongoing revision of IS: 456, which emphasizes performance-based durability provisions against carbonation and chloride induced reinforcement corrosion environment, exposure classifications, and service life design of concrete structure; the future revision of IS: 10262 must integrate durability-based mix-design principles by linking water-binder ratio, binder composition, and cover requirements directly to exposure categories derived from deterioration mechanisms and target service life.

4.3 Revision/formulation of standards in the area of cement and cementitious materials

The Indian Standards for cement and cementitious materials have evolved through a long scientific progression, beginning with early strength- and composition-based specifications in the 1950s-1970s and gradually shifting toward performance, durability, and sustainability. Core product standards such as IS: 269 (OPC), IS: 455 (PSC), IS: 1489 (PPC), IS: 16415 (Composite Cement) and related codes have undergone multiple revisions reflecting advances in clinker chemistry, mineral admixture utilization, energy efficiency, and emission reduction. The recent introduction and revision of standards for Portland limestone calcined clay cement (IS: 18189), composite cement (IS: 16415), slag-rich binders, and blended cements with fly ash, GGBS, silica fume, calcined clay, copper slag or LD slag reflect a shift towards low-carbon, resource-efficient cements aligned with circular economy principles. Despite these advances, full harmonization with ASTM C150/C595/C618, EN 197 series, and ISO 679/14021 is still evolving. Current scientific momentum emphasizes the need for further revision and formulation of Indian Standards toward internationally aligned, sustainability-driven, performance-oriented specifications that support modern concrete technology, durability assurance, and national decarbonization goals. Drafts of specifications for Portland Limestone Cement (PLC) and recommendations for the revision of fly ash-slag composite cement, IS: 16415 have been submitted to BIS for consideration and deliberation.

4.4 Revision of IS: 383 aggregates-specification: coarse and fine aggregates for concrete and IS: 2386 methods of test for aggregates for concrete

Since its first publication in 1952 and subsequent revisions in 1963 and 1970, IS: 383 focused exclusively on natural aggregates. A major shift occurred with the 2016 revision, which for the first time incorporated manufactured, recycled, and industrial by-product aggregates. The current revision aims to further broaden aggregate sources and establish more comprehensive quality controls extending beyond size and grading to include durability, chemical compatibility, and consistency across various aggregate types. This transition reflects advancements in material science, sustainability, and durability-based concrete design, aligning the aggregate standard with contemporary concrete technology. The revised IS: 383 Parts 1 and 2^[46,47], as listed below, mark a major advancement by incorporating a wide spectrum of new aggregate sources-including materials from the iron and steel industry, copper industry, C&D waste, and bottom ash from thermal power plants.

| Standard | Title |
|------------------|---|
| IS: 383 - Part 1 | Aggregates - specification: coarse and fine aggregates for concrete (under development) |
| IS: 383 - Part 2 | Aggregates - xpecification: coarse and fine aggregates for mortar and masonry (under development) |

Based upon the study carried out by NCCBM, IS: 383 is being revised. The standard will now include the different types of manufactured aggregates as mentioned in Table 3 and 4 along with their extent of utilization.

The revision of IS: 383 is supported by update versions of standards on testing - IS: 2386 - Part 1 to Part 5^[48-52] and standard on sampling methods - IS: 2430^[53]. The details of the same are as under:

| Standard | Title |
|-------------------|--|
| IS: 2430 | Methods for sampling of aggregates for concrete |
| IS: 2386 - Part 1 | Methods of test for aggregates for concrete : determination of physical properties |
| IS 2386 - Part 2 | Methods of test for aggregates for concrete : determination of mechanical properties |
| IS 2386 - Part 3 | Methods of test for aggregates for concrete : determination of durability properties |
| IS 2386 - Part 4 | Methods of test for aggregates for concrete : determination of chemical and hazardous properties |
| IS 2386 - Part 5 | Methods of test for aggregates for concrete : petrographic examination of aggregates |

In the area of sintered lightweight aggregate, the extensive research carried out at NCCBM has directly contributed to the revision of IS: 9142 Parts 1 and 2, resulting in the inclusion of new provisions addressing the engineering properties of structural lightweight concrete.

4.5 Revision of IS: 1199 analysis of fresh concrete and IS: 516 test methods for hardened concrete

IS: 1199 (Methods of Sampling and Analysis of Concrete) was first published in 1959, revised in 1959/1960, and later comprehensively updated in 2018 as IS: 1199 (Part-1 to Part-3) (2018), introducing modern test methods, fresh-concrete rheology, workability by newer apparatus, and improved sampling procedures. IS: 516 (Methods of Tests for Strength of Concrete) originated in 1959 and remained unchanged for decades until its major scientific upgrade in 2018-2021, when it was split into IS: 516 (Part-1 to Part-5) covering compressive, flexural, tensile, static modulus, and nondestructive tests with updated equipment standards and precision requirements. Both standards are presently undergoing further scientific addition of standards on test methods to align with high-performance concrete, digital testing systems, and

performance-based design practices. Additional IS: 1199 and IS: 516 standards are under development to further support comprehensive assessment of fresh and hardened concrete properties. Some of the IS: 1199 standards that are under the stage of formulation are as follows:

| Standard | Title |
|-----------------|--|
| IS: 1199 Part 8 | Determination of water soluble and acid soluble chlorides in fresh mortar and concrete |
| IS: 1199 Part 9 | Field tests for capturing heat signature and pumpability |

New standards related to IS: 516 that are under the development stage based upon the work carried out at NCCBM are as follows:

| Standard | Title |
|---------------------|--|
| IS: 516 Part 1/Sec1 | Determination of compressive strength of concrete using portions of beams broken in flexure (Equivalent cube method) |
| IS: 516 Part 2/Sec8 | Test method for electrical indication of concrete's ability to resist chloride ion penetration |
| IS: 516 Part 2/Sec9 | Determination of chloride diffusion coefficient |
| IS: 516 Part 3 | Making, curing and determining compressive strength of accelerated cured concrete test specimens |
| IS: 516 Part 5/Sec5 | Concrete cover measurement |
| IS: 516 Part 5/Sec7 | Creep of concrete cylinders in compression |
| IS: 516 Part 8/Sec2 | Determination of modulus of elasticity by electrodynamic method |
| IS: 516 Part 9/Sec1 | Determination of wear resistance : Underwater concrete |
| IS: 516 Part 9/Sec2 | Determination of wear resistance : Pavement concrete by revolving disc method |
| IS: 516 Part 12 | Determination of water soluble and acid soluble chlorides in hardened mortar and concrete |
| IS: 516 Part2/Sec5 | Surface resistivity of concrete |
| IS: 516 Part2/Sec6 | Bulk resistivity of concrete |
| IS: 516 Part2/Sec7 | Volume of permeable voids and determination of permeability |

4.6 Revision of IS: 9103 specifications of chemical admixtures for concrete

IS: 9103, first published in 1979 and revised in 1999 with later updated in 2013 and 2022, reflects the evolution of concrete admixture technology but still has significant scientific limitations. The standard continues to focus mainly on water reducers, superplasticizers and set-controlling admixtures, while important modern categories such as corrosion inhibitors, viscosity-modifying admixtures (VMA), rheology modifiers, permeability-reducing admixtures (PRA), shrinkage reducers,

durability enhancers and integral waterproofing additives remain outside its scope. Testing requirements also do not fully address compatibility with SCM-rich binders, high-performance concrete, ultra-low w/b ratios, or long-term durability performance. Moreover, IS: 9103 is not fully harmonized with international frameworks such as ASTM C494, ASTM C260, ASTM C1582, EN 934 series, or ISO admixture standards, which provide broader classification, clearer performance criteria and more rigorous testing protocols. These gaps highlight the urgent need for a comprehensive scientific revision of IS: 9103 to incorporate advanced admixture chemistry, performance-based evaluation, durability-driven specifications and global harmonization, ensuring that Indian concrete practice remains aligned with international standards. As discussed in 3.7 w.r.t advancement in the field of chemical admixtures, it is proposed to draft standards to cover recent advances in the field of chemical admixtures, they are as follows:

| Standard | Title |
|-----------------|--|
| IS: 9103 Part 1 | Specification for normal, mid-range, and high-range water-reducing admixtures for concrete |
| IS: 9103 Part 2 | Specification for accelerator, set-retarder and extended set-controller admixtures for concrete |
| IS: 9103 Part 3 | Specification for viscosity modifying admixtures including anti wash out admixtures for concrete |
| IS: 9103 Part 4 | Specification for air entraining admixtures for concrete |
| IS: 9103 Part 5 | Specification for shrinkage reducing admixtures for concrete |
| IS: 9103 Part 6 | Specification for corrosion inhibitor for concrete |
| IS: 9103 Part 7 | Specification for permeability reducing admixtures for concrete |

4.7 Revision/formulation of standards for thermal properties of concrete and temperature control of mass concrete

Indian Standards on thermal properties and temperature control in mass concrete-covering dams, deep rafts, and piled foundations-require a shift from empirical rules to performance-based management. Current codes such as IS: 456, IS: 16700, IS: 2911, and IS: 14591 provide limited guidance on hydration heat, thermal diffusivity, cracking risk, staged construction, and soil-structure restraint, lagging behind international references like USACE EM 1110-2-2201, ACI 207, and ICOLD Bulletins. Advances in hydration modelling, finite-element thermal analysis, and low-heat binders demand explicit standards addressing heat of hydration, thermal conductivity, creep-shrinkage interaction, construction sequencing, and differentiation between transient and steady-state thermal stresses. Comprehensive revisions are therefore needed

to integrate thermal simulation, low-heat materials, and performance-based stress control, ensuring durability and structural reliability in mass concrete applications.

5. CONCLUDING REMARKS

The comprehensive research undertaken by NCCBM has significantly advanced India's capabilities in concrete materials, construction technology, and standardization. Evidence-based studies on cementitious materials, aggregates, admixtures, thermal behavior, and structural performance have shaped major revisions of core standards, including IS: 456, IS: 383, IS: 9103, IS: 1199, IS: 516, and IS: 2386. These contributions have transformed Indian concrete codes from prescriptive, material-centric documents to modern, performance-driven frameworks aligned with global best practices. The adoption of ultrafine SCMs, recycled aggregates, advanced admixtures, and low-carbon binders, along with updated testing methodologies and durability-based design approaches, support sustainable and resilient infrastructure. Collectively, these revisions reflect a shift toward performance-based design, sustainable material utilization, advanced testing, and robust durability frameworks, ensuring that Indian standards remain responsive to emerging technologies, environmental imperatives, and the evolving demands of the construction sector.

6. FUTURE RESEARCH ROADMAP

The group aims to strengthen contributions to standard development and sustainable construction policies in India. The future research program emphasizes carbon-neutral binders, low-energy aggregate synthesis, multi-scale durability modelling, machine-learning-based mix optimization, and next-generation corrosion protection methods. NCCBM has already taken a lead in these areas and is actively working on the following two areas:

1. **Nano-engineered intelligent concrete:** Hydration of Portland cement involves dissolution, nucleation, and growth of calcium-silicate-hydrate (C-S-H) and other products. Nucleation is kinetically slow in conventional systems due to limited reactive surface area. Nano-additives, by providing abundant active nucleation sites, accelerate hydration and refine early microstructure. Nanomaterials not only improve strength and durability but also serve as functional modifiers introducing electrical conductivity, self-sensing capability, and enhanced resilience to micro cracking. NCCBM is working on Nano-Engineered Intelligent Concrete using Nano-silica (n-SiO₂) and graphene-based materials (GBMs) including graphene

oxide (GO), reduced graphene oxide (rGO), and graphene nanoplatelets (GNPs).

2. **Low-energy aggregate and concrete:** Low-energy aggregate synthesis using mineral carbonation converts CO₂ into stable carbonates within industrial by-products or fines, producing engineered aggregates while simultaneously achieving carbon sequestration and reducing the embodied energy of concrete. Mineral carbonation of concrete as well as aggregates.

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