"Temperature-Controlled Concrete for Mass Structures: A Review of Cooling Techniques, Materials (Coolcrete), and Thermal-Crack Mitigation."

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Abstract:

Mass concrete generates significant heat during cement hydration, resulting in high thermal gradients and a risk of early-age cracking. This review examines key temperature-control strategies, including thermal modelling, pre-cooling, embedded cooling pipes, SCM-based mixes, and advanced materials such as PCMs, radiative additives, conductive fillers, and cooling-concrete technologies. Findings indicate that thermal modelling tools and cooling pipes remain the most dependable methods, while innovative materials and digital monitoring systems provide valuable supplementary benefits. Major gaps persist in long-term field validation, standard test protocols, and integration with durability and sustainability metrics. The review highlights the need for hybrid approaches that combine optimized mix design, intelligent monitoring, and efficient cooling systems to support safer, more durable, and sustainable mass concrete construction.

Key words:

Temperature-controlled concrete; mass concrete; cooling pipes; hydration heat; Coolcrete; thermal cracking.

1. *Introduction:*

Mass concrete used extensively in structures such as dams, foundations, bridge piers, transfer slabs, pile caps, and large structural pours presents unique challenges due to the heat generated by cement hydration. As cement hydrates, a significant amount of heat is released; in large-volume concrete, the heat cannot dissipate quickly, leading to a rapid rise of internal temperature**.**

Because the concrete surface cools relatively quickly (by radiation, convection and conduction), while the interior remains hot, a temperature differential (core vs surface) develops. As concrete cools later, the internal contraction is restrained, causing thermal stresses**.** If these stresses exceed the tensile strength of early-age concrete, cracking occurs compromising structural integrity, durability and long-term performance.

Moreover, if peak internal temperatures exceed certain thresholds (often cited around 70 °C, depending on cement type and aggregates), there is increased risk of deleterious chemical reactions (e.g., delayed ettringite formation — DEF), micro-cracks, reduced durability, and long-term deterioration. Given these risks, in large-volume concrete works it becomes essential to adopt a thermal-control plan as part of the construction process. The guidelines compiled in the standard ACI 207.4R – Cooling and Insulating Systems for Mass Concrete emphasize methods such as pre-cooling materials (water/aggregate), using insulating or cooling-formwork, employing embedded cooling systems (cooling pipes), or modifying concrete mix (using lower-heat cements or supplementary cementitious materials) to reduce heat generation and manage thermal gradients.

Recently, the concept of "temperature-controlled concrete", marketed under brand names such as Coolcrete, has gained attention especially in contexts where large pours or mass concrete are required. According to the manufacturer, such concretes are formulated to reduce the heat of hydration, thereby lowering the internal temperature rise and minimizing thermal cracking and risks like DEF.

However, despite these developments, a systematic synthesis of recent advances, comparative performance, advantages and limitations across different temperature-control strategies embedded cooling, mix design, passive "cooling-concrete" materials, and their monitoring & performance in real field conditions seems lacking in open literature. While many individual studies focus on embedded pipe cooling with numerical simulation or field monitoring, and a few examine material-based strategies (e.g., low-heat cements, admixtures, phase-change materials), there remains a need for a comprehensive review bringing together all methods, comparing effectiveness, practical challenges, gaps in knowledge, and suggesting directions for future research. This paper aims to fill that gap.

The present review surveys:

- The fundamentals of hydration heat generation and thermal stress in mass concrete;
- The spectrum of temperature-control strategies (pre-cooling, embedded cooling, mix-design / material-level modifications, newer "temperature-controlled" concretes / Coolcrete / admixtures / phase-change-materials, and passive thermal-control measures);
- Monitoring and evaluation techniques from laboratory and field studies;
- Comparative performance of different strategies (in terms of maximum temperature, temperature gradient, crack incidence, feasibility under real construction conditions);
- Practical challenges, drawbacks, knowledge gaps;
- And future research directions, especially considering novel material-based cooling concretes, optimization of embedded systems, hybrid approaches, and long-term durability monitoring.

By synthesizing past and recent research across these aspects, this review seeks to provide engineers, researchers, and practitioners with a consolidated understanding of current best practices and innovations aiding design of robust thermal-control plans for mass concrete works, and guiding the development and adoption of new materials and techniques such as Coolcrete.

1.1 Background and Fundamentals:

Mass concrete elements, due to their large dimensions, experience slow heat dissipation after casting. This makes them particularly vulnerable to early-age thermal cracking. Understanding the fundamentals of heat generation, temperature rise, and stress development is essential for evaluating temperature-control strategies such as cooling pipes, material modifications, and "temperature-controlled" concretes like Coolcrete.

1.2 Heat of Hydration and Temperature Rise:

Cement hydration is an exothermic process. As the cement reacts with water, it releases heat that raises the temperature of the concrete mass. In large pours, the heat cannot dissipate rapidly because of low thermal conductivity and the insulating effect of surrounding concrete. This results in:

- High core temperature (Tmax)
- Higher and prolonged temperature rise compared to ordinary structural elements
- Delayed cooling phase, during which thermal contraction becomes critical

The amount of heat generated depends on:

- Cement type (OPC releases more heat; blended cements release less)
- Cement content (higher cement → higher heat)
- Water–cement ratio
- Use of supplementary cementitious materials (SCMs)
- Ambient temperature and formwork insulation

- Size and geometry of the concrete element

1.3 Thermal Gradients in Mass Concrete:

A key characteristic of mass concrete behaviour is the difference in temperature between the hot interior and the relatively cooler exterior. This is known as the thermal gradient (ΔT):

$$\Delta T = T_{core} - T_{surface}$$

When ΔT becomes large, the interior expands while the cooler surface restrains the expansion. Later, as the core cools and contracts, the outer regions may restrain the contraction. Both stages can lead to tensile stresses exceeding the early-age tensile strength of concrete.

Typical critical limits (based on research and ACI 207 guidelines):

- **Maximum temperature (T_{max})**: should generally be kept below **65–70°C** to avoid risks such as Delayed Ettringite Formation (DEF).
- **Allowable temperature differential**: often recommended to be within **20–25°C**, though it depends on mix design and structure.

1.3 Mechanism of Early-Age Thermal Cracking:

Thermal cracking develops due to **restraint of temperature-induced volume changes**. The mechanism proceeds in three stages:

i. **Heating Phase (Hydration Peak)**

- Core temperature rises.
- Concrete expands.
- Surrounding cooler regions or external restraints limit expansion → tensile stress at surfaces.

ii. **Cooling Phase**

- Heat dissipates gradually.
- Core contracts.
- Surfaces or adjoining structures restrain contraction → tensile stress inside the member.

iii. **Crack Formation**

- If tensile stress > tensile capacity of early-age concrete, cracks form.
- Cracks can be surface-deep or penetrate through the section depending on restraint level.
- Early-age tensile strength is low (typically 1–3 MPa within first 24–48 hours), making concrete particularly vulnerable.

1.4 Factors Influencing Temperature Development:

Several parameters affect temperature rise and thermal stress development:

(a) Mix-Design Factors

- Cement type (low-heat cement reduces Tmax)
- Cement content
- Use of SCMs (fly ash, GGBS, silica fume)
- Use of retarders or hydration-control admixtures
- Aggregates' thermal properties

(b) Environmental and Site Factors

- Ambient temperature
- Humidity and wind speed
- Formwork insulation or exposure
- Casting sequence and rate of placement

(c) Structural Geometry

- Thickness and volume
- Surface-to-volume ratio
- Boundary conditions (subgrade, adjacent concrete, reinforcement congestion)

(d) Curing Conditions

- Water curing or membrane curing
- Use of insulating blankets
- Duration and method of curing

1.5 Need for Temperature-Control Methods:

Because thermal gradients and overheating cannot be avoided in large pours**,** purposeful temperature management is essential. Uncontrolled heat of hydration leads to:

- Early-age cracking
- Increased permeability
- Reduced durability and service life
- Potential DEF-related deterioration
- Structural distress requiring costly repair

Thus, techniques like pre-cooling, post-cooling (embedded pipes), improved mix design, material-based temperature control (Coolcrete), and passive cooling strategies are widely adopted in modern mass concrete construction. A systematic understanding of these approaches enables engineers to select suitable combinations based on project conditions and performance requirements.

2. Literature Review:

Research on temperature-controlled concrete has expanded significantly due to the need to control thermal stresses, prevent early-age cracking, and ensure the long-term durability of mass concrete. The literature may be grouped into four major themes: temperature prediction models, cooling techniques, material-based approaches, and field applications.

2.1 Temperature Prediction and Thermal Modeming:

Bazant and Thonguthai (1978) conducted one of the earliest comprehensive studies on coupled heat transfer and hydration in mass concrete. Their finite-element model demonstrated how hydration kinetics influence temperature rise and thermal stress development. **Schindler and Folliard (2005)** expanded on this by developing a hydration model capable of predicting temperature evolution more accurately for modern blended cements.

Kim et al. (2013) simulated temperature distributions using three-dimensional CFD-based models and showed that pipe spacing and casting sequence significantly affect the temperature profile. Similarly, **Cheng et al. (2016)** investigated boundary conditions such as ambient temperature, insulation, and lift thickness, emphasizing their importance in predicting peak temperatures and thermal gradients. These studies laid the groundwork for evaluating temperature-control strategies before implementation on site.

Chen et al. (2024) carried out detailed FEM simulations to study cooling-pipe spacing, water temperature, and flow rate, finding that lower water temperature and tighter spacing reduce peak temperatures but may increase local gradients.

Wang(2024) introduced multi-objective optimization for cooling-pipe systems, demonstrating that optimized flow schedules can reduce peak temperatures with minimal energy use.

Zhang (2023) improved analytical–numerical formulations for predicting temperature distribution in concrete with embedded pipes, providing higher accuracy for construction scheduling.

Sun (2024) combined real-time sensing and FEM modelling, showing that adaptive flow-rate adjustments significantly lowered both maximum temperature (T_{max}) and temperature differential (ΔT).

2.2 Cooling Techniques and Temperature-Control Strategies:

Wong and Kwan (2008) examined pre-cooling of aggregates and concluded that cooling coarse aggregates is more effective than cooling water alone due to higher thermal mass. Najjar et al. (2017) also found that combining chilled water with ice replacement can significantly reduce initial placement temperature.

Roller and Russell (2012) documented successful use of embedded cooling pipes in dam construction and demonstrated how circulating cold water effectively reduces peak internal temperatures. **Li et al. (2019)** optimized the spacing and flow rate of cooling pipes, showing that moderate flow rates with closer pipe spacing provide the best thermal control with minimal energy usage. Innovative techniques were also explored.

Hunger et al. (2010) tested phase-change materials (PCMs) in concrete and reported that latent-heat absorption successfully reduced early-age temperature peaks. These studies collectively highlight the wide range of cooling mechanisms available for temperature-controlled concrete.

3.3 Material-Based Approaches for Temperature Reduction:

Mehta and Monteiro (2014) reported that blended cements such as fly ash and slag significantly reduce the heat of hydration due to slower pozzolanic reactions. Supporting this, **Thomas and Wilson (2003)** observed that high-volume fly ash (HVFA) mixtures can reduce peak temperatures by up to 25°C compared to conventional OPC mixes. **Chini et al. (2009)** investigated hydration-controlling admixtures, including retarders and SRAs, showing that they can delay heat release and minimize thermal cracking risk when used in appropriate dosages. Nano-materials have also been studied in this context.

Sanchez and Sobolev (2010) found that nano-silica contributes to a refined pore structure and improved micro-crack resistance, helping reduce temperature-induced cracking in mass concrete.

Deng et al. (2023, 2024) developed temperature self-controlled concrete (TSC*)* containing conductive or electro-thermal elements enabling controlled heating/cooling; they reported successful lab- and pilot-scale stabilization of temperature fluctuations.

2.4 Field Applications and Case Studies:

ACI Committee 207 (2017) reported several successful applications of temperature-controlled concrete in major infrastructure projects such as dams, mat foundations, and bridge pile caps, highlighting the effectiveness of cooling pipes and low-heat cements.

Kong et al. (2018) demonstrated that embedded temperature sensors allow real-time monitoring and adjustment of cooling strategies, improving control over temperature gradients.

Park et al. (2020) advanced this by using a digital-twin model to predict thermal behaviour during construction, enabling dynamic adjustments in cooling-water flow and insulation levels. Their findings confirm the importance of integrating modelling tools with field monitoring for optimal thermal performance.

3. Discussion & Comparative Analysis:

3.1 Strengths of the Existing Research:

- **Clear maturity of modelling tools** - A long history of thermal–hydration models (analytical, FEM, CFD) gives researchers and practitioners reliable prediction tools for T_{max} and ΔT, enabling pre-construction planning and optimization of cooling systems.
- **Well-developed active cooling practice -** Embedded cooling-pipe systems are backed by multiple lab, numerical, and full-scale field studies showing consistent reductions in core temperature and proven use in large projects (dams, mat pours). Design guidance and case studies exist.
- **Diverse material strategies explored -** A broad range of material approaches (SCMs, low-heat cements, PCMs, radiative additives, nanomaterials) have been investigated, providing several mechanisms to reduce heat generation or buffer temperature rise.

- **Integration of monitoring and control -** Recent studies demonstrate effective use of sensor networks and adaptive cooling strategies (real-time flow control, digital twins), moving research from static prescriptions to dynamic management.
- **Move toward hybrid solutions -** Literature increasingly recognizes that combined strategies (mix design + active cooling + surface treatments + monitoring) perform best in practice.

3.2 Limitations in the Literature:

- **Insufficient long-term field validation for novel materials -** Many promising material-level innovations (radiative concretes, TSC, PCM-concretes, commercial "CoolCrete" products) are demonstrated mainly in laboratory or small pilot tests; comprehensive long-term field data (durability, mechanical performance, lifecycle) are scarce.
- **Local gradient / post-cooling cracking under-examined -** Numerical and experimental studies note that aggressive cooling (very cold water or high local flow) can create high local ΔT near pipes and induce micro-/macro-cracks; however, systematic guidelines to avoid this (e.g., transition zones, staged cooling) are limited.
- **Fragmented reporting of parameters -** Many studies omit full reporting of critical metrics (exact pipe spacing, inlet/outlet temperatures, flow rates, thermal boundary conditions, aggregate thermal properties), making cross-study comparisons and meta-analysis difficult.
- **Limited standardization of test protocols -** There is no universally adopted lab-to-field protocol for validating passive radiative materials, PCM embedment methods, or TSC behaviour under real site cycles.
- **Scale-up challenges underrepresented -** The behaviour of PCMs, microencapsulated additives, or electrically conductive elements often changes when scaled from lab specimens to cubic-metre pours; few papers address scaling laws or constructability issues.
- **Economic and sustainability assessments are limited -** Few studies present life-cycle cost analyses or carbon/energy trade-offs of active cooling vs material approaches, which are essential for engineering decisions.

3.3 What Is Well-Studied:

- **Hydration kinetics and thermal modelling** — both empirical and mechanistic models for temperature prediction are mature and validated across many projects.
- **Cooling-pipe design basics** — effectiveness of embedded cooling, general trends on spacing and flow, and dam/mass-concrete applications are well documented.
- **Effect of SCMs on heat generation** — many studies quantify the reduction in heat release for fly ash, slag, and similar SCMs.
- **Sensor deployment & monitoring methods** — thermocouples, IR thermography, and data acquisition techniques for tracking temperature profiles are well characterized.

3.4 What Is Not Adequately Addressed:

- **Field-scale durability of novel materials** (radiative coatings, PCMs, TSC) under years of environmental and load cycles.
- **Standardized optimization frameworks** that balance T_{max} reduction, local ΔT avoidance, energy use, water consumption, cost, and constructability. Existing optimizations often consider a subset of these variables.
- **Guidelines for staged/adaptive cooling schedules** tied to real-time sensor feedback (when to increase/decrease flow, how to ramp temperature) rather than heuristic rules.
- **Comprehensive life-cycle and sustainability assessments** comparing active cooling, passive materials, and hybrid approaches—including embodied carbon and operational energy.
- **Robust scaling studies** that map laboratory PCM/TSC performance to cubic-metre and field pours, with attention to mixing, segregation, and placement effects.

- **Integration with structural performance outcomes** (e.g., quantified reductions in permeability, service life extension, or residual strength improvements) rather than just temperature metrics.

3.5 Critical Evaluation & Recommendations:

- **Active cooling is reliable but must be designed holistically -** Embedded pipes work; however, research must shift from "does it cool?" to "how to cool without creating dangerous local gradients." Practical guidance is needed: transitional buffers, staged cooling ramp-down, minimum allowable local ΔT, and sensor-driven control logic.
- **Material innovations are promising but premature for widespread use -** Radiative concretes, PCMs, and TSCs merit continued R&D, but the community should require multi-season, multi-project proof (mechanical performance, compatibility with SCMs, freeze-thaw, chemical durability) before recommending them for critical mass structures.
- **Standardized reporting and test protocols are urgently needed -** Journals and committees should push for minimum reporting checklists (mix details, pipe layout, flow rates, sensor placement, ambient conditions) to permit meta-analysis and guideline development.
- **Optimization must be multi-objective and practical -** Future optimization studies should include energy, water use, cost, and constructability; propose Pareto-optimal solutions that project engineers can implement.
- **Emphasize adaptive control and digital integration -** Real-time monitoring + control (digital twins, automated flow control) reduces risk and energy use, but algorithms should be validated with field pilots and robust fail-safes for construction variability.
- **Prioritize lifecycle and sustainability metrics -** Given the carbon impact of cementitious construction, evaluate temperature-control strategies not only for immediate performance but for whole-life CO_2 and energy.
- **Encourage collaborative field trials -** Industry–academia partnerships to run standardized, instrumented field trials of PCMs, radiative concretes, and Coolcrete products will accelerate trustworthy adoption.

3.6 Research Gaps:

i. **Limited Long-Term Field Validation of Emerging Materials**

- ➢ Most studies on PCM-concretes, radiative cooling additives, thermally conductive concretes (TSC), and commercial "Coolcrete" products are confined to laboratory or small pilot experiments.
- ➢ There is insufficient multi-season, real-project evidence on durability, structural performance, shrinkage behaviour, and long-term thermal stability.

ii. **Inadequate Understanding of Local Thermal Gradients**

- ➢ Research focuses heavily on peak temperature reduction (T_{max}) but does not fully analyse local temperature gradients created by cooling pipes, PCM clusters, or heterogeneous mixes.
- ➢ Lack of guidance on safe limits, gradient-induced cracking mechanisms, and mitigation strategies during active cooling.

iii. **Absence of Standardized Testing & Reporting Protocols**

- ➢ No unified methodology exists for evaluating cooling efficiency, PCM performance, radiative materials, or digital cooling controls.
- ➢ Studies often omit essential data (pipe spacing, flow rate, inlet/outlet temperatures, hydration properties, sensor placement), making cross-comparison difficult.

iv. **Scale-Up and Constructability Issues Not Systematically Studied**

- ➢ Behaviour of PCM microcapsules, cooling-pipe layouts, conductive fillers, and special materials changes significantly between lab scale and full-scale pours.
- ➢ Gaps remain in understanding mixing practicality, segregation risks, placement challenges, and quality control during large pours.

v. **Limited Integration With Structural & Durability Performance**

- Many studies assess only thermal performance, ignoring how temperature control strategies influence long-term properties such as permeability, cracking, stiffness degradation, and freeze-thaw durability.
- Lack of large datasets linking thermal control to service life extension.

vi. **Weak Development of Adaptive / Intelligent Cooling Frameworks**

- Real-time sensor-based cooling control is promising but underdeveloped.
- Few studies present validated algorithms for adaptive flow control, feedback loops, or predictive digital twins tailored to mass concreting.

vii. **Insufficient Multi-Objective Optimization Studies**

- Existing optimization attempts typically focus on thermal parameters alone.
- There is a gap in multi-criteria frameworks that include cost, energy use, water consumption, environmental impact, and constructability.

viii. **Sparse Sustainability and Life-Cycle Assessments**

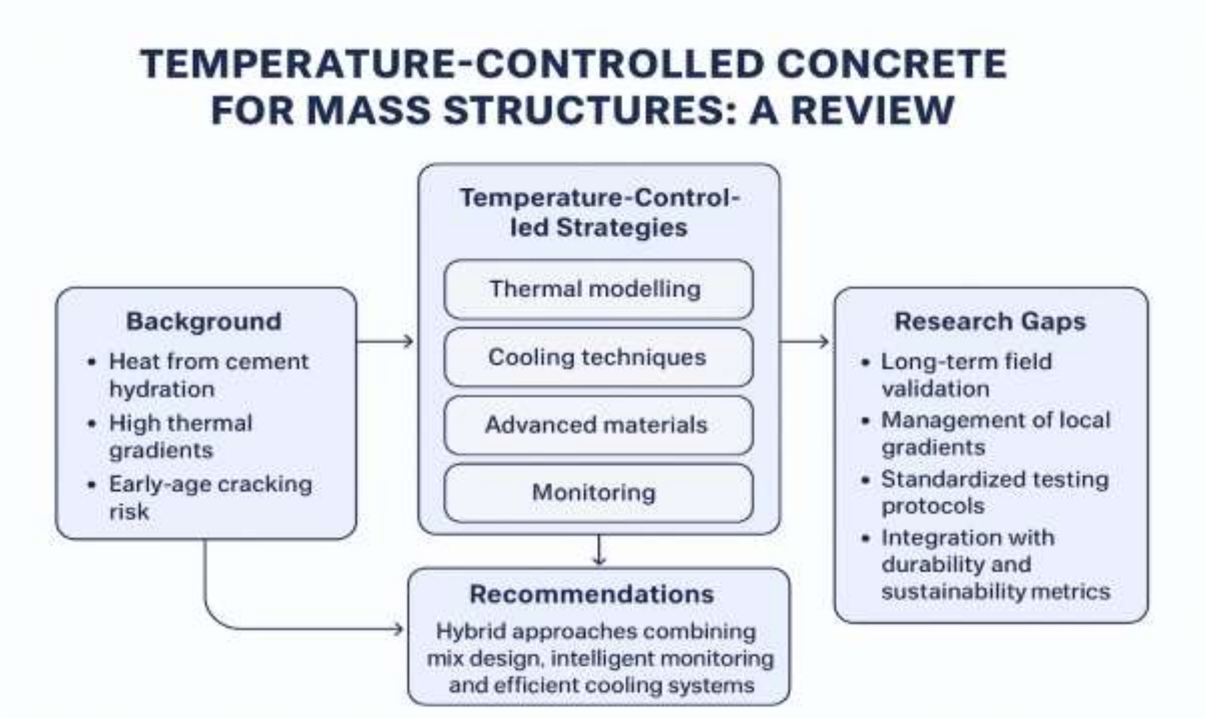
- Very few studies evaluate the embodied carbon, operational energy, or long-term environmental benefits/penalties of different cooling strategies.
- No comparative LCA exists for:
  - passive vs. active cooling,
  - hybrid systems,
  - materials-based vs. mechanical cooling approaches.

ix. **Inadequate Field Guidelines for Hybrid Systems**

- Research recognizes the potential of hybrid systems (e.g., SCMs + cooling pipes + surface cooling + sensors), but standardized design charts, scheduling rules, and construction guidelines are still lacking.

x. **Insufficient Data for Meta-Analysis and Code Development**

- Lack of openly shared datasets and inconsistent reporting prevent formation of generalized empirical correlations or standards.
- This hinders development of design codes for modern cooling approaches.



4. Recommendations & Future Research:

i. Field Validation & Real-World Performance

- Conduct large-scale field trials of PCM concretes, radiative cooling additives, and thermally conductive mixes in actual dam/raft/pile cap projects.
- Monitor temperature, strain, microcracking, and durability for at least 1–2 years to establish real-world behaviour.
- Develop benchmark case studies comparing traditional cooling vs. Coolcrete-based cooling.

ii. Standardization & Testing Framework

- Create standard test methods for evaluating temperature-reduction materials (PCM, conductive fillers, reflectivity agents).
- Propose uniform reporting parameters: pipe spacing, flow rate, hydration model, insulation thickness, sensor depth, T_{max}, ΔT, and crack index.
- Develop international guidelines in collaboration with ACI, BIS, and CEB-FIP for mass-concrete temperature control.

iii. Advanced modelling & Digital Tools

- Develop AI/ML models to predict temperature rise based on cement type, mix proportions, geometry, and environmental conditions.
- Create digital-twin platforms that integrate sensor data with real-time thermal simulation.
- Enhance numerical models to capture local thermal gradients, thermal shock, and heterogeneous material distribution.

iv. Hybrid Cooling Strategies

- Investigate integrated systems combining:
  - SCMs (fly ash/slag)
  - cooling pipes
  - PCM microcapsules
  - surface insulation and fogging
- Identify optimal combinations for different climatic regions (hot/dry, humid, cold).
- Develop decision-making charts for choosing between passive, active, or hybrid cooling.

v. Material Innovations

- Explore new low-heat binders: LC3, high-volume slag/fly ash, and alkali-activated binders.
- Improve PCM microcapsule stability, dispersion, and long-term compatibility with cement.
- Investigate thermally conductive additives (graphene, steel fibers, basalt fibers) for uniform heat dissipation.
- Study the effect of cooling strategies on durability, including permeability, microstructure, shrinkage, and cracking.

vi. Environmental & Energy-Based Optimization

- Perform life-cycle assessments (LCA) and energy analyses of cooling methods (ice replacement, chilled water, cooling pipes).
- Develop sustainable thermal-control strategies for low-carbon construction.
- Identify low-energy alternatives suitable for remote or resource-limited locations.

vii. Cost–Benefit Models

- Create models that integrate cost, time, energy use, temperature performance, and durability for choosing the best cooling method.
- Evaluate feasibility of PCM concretes and conductive mixes in commercial construction, not only dams or nuclear structures.

viii. Guidelines for Construction Practices

- Develop practical guidelines for:
  - placing and spacing cooling pipes
  - pipe pre-testing & flow calibration
  - insulation thickness selection
  - temperature monitoring plans (sensor location, frequency)
- Prepare risk assessment tools for predicting cracking during construction scheduling.

ix. Open-Access Temperature Databases

- Establish a global temperature-rise database covering hydration kinetics, mix proportions, climatic zones, and cooling techniques.
- Enable meta-analysis-based development of next-generation empirical formulas.

x. Integration with Structural & Durability Performance

- Intensify research linking thermal control → structural safety → service life.
- Study how reduced peak temperature affects long-term cracking, stiffness, and residual strength.
- Propose design guidelines for integrating temperature control into structural design workflows.

5. Conclusion:

Temperature control in mass concrete is crucial for preventing early-age thermal cracking and ensuring long-term durability. This review shows that prediction models, cooling pipes, and SCM-based mix designs remain the most dependable methods, while newer solutions—such as PCMs, radiative additives, thermally conductive mixes, and Coolcrete offer promising but still developing alternatives.

However, major gaps persist, including limited long-term field evidence, lack of standard testing protocols, and insufficient integration of thermal control with structural performance and sustainability metrics. Future progress will depend on hybrid strategies, real-time sensor-based control, digital twins, and broader field validation to transform emerging technologies into reliable, practical, and code-adoptable solutions.

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