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Assessment and Monitoring of Concrete Properties in Dam Construction: Practices in Turkey and Around the World [2026]

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Keywords

Mass concrete, Concrete dams, Quality Control, Life-cycle assessment, Durability assessment, Non-destructive testing, Service life management, Structural health monitoring.

Abstract

Concrete dams are hydraulic structures whose long-term safety depends on durability, thermal responsiveness, and time-dependent performance of the material, rather than only on initial strength. During their service life, concrete dams are affected by mechanical, thermal, fluid-related, and chemical factors. If these factors are not properly controlled, it may cause the concrete to deteriorate. This paper presents a state-of-practice comparative review based on the analysis of international standards, laboratory testing results, and operational monitoring practices, with a focus on analyzing performance gaps and decision-oriented implications for Turkish dam engineering practice. The mechanical, transport-related, thermal, and aging properties of mass concrete are examined with respect to the main processes that can cause it to undergo degradation. Global norms, lab testing methods, and surveillance methods are considered during the comparison with the ones that are used in Turkey. The evaluation demonstrates that one of the major challenges in Turkey is the complexity of incorporating long-term material monitoring records with construction-phase quality assurance procedures: whereas global strategies rely on synchronized lab profiling, non-destructive evaluation, and structural health monitoring. The main contribution of this study is to join global standards, operational oversight methods, and material-level performance measures into a life cycle-oriented evaluation framework that may be used for building concrete dams. This configuration may enhance engineering decision-making about planning for durability, preventing thermal fissures, and monitoring long-term performance. The results may be applied to improve surveillance methods and design methods that are based on durability in current and future concrete dam projects.

1. Introduction

Concrete dams rank among the most complex and long-lasting civil engineering structures and play a critical role in national infrastructure by supporting water supply, hydropower generation, flood protection, and irrigation. Dams are distinguished from other reinforced concrete structures by their large scale, tightly controlled systems that are permanently under hydrostatic pressure, constant temperature changes, seepage effects, and chemical reactions with water. Generally, their intended service life is designed to be more than 100 years, therefore, the performance of a concrete dam is determined not solely by its initial strength but also by its durability, resistance to time-dependent deformations, and ability to withstand physical and chemical degradation processes.

Even though there are a sufficient number of articles regarding international experience and a variety of manuals about the operation of concrete dams, there is no fully integrated life-cycle-oriented synthesis that connects concrete material properties, functional zoning, monitoring techniques, and durability management strategies. Furthermore, due to the scarcity of comparative assessments that combine both global best practices and national methodologies—particularly the ones that are applied in Turkey—this study conducts a corresponding comparative analysis [1].

Despite ICOLD bulletins, ACI recommendations, USBR manuals, and DSİ technical requirements that often examine dams constructed of concrete from discrete material, structural, or operational viewpoints, this study aims to provide a cohesive and comparative synthesis. This work's uniqueness lies in the clear connection between concrete material behavior, functional zoning criteria, and monitoring strategies; simultaneously with a comparative gap analysis of worldwide practices and current national implementations.

This report is organized as a comparative review of current practices and deals with the subsequent research questions:

- Which specific material properties of concrete are essential for the long-term safety and durability of concrete dams?
- How can global practices integrate quality control, monitoring, and durability management processes throughout the dam life cycle?
- What distinguishes worldwide best practices and existing national strategies, primarily in Turkey, and how may these differences be addressed?

Methodological approach: This type of overview is mainly concerned with a systematic assessment of peer-reviewed scientific works, worldwide norms, and practical recommendations which are accessed through search results in the “Scopus” and “Web of Science” databases. The analysis is further supported by official documents issued by relevant professional associations. The evaluation covers the period from 2000 to 2024. It

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also includes earlier key sources that are still used in dam engineering today. The review is based on publications and standards issued by ICOLD, ACI, USBR, ASTM, EN, GOST, SP, and DSİ. The study considers the United States, China, Russia, Brazil, and Turkey. These countries were chosen because they have many dams, different climate conditions, and long experience in durability studies and monitoring. The paper deals only with mass hydraulic concrete and industrial concrete applications. All selected sources were compared in a systematic way. The objective was to identify common tactics, methodological variances, and existing limitations. Particular focus is placed on domains where engineering practice within Turkey could be enhanced.

2. Concrete in Dams: Key Requirements, Properties, and Durability Factors

2.1. Operational framework and efficiency specifications for dam concrete

Concrete used in dam construction differs from that used in conventional structures. This difference is caused by simultaneous mechanical, thermal, hydraulic, and chemical actions. During the service life of a dam, concrete remains in constant contact with water and hydraulic pressure. For this reason, dam concrete must be able to withstand temperature changes. These changes result from cement hydration and varying environmental conditions. In zones exposed to water, cyclic processes occur. These encompass wetting and drying, along with freezing and thawing. Such cycles can induce supplementary stresses in the concrete and impact its long-term efficacy.

In contrast to conventional structures, where isolated defects may be corrected without risking overall safety, impairment in essential dam areas may trigger permanent decomposition processes that impact seepage management, longevity, and enduring stability. Thus, the effectiveness specifications for dam concrete are determined not by a singular variable but by a network of interconnected criteria, encompassing sufficient strength and flexibility, resilience to energy induced splitting, very little permeability, durability towards physicochemical degradation, and dependable constructability for extensive placements. These criteria establish the foundation for property selection, evaluation, and oversight procedures elaborated in the subsequent sections [2].

2.2. Basic groups of concrete properties to be determined and monitored

For concrete dams, material properties must be seen as time-varying and interrelated, not as separate indicators. Long-term mechanical, thermal, hydraulic, and chemical effects require a systematic arrangement that connects how concrete behaves and deteriorates, as well as what monitoring is required. So, the attributes of concrete dams are split into four groups: mechanical, physico-transport, thermal/time-dependent, and durability-related (Figure 1). This classification provides a functional foundation for making decisions about quality control and monitoring [3].

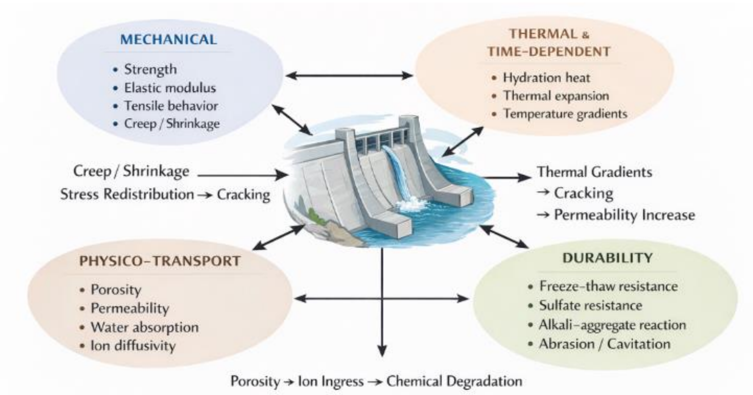

Figure 1. Interrelation between concrete property groups and degradation mechanisms in concrete dams

- *Mechanical Properties*

The mechanical properties govern the load-bearing capacity, deformation behavior, and cracking response of a material. In dam engineering, compressive strength alone is inadequate for characterizing structural performance. The elastic modulus regulates stress distribution in substantial concrete masses and directly influences crack development in the material. Tensile and bending strengths are crucial factors since cracking enhances permeability and accelerates material breakdown.

Processes such as creep and shrinkage strongly affect the development of stresses in concrete. Autogenous shrinkage is important in modern hydraulic mortars with low water-to-binder ratios or high-performance binders. In contrast, it is often neglected in conventional dam concrete. At early ages, the interaction between autogenous shrinkage and internal temperature gradients may reduce tensile strains. This interaction can delay crack formation. For this reason, thermal and mechanical effects should be evaluated together, rather than as separate processes [4].

- *Physical and Transport Characteristics*

The interaction between aggressive environments and concrete is governed by the physico-transport properties of the material. Porosity, permeability, and diffusion coefficients are among such properties. They regulate the transfer of moisture, as well as the penetration of chlorides, sulfates, and other aggressive chemicals. In reinforced zones, accelerated chemical deterioration and corrosion are observed. They are often attributed to the increased connectivity of the pore system. This system facilitates transport processes. For this reason, it is necessary to monitor changes in these properties since they can enable engineers to identify internal damage before it becomes externally visible.

➢ *Thermal and Time-Dependent Properties*

Thermal behavior is highly important aspect in massive concrete structures because of how hydration heat is released. Thermal stresses can build up between the core and surfaces when the temperature rises and then falls, which can exceed the tensile capacity if not effectively regulated. Some important factors are the heat of hydration, the thermal expansion coefficient, and the means by which the material's shape changes with respect to the temperature. The conditions for early-stage recovery are crucial, as improper regulation of temperature and moisture may adversely affect microstructural development, porosity, and long-term durability [4].

➢ *Durability and Resistance Properties*

Processes such as wet-dry cycling, freeze-thaw cycles, sulfate attacks, alkali-aggregate reactions, abrasions, and cavitation are considered to be durability properties that are indicators of resistance to long-term environmental consequences. For instance, freeze–thaw resistance is simultaneously reduced, and aggressive ion movement is facilitated by an increase in porosity, which is tightly interdependent. As a result, durability assessment is conducted through an integrated examination, rather than the testing of specific variables in isolation [5].

Table 1. Mapping of concrete property groups to tests and monitoring techniques

Property group	Key parameters	Typical laboratory tests	Monitoring / NDT techniques
Mechanical properties	Strength, elastic modulus, creep, shrinkage	Compression test, tensile test, creep and shrinkage tests	Geodetic monitoring, crack gauges
Physico-transport properties	Permeability, diffusivity, porosity	Water absorption, permeability test, RCPT	GPR, electrical resistivity
Thermal / time-dependent	Heat of hydration, temperature gradients, thermal expansion	Adiabatic calorimetry, thermal expansion tests	Thermocouples, distributed temperature sensing (DTS)
Durability	Freeze–thaw, abrasion, ASR, sulfate resistance	Freeze–thaw test, abrasion resistance, chemical resistance tests	Visual inspection, surface scanning

2.3. Types of concrete dams and influence of structural type

Concrete requirements depend on dam type and structural behavior:

Table 2. Concrete requirements and controlling factors for different dam types

Dam type	Dominant structural behavior	Key concrete requirements	Critical control / monitoring aspects
Gravity dam	Mass action, high thermal gradients	Low heat of hydration, thermal crack resistance	Temperature control during placement and curing
Arch dam	Stress concentration, load transfer to abutments	Adequate strength, elastic modulus, crack resistance	Stress–strain monitoring, deformation control
Buttress dam	Complex geometry, multiple joints	Uniform concrete quality, reliable construction quality	Joint quality control, construction uniformity
RCC dam	Layered construction, rapid placement	High compaction quality, strong interlayer bonding	Density control, layer bonding inspection

The main concrete requirements and controlling factors for different dam types are summarized in Table 2. These variances indicate the need for property determination and monitoring systems tailored for each type of dam [7].

2.4. Functional zoning of dam concrete as a basis for control and monitoring

Functional zoning is based on the idea that different portions of a dam have different exposure and performance needs. The zoning idea of this study (Figure 2) is grounded on international standards and technical guidelines such as ICOLD, USBR, and DSİ, and has been adapted to increase the priority of monitoring [8].

Table 3. Functional zoning of dam concrete, material requirements, and monitoring priorities

Zone	Function	Key material requirements	Monitoring priority
B1	Internal mass concrete	Low heat of hydration, crack control, deformation stability	Temperature monitoring, deformation measurements
B2	External concrete surfaces	Freeze–thaw resistance, crack resistance, low shrinkage	Surface cracking inspection
B3	Variable water level zone	Low permeability (w/b ≤ 0.40–0.45), chemical resistance	Moisture and permeability monitoring
B4	Structural (load-bearing) concrete	High compressive strength, elastic modulus control	Deformation and stress monitoring
B5	Flow and pressure affected zones	High density, resistance to hydraulic pressure	Pressure effects and surface wear
B6	Abrasion- and cavitation-resistant zones	High abrasion and cavitation resistance, silica fume addition	Surface damage and erosion monitoring

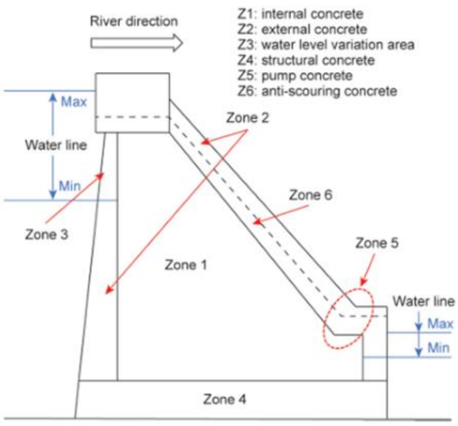

Figure 2. Functional zoning of dam concrete as a basis for quality control and monitoring strategy

The dam structure is divided into distinct functional zones that correspond to varying exposure conditions and performance criteria: internal mass concrete (Zone 1), external concrete surfaces (Zone 2), variable water level zone (Zone 3), foundation and structural concrete (Zone 4), pump and auxiliary concrete (Zone 5), and anti-scouring concrete in hydraulically loaded regions (Zone 6). The zoning idea associates environmental actions with specific material attributes, testing methodologies, and monitoring metrics [9].

- B1 Zone — Internal Concrete (Mass Concrete)

Zone B1 is the interior of the dam and is identified by its minimal exposure to external environmental actions, which is in accordance with the methodologies employed in the ICOLD and USBR guidelines. The service conditions are predominantly influenced by stress fractures that result from the heat generated during cement hydration, as well as long-term compressive stresses. Thermally induced cracking and delayed cracking, which are the result of the combined effects of creep and shrinking, are the primary hazards. Several factors such as the heat of hydration, elastic modulus, creep, and contraction are the key parameters for this zone. Regulating internal temperature may be accomplished by the use of thermocouples while the observation of long-term deformations can be obtained through geodetic measurements, which are among the monitoring priorities.

- B2 Zone — External Concrete

Zone B2 is made up of concrete parts that are directly subjected to weather conditions and changes in daily and seasonal temperatures. The main activities are defined as freeze–thaw cycles, thermal deformations, and shrinkage. Whereas major risks included are surface wear, cracks opening, and water getting in. In this particular zone, crack resistance, freeze–thaw durability, and less surface permeability are among the most important qualities of concrete. The monitoring can be done by visual checks, crack mapping, and surface non-destructive testing methods.

- B3 Zone — Variable Water Level Zone

The region subjected to cyclic precipitation and drying is defined as Zone B3 in the ICOLD and USBR recommendations, and it is explicitly recognized as one of the most critical zones from a durability perspective. The governing actions in this zone include the penetration of chlorides and sulfates, the development of chemical corrosion processes, and capillary water absorption. Due to the fact that exposure cycles may repeat it imposes risk of the acceleration of concrete degradation. The parameters that control this risk are permeability, diffusion resistance, and chemical durability. The water-to-binder ratio for this zone is typically around 0.40–0.45 [5], so that it aligns with international standards. This range is suitable for reducing capillary absorption and intrusion of aggressive ions. Monitoring priorities in this zone include control of moisture conditions, assessment of surface conditions, and the use of permeability indicators.

- B4 Zone — Structural (Load-Bearing) Concrete

Zone B4 acts as a distributor of main loads along the dam and regions where tensile stresses form. High compressive stresses and deformation compatibility are the main factors that need to be considered in this area. The primary idea of this zone is to deal with the extreme bending moment and stiffness mismatch in the structure. Young's modulus and compressive strength are among the most important properties in this zone because they directly influence the durability of the dam. Geodetic methods and extensometers are used for identifying deformation and displacement. (Dong et al. (2024)) [6].

- B5 Zone — Effects of pressure and flow on concrete

Zone B5 covers several sections of the structure where hydrodynamic pressure and impact forces are present. Also, it includes water exits and interior galleries. This area deals with surface damage and pressure-related defects. The main features of concrete include increased density, strength, and resistance to water pressure. Monitoring processes in this zone prioritize pressure testing and targeted surface inspections. Therefore, it can be said that zone B5 is characterized by pressure effects rather than wear from abrasion.

- B6 Zone — Concrete resistant to abrasion and cavitation (Anti-Scouring Concrete)

Zone B6 deals with energy dissipation structures and spillways. They tend to be considered as the most serious service conditions in ICOLD and USBR practice. For the predominant factors in this zone, one may include abrasion, cavitation, and high-velocity flow. Whereas main hazards are increasing surface loss and turbulence damage. Abrasion and cavitation resistance along with strong surface durability in concrete are key properties in this zone. For monitoring part, locating cavitation-prone regions and surface damage are regarded as crucial subjects.

Although zones B5 and B6 are functionally different, they can partly overlap in space. Zone B5 is mainly affected by hydrodynamic pressure, while Zone B6 is influenced by abrasion and cavitation. These differences require improved surface durability, not only high concrete density [10].

2.5. Key aspects of testing, monitoring, and ınterpretation

In order to compare concrete mixtures, accelerated laboratory durability tests can be used. Because of scaling effects, simplified exposure conditions, and artificial time acceleration, they can limit the extrapolation to the real service life of concrete dams. It is usually assumed that dams serve for more than 100 years. As a result, these tests can be considered just as suggestive techniques but not as long-term in-service behavior manuals.

3. Determination and Monitoring of Dam Concrete Properties

The assessment of concrete properties in hydraulic engineering should not be treated as a one-time quality check. It should be considered a life-cycle-oriented engineering process. Unlike conventional concrete structures, dams are exposed to long-term climate effects, large temperature gradients, and continuous hydraulic loading. For this reason, concrete performance cannot be evaluated using a single method. It requires the combined use of laboratory testing, construction-stage control, and operational monitoring. Each approach serves a different purpose and has its own limitations [11].

Dam concrete is a time-dependent material. Its properties change during the service life of the structure. Crack resistance, permeability, and stiffness can change over time and under different exposure conditions. For this reason, concrete evaluation is not limited to the assessment of initial strength. It mainly focuses on durability-related criteria. These include density, water-tightness, thermal stability, and resistance to progressive deterioration processes [12].

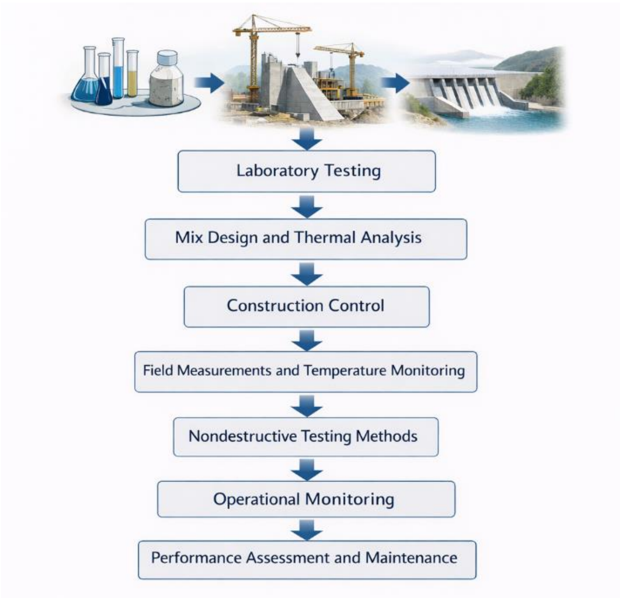

Figure 3. Life-Cycle assessment and monitoring of dam concrete properties

3.1. Laboratory assessment of dam concrete properties

For determining the prospective performance of dam concrete, laboratory analysis may be used. By conducting such analysis, the optimization of adjustments to mixed proportions, aggregate sizing, binder selection, and water-cement ratio can be reached. In hydraulic engineering, compressive strength tests are considered to be a standard compliance check rather than a primary decision for a design.

Properties that are responsible for long-term durability, including microstructural integrity, density, and permeability, are usually emphasized during experiments. Laboratory experiments on permeability and absorption offer indirect indicators of resistance to water penetration and aggressive ion transport. However, their representativeness is limited by idealized curing conditions and scale effects. Similarly, laboratory density measurements fail to fully capture the heterogeneity of compaction and segregation that occurs during the placement of mass concrete [4].

A critical component of laboratory evaluation is thermal behavior. Tests that measure the heat of hydration and temperature rise are carried out in order to reduce the risk of thermal fracture. Figure 4 shows a diagram illustrating how temperature changes over time during hydration and then cooling. It also shows the difference between adiabatic laboratory circumstances and regulated cooling in real dam construction.

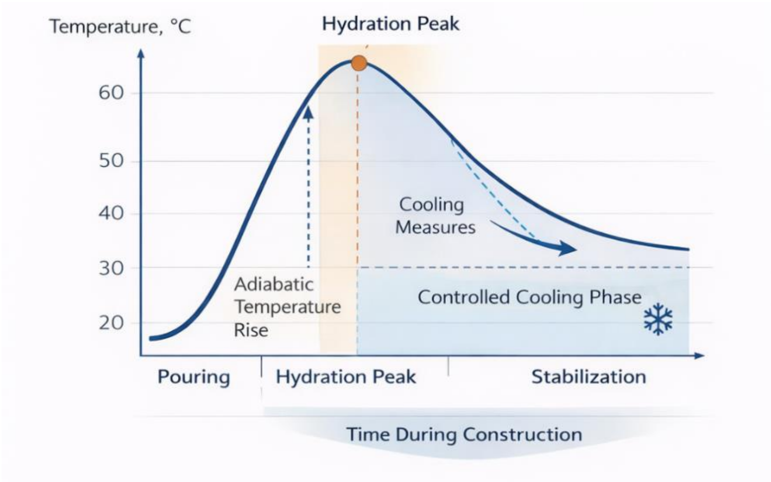

Figure 4. Typical temperature development in mass concrete during construction, showing hydration peak and controlled cooling phase

Laboratory thermal models simplify the actual boundary conditions and restraint effects present in dam structures. Therefore, laboratory results should be regarded as design boundary conditions rather than precise predictions of in-situ behavior [14].

Laboratory tests set limits on how well concrete can perform, but these properties can only be realized through control during construction and long-term monitoring. Table 4 shows how the stages of laboratory, construction, and operational assessment work together.

Table 4. Integrated Methods for Determining and Monitoring Properties of Dam Concrete

Assessment Stage	Primary Focus	Typical Methods	Engineering Significance
Laboratory design stage	Formation of material properties	Strength tests, permeability tests, thermal tests	Durability-oriented concrete mix design
Construction quality control	Verification of execution quality	Density control, consistency tests, temperature monitoring	Compliance with design assumptions
Operation and monitoring stage	Long-term performance assessment	UPV, Impact-Echo, GPR, embedded sensors	Early warning and service life management

3.2. Construction-Stage Control: Common deviations and risks of failure

Quality control during construction is the most important and risky part of figuring out the properties of concrete. In real construction, placement continuity, compaction efficiency, curing regimes, and thermal exposure all change.

Ve-Be time and in-situ density measurements are generally used to estimate the workability of roller-compacted concrete (RCC) in dam construction. Ve-Be time provides an effective measure of consistency; nonetheless, it is highly sensitive to variations in the mixture's moisture content. If moisture levels are not carefully controlled, the test may give an overly optimistic indication of the mixture's compactability. If the targeted density is not achieved, it may alter some of the properties. These properties include increased permeability, reduced interlayer bonding, and decreased long-term durability of the material.

Both the laboratory experiments and research on extensive dam construction have shown that moisture fluctuations seriously affect Ve-Be time in RCC mixtures. Another research that was conducted by Andrade et al. (Brazil) [15] illustrates that even little alterations in unit water concentration led to substantial decreases in Ve-Be time. However, this decrease cannot confirm adequate compaction potential. Specifically in combinations with high fine content or mineral additions. Later, it was justified by field experience in Olivenhain RCC that analogous Ve-Be values may align with changing moisture levels. This alignment may result in differences between attained density and interlayer adhesion under actual construction circumstances (Bennett et al., USA) [16]. By using this information, it can be concluded that Ve-Be time needs to be regarded as a consistency metric that should be considered with moisture management and on-site density measurements.

Temperature data obtained by integrated sensors allows to control lift thickness and cooling techniques. However, the interpretation of data can be less reliable if there exist some flaws in sensors, such as location, signal drift, or localized thermal anomalies. Generally, construction-stage control should be considered as a risk management instrument rather than a failsafe system that does not consider any operational uncertainties [17].

3.3. Non-Destructive Testing and Monitoring: Limits of detection and interpretation

During the operational life of a concrete dam, several assessments are increasingly used in worldwide practice. These evaluations include non-destructive testing (NDT) techniques and continuous monitoring systems. Other popular methods include Ultrasonic Pulse Velocity (UPV), Impact-Echo, and Ground Penetrating Radar (GPR), which provide valuable information about the condition of concrete. However, the use of such tests is not always reliable since these methods possess significant constraints. Those constraints can be characterized as the inability of examining in depth and their inaccuracy within massive concrete structures.

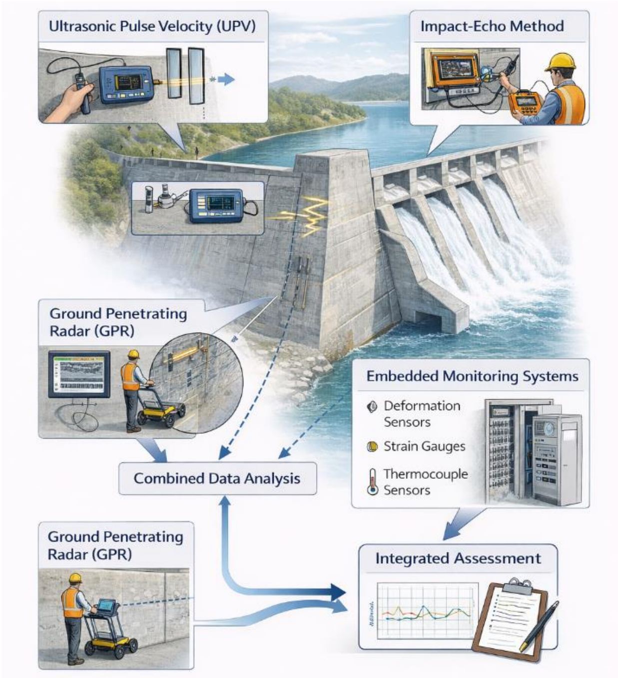

Figure 5. Combined use of non-destructive testing and monitoring systems for dam concrete assessment

By the means of recent studies, it has been observed that Ultrasonic Pulse Velocity measurements are controlled by the saturation state and temperature of concrete. Afterwards, in the experimental work by Zhang et al. (2021) [18] it was shown that increased moisture content may reduce ultrasonic wave velocity even if the material is not damaged. Consequently, such an increase may give the risk of false-positive interpretations. Hence, in large-scale, moisture-affected concrete structures, UPV data should be thoroughly analyzed, which is also supported by other studies conducted by Grosse and Ohtsu (2020) [19].

In dam galleries, the limitations of GPR are clearly seen. Those limitations include the loss of strength of electromagnetic signals due to high water content and pore saturation. As stated in the study by Alani et al. (2020) [20] and Solla et al. (2021) [21], the electromagnetic signals lose their strength and thus cannot penetrate deeply. After the reduction in electromagnetic wave strength, it makes them less able to penetrate-often to less than 1.0-1.5 m. In such settings, moisture zones, reinforcement, or embedded parts can be mistaken for voids or damaged areas.

The Impact-Echo method also has its shortcomings in large volumes of concrete. It was identified that when the thickness of concrete is more than about 1.0–1.2 m, reflections from boundaries and interfaces make the results harder to interpret.

Table 5. Limits and constraints of NDT in mass concrete dams

NDT method	Typical reliable detection depth	Major limitations in dam galleries	Main sources
UPV	~1.5–2.0 m	Sensitivity to moisture and temperature; velocity reduction without actual damage	Zhang et al. (2021); Grosse & Ohtsu (2020)
Impact-Echo	~1.0–1.2 m	Loss of resolution in thick sections; boundary reflections	Zhu & Popovics (2020)
GPR	< 1.0–1.5 m (wet concrete)	Severe signal attenuation; false anomalies	Alani et al. (2020); Solla et al. (2021)

In table 5, each of the Non-Destructive Testing (NDT) techniques were summarized along with the shortcomings they possess. It is critical to understand that NDT findings are solely probabilistic indicators, and no definite conclusion can be made based on these results. Incorrect results that are taken into consideration may bring additional costs for unnecessary repairment procedures and inefficient use of maintenance resources [24].

3.4. Limits of combining laboratory, construction, and monitoring data

Integrated approaches that combine laboratory testing, construction control, and operational monitoring are widely used. However, this integration has inherent limitations. These limitations must be recognized to prevent assertiveness in the assessment of the results.

Uncertainty exists throughout a dam's life cycle because to material variability, environmental exposure, and measurement limits. Laboratory tests are carried out under controlled conditions and reflect idealized boundary scenarios; however, deviations from these assumptions accrue during construction and operation, resulting in progressive uncertainty increase [25].

Long-term monitoring systems might have data drift because sensors get older, temperatures change, moisture gets in, calibration is lost, or electronics break down. As a result, long-term changes in temperature, deformation, or wave velocity that are seen may be caused by the way the sensor works instead than the concrete really breaking down.

The reliability of embedded and surface-mounted sensors is determined by installation quality, survivability during concrete laying, and environmental exposure. Sensor replacement is typically impractical in large concrete structures, making early installation faults or slow degradation difficult to repair. Thus, monitoring data should be considered as conditionally dependable rather than absolute indications of material state.

These broad constraints are also apparent in national practice. Even while Turkish dam engineering is becoming more in line with international integrated laboratory–construction–monitoring frameworks, they are not always put into practice in the same way. In substantial RCC and mass concrete dam projects, performance-based assessment has been incrementally implemented; however, its efficacy is frequently diminished by organizational fragmentation, poor monitoring coverage, and the utilization of diverse data sources.

Monitoring systems are often introduced to meet contractual or regulatory needs. They are not always planned as tools for long-term engineering decisions. ICOLD (2018) [26] points out that weak links between monitoring data and laboratory or construction records can cause errors in interpreting. These issues may arise from the aging of sensors or changing environmental conditions. Non-Destructive Testing (NDT) results are influenced by variations in moisture and temperature as laboratory and field studies show. (Zhang et al., 2021) [18] When a common interpretation method is lacking, the evaluations are based on judgement that is specific for a project rather than consistent criteria (Grosse & Ohtsu, 2020) [19]. Furthermore, in some inspection galleries the signal quality of a ground penetrating radar may reduce because of the high moisture content in concrete that blocks the signal. This reduction in signal quality, consequently, may lead to false identification of internal defects (Alani et al., 2020; Solla et al., 2021) [20, 21].

In Turkey, there are still no national guidelines for the interpretation of NDT data in large concrete dams. This absence restricts the practical use of monitoring results and weakens the reliability of long-term performance evaluations [37].

4. International Experience in Dam Concrete Durability: Implications for Turkey

The main goal of this chapter is to identify practical solutions for improving dam concrete performance in Turkey. This is done through a comparison of international approaches to quality control and long-term durability. The United States, China, Russia, Brazil, and Turkey were selected for this analysis. These countries have extensive experience in large concrete dam construction. They also represent a wide range of climatic and environmental conditions. In addition, they apply well-established engineering standards and maintain long-term monitoring records. Differences in regulatory systems, construction methods, and quality control approaches provide a strong basis for comparison. This allows the analysis to go beyond a descriptive review and focus on practical performance-related issues [28].

Table 6. Comparison of Dam Concrete Durability and Quality Control Practices

Assessment Aspect	USA	China	EU / Russia / Brazil	Turkey (Current Practice)	Identified Gap	Realistically Adoptable Measures for Turkey
Quality control philosophy	Risk-based, predictive	Fully integrated, AI-based	Compliance-oriented	Compliance-based	Limited predictive capability	Adoption of risk-based and predictive maintenance strategies without changing core regulations
Laboratory–field–monitoring integration	Centralized databases	Digital twin platforms	Partial integration	Fragmented datasets	Weak feedback loops	Creation of a national durability database under DSİ integrating lab, construction, and monitoring data
Monitoring system maturity	SHM + NDT integration	Dense sensor networks + AI	Climate-driven monitoring	RTSMS, BİDS, NDT	Limited analytics	Expansion of RTSMS with analytical and trend-evaluation modules
Use of durability indices	Implicit indicators	Explicit Durability Index	Qualitative indicators	No durability index	No unified metric	Introduction of a simplified, regulation-based Concrete Durability Index
Thermal behavior management	Numerical models + feedback	Continuous thermal modeling	Design-stage focus	Design-stage focused	Weak operational calibration	Linking operational temperature monitoring to design-stage thermal models
NDT interpretation	Cross-validated	Sensor-integrated	Project-specific	Fragmented interpretation	False positives	Development of national NDT interpretation guidelines adapted to mass concrete
Decision-making support	Predictive planning	AI-assisted early warning	Mostly reactive	Compliance-oriented	Limited decision support	Gradual implementation of early-warning systems within RTSMS
Service life prediction	Widely applied	Core system component	Limited	Rare	No service-life models	Gradual adoption of service-life prediction models for major dams

4.1. Initial quality control of dam concrete: materials and mix design

The safety, durability, and long-term reliability of concrete dams depend strongly on the quality of the concrete. Dams differ from most civil engineering structures. They are permanently exposed to hydrostatic pressure, internal temperature gradients in large concrete volumes, seepage, cyclic environmental actions, and chemical effects. Because of these conditions, early decisions on material selection and mix design are critical. Poor decisions at this stage can cause uneven stress distribution. They can also reduce serviceability and structural reliability over the dam's service life.

In dam engineering, pre-construction quality control is a broad analysis that does not only include standard checks of the materials but it is a thorough verification procedure that makes sure that the concrete has stable mechanical, thermal, and durability-related properties that are suitable for the dam's unique type of structure, the conditions in which it will be used, and the demands of its operation. This stage is becoming increasingly recognized as a key risk-control phase by international practice, during which longterm performance criteria are mostly set [29].

In contemporary dam projects, pre-construction quality control is typically structured around interconnected components, including the verification of cement and supplementary cementitious materials, aggregate evaluation, assessment of water and chemical admixtures, concrete mix qualification, thermal verification for mass concrete, and durability-oriented testing. The overall architecture is comparable all over the world, although the level of analysis, testing frequency, and level of integration vary a lot from country to country [29].

- *Control of Cement and Supplementary Cementitious Materials*

Cement's role in construction is defined as the main binding agent that influences several factors such as hydration kinetics, strength progression, heat production, and microstructural development in dam concrete. Factors affecting peak temperature rise and thermal stress development are considered to be crucial in mass concrete applications, since excessive heat of hydration can create thermal gradients between the core and exposed surfaces that may result in cracking and diminished durability.

Cement production in Turkey follows European standards. These standards focus on fineness, setting time, strength development, and chemical composition. Thermal performance is usually checked at the design stage or when the cement source is changed. However, continuous calorimetric control during construction is rarely applied in a systematic way. In contrast, large dam projects in the United States and China often use batchby-batch cement verification. This process includes heat-evolution measurements. Such a control helps to detect material variability at an early stage and improves thermal risk management. In Russian practice, mechanical testing is combined with detailed chemical and mineralogical analysis. Brazilian practice places greater emphasis on sulfate resistance and chemical stability under aggressive environmental conditions.

In global practice, supplementary cementitious materials (SCMs)—such as fly ash, blast furnace slag, natural pozzolans and silica fume—are widely used. They are applied to control hydration heat, reduce permeability, and improve long-term durability. Systematic evaluation of SCM quality and cement–SCM compatibility is considered essential for the reliable performance of mass concrete dams [30].

- Mechanical Performance and Durability Assessment

The key element of concrete employed in dam construction is rocks. Their inherent characteristics are essential for the long-term durability, thermal behavior, and integrity of the structure. Therefore, the selection of aggregates is a highly important process that should not be only limited to evaluations of purity and particle size distribution. The assessments must include their resilience to wear, cyclic freezing and thawing, and potential chemical reactions with alkalis. In Turkey, aggregate control follows European and DSİ standards. These standards cover grading, moisture control, and basic durability tests. Long-term ASR studies are usually carried out only when specific concerns arise.

In contrast, the United States and China apply more comprehensive qualification procedures. These procedures consist of both rapid and long-term ASR testing. Quarry-specific databases are used to support the results. Russian practice emphasizes on resistance to frost because of severe climate conditions in their region. Brazilian practice focuses more on resistance to chemical attack in humid environments. These differences show that aggregate qualification should be selected based on the environment in the region and degradation mechanisms. Relying only on standard acceptance criteria may not be sufficient for long-term dam performance.

- *Water Quality and Chemical Additives: How They Interact and Affect Longevity*

The characteristics of water and the types of chemical additives used have a significant impact on how quickly concrete is set. Additionally, those properties influence how easy it is to work with concrete, how strong it becomes, and its lasting durability. During the construction of dams, cements and additives' compatibility should be studied carefully. This factor is highly important since if they don't work well together, it can result in concrete that sets too slowly, shrinks more than expected, or becomes more permeable.

European standards of water quality control are used in Turkey. Admixtures' evaluation is mostly based on basic performance and strength tests. In contrast, for the same tests the United States and China apply stricter verification procedures. Regular water quality checks and compatibility tests are usually used in these procedures. To support these evaluations, calorimetry and durability-related tests are typically conducted. Some countries such as Russia and Brazil place strong emphasis on compatibility studies before construction. In addition, they tend to monitor dissolved salts and organic content in mixing water. Hence, as international experience suggests, checking the compatibility of materials before the construction may significantly reduce possibilities of their mismatch on the construction site. Thus, this factor needs to be considered seriously.

- *Testing and qualifying the concrete mix*

The concrete mix designs for dams should be selected thoroughly since they are responsible for deformation behavior, permeability, crack resistance, and long-term stability in dams. For determining the performance of fresh concrete and its mechanical and durability related properties of the hardened one, laboratory qualification procedures must be carried out.

Comparative practice shows that the US and China have the most thorough mix qualification procedures, which include testing for durability and time dependence again. Turkey and Russia usually use a medium level of testing intensity, while Brazil focuses on chemical durability in harsh conditions. More and more people agree that routine testing of shrinkage, creep, and permeability needs to be done more often in order to make better predictions about how long a service life will last.

- *Evaluation and Verification for Mass Concrete: Rise in Temperature and Strategy for Placement*

Thermal verification is an important part of making sure that mass concrete walls are of good quality. Because the placement volumes are big and the boundary conditions are tight, hydration heat causes the internal temperature to rise a lot. This is followed by cooling that causes thermal gradients that can cause tensile loads that are higher than the early-age tensile strength [31].

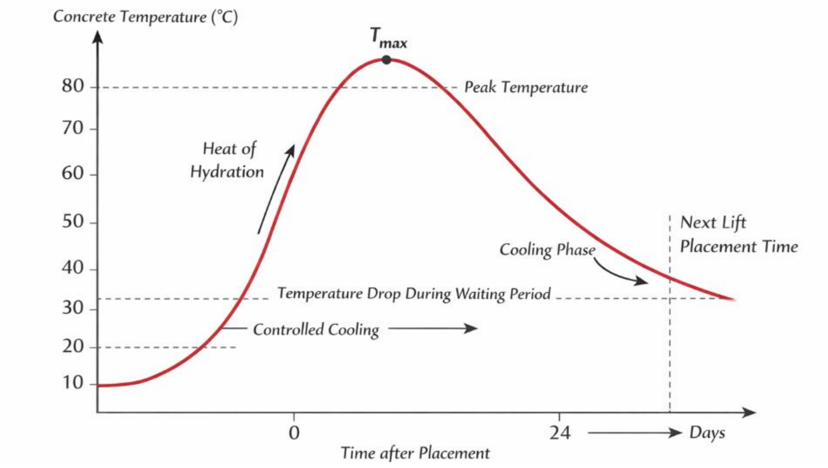

Figure 6. Thermal progression in main concrete throughout hydration and cooling phases

For engineering verification, can use simplified exponential relationships to figure out how much the temperature will drop during the time between layers of concrete:

$$\Delta T(t) = T_o e^{-kt} \tag{1}$$

Where k is the thermal dissipation coefficient that shows how the material and the conditions at the border affect it. Importantly, k is not a constant; it changes depending on the type of insulation on the surface, the curing circumstances, and the amount of time it has been exposed. Reported values typically range from $K \approx 0.02 - 0.06\text{h}^{-1}$ for insulated or covered surfaces to $K \approx 0.06 - 0.10\text{h}^{-1}$ [33] for exposed concrete surfaces, showing how sensitive thermal verification is to how the building was built. Analytical verification is sometimes supplemented by field temperature monitoring with embedded thermocouples, facilitating adaptive management of installation schedules and cooling tactics.

- *Pre-construction testing that prioritizes durability*

The objective of durability testing is to evaluate the resistance to long-term degradation mechanisms, including sulfate attack, chloride ingress, carbonation, freeze–thaw cycles, and permeability-related damage. Long-term viability under particular site exposure factors can be predicted through pre-construction durability tests. However, these tests are not so frequently conducted compared to the ones in the United States or China. To improve predictability and decrease early-age product defects, expanded systematic durability tests should be applied. Consequently, the incorporation of these test results into centralized quality management systems may bring the desired outcome [34].

The general structure of pre-construction quality control is consistent across countries. However, the main differences are in the depth of analysis, frequency of testing, and integration with monitoring systems. The long-term performance, durability uncertainty, and thermal risks are all influenced by these differences. All available durability-focused methodologies in preconstruction step were summarized in Table 7. It provides a relevant to the Turkish context tests that can be applied. They mainly emphasize strengths, limits, and transferable aspects of international experience based on a comparative gap analysis.

Table 7. Comparison of durability-oriented pre-construction tests for dam concrete

Durability Aspect	Typical Tests	USA / China Practice	Turkey Practice	Identified Gap	Feasible Improvement
Sulfate resistance	Expansion tests, chemical attack tests	Routine long-term testing (≥6–12 months)	Selective testing	Limited long-term datasets	Increase test duration and frequency
Chloride ingress	RCPT, diffusion tests	Regular testing + performance thresholds	Limited frequency	Insufficient transport data	Performance-based chloride limits
Freeze–thaw resistance	ASTM C666 / equivalent	Mandatory for exposed zones	Applied selectively	Partial coverage	Zone-based mandatory testing
Permeability	Water penetration, absorption	Systematic testing for mass concrete	Performed but not continuous	Limited trend analysis	Database-based tracking
Shrinkage and creep	Long-term deformation tests	Integrated into mix qualification	Rarely routine	Missing time-dependent data	Routine inclusion in qualification
Thermal durability	Adiabatic calorimetry	Mandatory + linked to placement strategy	Design-stage focused	Weak construction feedback	Construction-stage calorimetry

Looking at this analysis it can be concluded that Turkey demonstrates strong regulatory alignment and laboratory capabilities. Although some flaws remain in the creation of long-term durability tests. Also, the integration of durability test results into monitoring and decision-support systems is not fully adapted. Comparisons made in Table 7. offer various improvements pathways available. The majority of them require increased focus on testing frequency, data continuity, and integration rather than institutional change.

4.2. Worldwide dam engineering practices

The best dam-building nations use a combination of national regulations, technical codes, and specific criteria for regions in the quality of dam concrete. This approach is used in order to ensure long-term structural performance, thermal response, and durability of hydraulic structures.

In the United States, technical documents such as USACE and USBR are utilized in dam concrete practice. Among these documentations there are famous EM 1110-2-2000 Standard Practice for Concrete for Civil Works Structures and EM 1110-2-2200 Gravity Dam Design [33, 35]. These documents require some strict controls that should be present during the evaluation of mass concrete. Those are thermal control, the establishment of permeability limitations, the implementation of crack-prevention measures, and continuous monitoring. To verify concrete mix performance, it should align with permeability assessment (ASTM C1202) [37], thermal characterization, and elastic modulus determination (ASTM C469) [38], along with the strength test. For large-volume concrete structures, thermal analysis and temperature monitoring should be conducted.

The performance-based durability framework in the European Union is established by EN 206 supported by Eurocode 2 (EN 1992) and other corresponding documents. This system categorizes environmental exposure into categories such as XF, XA, and XS [39, 40]. Europeans prioritize good curing quality, limited crack widths, low permeability, and freeze-thaw resistance in dams which are exposed to changing water levels and harsh winter conditions. Monitoring is mostly done for checking compliance with design requirements, not to predict its performance in the future.

Chinese practice uses different approach that includes an advanced coordinated framework for managing dam concrete. It places special attention to ultra-high dams and roller-compacted concrete (RCC) constructions. Their standards rely on uninterrupted thermal monitoring, strict control during the construction, and overall performance evaluation after commissioning based on technical standards of SL 601-2013 and SL 268-2001 [41, 42]. China's strategy is mainly dependent on broad sensor coverage, unified data processing platforms, and growing use of digital twin systems that help to cross-check model predictions simultaneously with real time structural behavior.

Russian dam engineering relies on a conservative design method that emphasizes lasting physical and chemical stability in extreme climates. For evaluations of sulfate resistance, crack development, deformation, and freeze-thaw performance standards such as SP 41.13330 [43] are used. In subzero regions, Russians mostly emphasize on constant seepage monitoring and deformation modeling since they are critical to safety assessments in such areas.

In Brazil and other tropical regions, durability is mainly affected by chemical attack, flowing water, and cavitation. Brazilian practice mostly follows ICOLD guidance. They put focus on erosion resistance and surface condition in high-flow zones [25, 28].

In Turkey, dam concrete quality control is regulated by the State Hydraulic Works (DSİ) and European standards. These are supported by technical specifications. Concrete production and durability classification follow TS EN 206. Laboratory testing of hardened concrete follows the TS EN 12390 series. Non-destructive testing methods defined in TS EN 12504 are used for in-situ and post-placement evaluation [40, 44, 45]. This system ensures compliance with European norms. It also supports structured material certification and quality control during construction. . The main difference between countries' standards lies in the way tests and monitor data are applied and used in engineering decisions.

In the United States and China, data systems are proactive and connected. They integrate laboratory results, construction monitoring, and operational data together. This approach helps with maintenance planning, durability evaluation, and temperature control. In contrast, European and Turkish practices are mostly focused on meeting formal requirements. They rely on fixed acceptance limits. Long-term monitoring data are rarely used to guide design or construction decisions.

This difference explains the reason why similar standards can lead to different levels of performance predictability. Turkey has strong regulations and well-developed laboratories. However, performance-based concrete management still has some shortcomings with linking monitoring results and decision-making. As shown in Table 8, these international comparisons may help with identifying practical improvement measures. They focus on better thermal risk control and durability assessment. Importantly, these improvements can be achieved without major institutional changes.

Table 8. Comparison of gaps in dam concrete quality control practices

Country	Key Strength	Evidence / Application	Identified Gaps / Limitations
USA	Full automation and predictive performance assessment	Integrated systems combining laboratory data, sensors, and numerical models; monitoring intervals of 5–10 minutes in large dam projects (USACE, 2021; ICOLD, 2020)	High implementation and maintenance costs; system complexity
China	AI integration, digital twins, and high-frequency monitoring	Real-time structural monitoring systems (RTSMS) and digital twin platforms for RCC and super-high dams; measurements every 5–15 minutes (Wang et al., 2020; Zhou et al., 2023)	Extremely high data density; substantial infrastructure and data management demands
Russia	Deep engineering interpretation and cold-climate expertise	Strong focus on frost resistance, dynamic elastic modulus, creep behavior, and physicochemical durability (SP 41.13330; ICOLD, 2019)	Lower automation level; limited real-time assessment capability
Brazil	Chemical and biological durability in tropical environments	Emphasis on resistance to aggressive chemical exposure, filtration behavior, abrasion, and cavitation (ICOLD, 2018; Andrade et al., 2020)	Lower testing frequency; high moisture affects reliability of some NDT methods
Turkey	Alignment with European standards and strong laboratory capacity	Quality control aligned with EN standards and DSİ technical specifications; extensive laboratory infrastructure and systematic construction-stage control (ICOLD, 2019; DSİ, 2020; TS EN 206; Özdemir et al., 2021)	Limited continuous digital monitoring; fragmented data integration and lower frequency of lasting durability and NDT evaluations

4.3. Geodetic methods used to monitor dam deformation

Visual examinations and material testing are not enough to assess the long-term safety of concrete structures. The global structural response must be considered in the thorough analysis during the operational phase. This is required due to exposure of dams to hydraulic loading, temperature changes, seepage forces, and actions caused by the environment.

Conventional Deformation Analysis (CDA) is used as a primary geodetic method. It helps to identify coordinate changes between the phases of considerable deformations in structures. CDA results are generally represented as displacement vectors. They are evaluated based on hypothesis testing inside a traditional geodetic adjustment method [46]. Formulations by Gauss–Markov and test statistics are given in Appendix A; this section places a great emphasis on interpretations done by engineers and the significance of materials chosen.

➢ *Correlation between Measured Displacements and Concrete Behavior*

Geodetic method such as CDA do not evaluate the material properties. For example, compressive strength, permeability, or microcrack density are not considered in the analysis. Instead, it records displacement patterns that represent the total structural reaction of the dam. This response is based on time-dependent and environment-dependent mechanisms in concrete, including:

• Thermal stresses, which are caused by variations in temperature and continuous loss of heat. It is then followed by hydration, and reveal as reversible (seasonal) and partially irreversible deformation components;

• Creep and shrinking that result in slow, permanent deformation. These processes are achieved by continuous application of loads and changing temperature and humidity conditions;

• Stiffness loss resulted from degradation. It usually consists of cracks, chemical damage, or flexible joints that reduce stiffness and change displacement size and phase under identical loads.

Therefore, CDA reveals long-term deformation patterns that should be regarded as structural-scale indicators. They reflect changing material behavior and not only geometric observations. This explanation aligns with current synthesis efforts in dam deformation monitoring. In this synthesis, recorded displacements are thought to be affected by creep and temperature-related factors. Appendix A includes complete mathematical formulation of CDA needed to assess engineering aspects of concrete dam [47].

➢ *Combined Analysis to Estimate Material Properties*

To determine material properties, inverse analysis of CDA derived deformation data and numerical simulations with temperature records might be used to interpret geodetic displacements. Effective values of elastic modulus E, creep coefficient φ, and thermal expansion coefficients are updated by comparison of observed displacement vectors with computed structural responses. This approach ensures convergence between measurement and prediction. To get material degradation over time, structural health monitoring with advancements and dam safety evaluations along with the inverse methods can be used. Previously, it was not possible with traditional localized testing (Xu et al., 2021; Li et al., 2022). Sun et al. (2020) [48, 49, 50] says that long trends in geodetic deformations may lead to several shifts in massive concrete structures. These include change in global stiffness, increase in creep intensity, and dynamic redistributions of thermal strains using thermo-mechanical finite element models. Therefore, CDA can be used not only as a tool for detecting geometric distortions, but also as a performance-based evaluation approach. The one that may serve as a link to visible structural behavior and mechanical state of concrete.

➢ *Role of CDA in a concrete-based evaluation*

CDA is not only significant due to the complete mathematical derivation, but its function as a decision support method in a materials-based evaluation that:

• Determines considerable deformation;

• Distinguishes expected results from anomalies;

• Helps to additionally check performance-based evaluation.

This check is done by using temperature monitoring, seepage data, NDT results, and durability indicators [51].

4.4. Current practice and key limitations in turkey

In Turkey, national rules regulate quality control and testing of concrete for dam construction. These rules are aligned with European standards. They mostly make use of TS EN 206, TS EN 12390, and TS EN 12504 [39, 44, 45]. The State Hydraulic Works (DSİ) provides supervision for all substantial dam projects. These cover material selection, construction methods, inspection procedures, and completion criteria. Advanced laboratory infrastructure is a strong side of Turkish practice. Quality control during construction is generally strict. It is particularly evident in reinforced concrete and mass concrete dams.

A systematic approach is used for concrete mix design. In this approach, strength verification is regularly performed. Standard evaluation process includes durability-related tests. During the design phase, temperature effects from cement hydration are usually addressed and then checked again during construction. However, when compared with leading international practice, the main limitation is not the lack of testing or monitoring. The key issue is how the collected data is used. The obtained data needs to be combined into a single performance-based evaluation system. It should include laboratory testing, construction control, and operational monitoring, which are usually treated separately. Creep, heat strain, and progressive stiffness degradation are referred to as temporary concrete behavior. These effects may appear as long-term deformations at the structural level. Geodetic monitoring is used for detecting such deformations. In current Turkish practice, deformation data are mainly used to check structural safety. Their potential for evaluating material performance and degradation processes is still limited.

As a result, gaps remain in real-time data integration. NDT results are still not uniformly interpreted. Long-term durability data are not always stored and managed in a structured way. Addressing these issues does not require major institutional changes. Instead, it needs better data integration and interpretation methods that are model based. Such approaches have already been applied to international practice. This context leads to the next section. It examines the use of digital twin concepts and incorporation of monitoring systems. Chinese experience is specifically studied because of its potential integration of performance-based dam management in Turkey [52].

4.5. Strategic approaches for turkey: digital twin–based monitoring of concrete dams

Traditional monitoring techniques have some limitations that are dependent on irregular measurements and separated data interpretation. These limits lead to a progressive decline in concrete dams, increased seismic risks, and demands for real-time safety assessments. Structural behavior can be examined by conventional monitoring systems. However, they cannot give information about the time-dependent interactions during thermal effects, concrete deterioration, and overall structural reaction.

Recently, digital twin-based monitoring has been regarded as a progression of structural health monitoring (SHM) systems in global experience. Its main advantage is constantly updating numerical representation of a physical structure. Also, it synchronizes in real time with monitoring data and may simulate both present and future performance states. Whereas static analytical methods are unable to perform the same tasks.

In Turkey, the integration of digital twins might be helpful since several concrete dams are in high seismic zones. Some of them exhibit signs of deterioration, thus this implementation would serve as risk-informed dam safety management.

➢ *Digital Twin Framework for Concrete Dams*

For concrete dams' digital twin system should be considered as an integrated system that combines:

• A 3D physics-based finite element model (FEM) that shows thermo-mechanical and hydraulic processes,

• Continuous measurements of deformation, temperature, seepage, and chemical indicators,

• Model parameters that use inverse analytical approaches,

• Simulations tools for scenario prediction.

Such a system would enable smooth transition from static condition assessment to adaptive, performance-based decision support.

➢ *Incremental Strategy for Execution in Turkey*

For integrating digital twin systems nationwide, a systematic strategy needs to be applied. Full adoption of these systems on all concrete dams might not be the best option. Instead, it is better to start installing them on strategically important dams first.

Concrete dams such as Deriner, Ilısu, Ermenek, and Oymapınar can be appropriate candidates for testing this system. All of them are exposed to seismic and hydraulic hazards along with the complexity of the whole structure. For the very beginning, the main objectives are:

• Revise sensor architecture and incorporate parameters for monitoring,

• Build one digital twin model that links 3D geometry, structural analysis, and real-time data,

• Set up early warning systems that are based on performance limits,

• Evaluate data reliability and adjust numerical models during operations.

Multi-parameter risk assessment should be included in the experimental system. It would help with simultaneous monitoring of movement, temperature, stress levels, and seismic responses. The efficiency of the pilot must be assessed before implementing it all over the country. The analysis should be based on its technical performance, cost-effectiveness, and usability.

➢ *Benefits for Dam Safety Management in Turkey*

Through the integration of digital twin-based monitoring systems in Turkey, several benefits are expected to happen. Main expected outcomes are as follows:

• Real time monitoring of structural and material response,

• Early detection of unusual deterioration and deformation,

• Fast and reliable analysis of post-earthquake damage,

• Less need for occasional inspections and manual checks,

• More objective and efficient decision-making,

• Predict necessary improvements in maintenance and repairments,

• Extending the service life and improving the safety of aging structures.

Digital twins' assessment is especially beneficial in seismic occurrences as those in Turkey. The main reason is in analysis that delivers actual structural performance based on evidence instead of operational limits. Such an approach may significantly enhance risk-informed management.

5. Conclusions

This study examined how concrete properties are measured and evaluated in dam engineering. The focus was on material behavior, durability, and quality control over the total service life of concrete dams. Dam concrete differs from ordinary concrete structures. It experiences mechanical loading, water pressure, temperature variation, and chemical exposure simultaneously. These effects are always present, thus longterm performance depends more on durability and time-dependent behavior rather than initial strength only.

The analysis shows that dam concrete behaves as a complex system. Mechanical, transport, thermal, and durability-related properties are all linked to each other. Each factor influences others as time passes. Therefore, crack formation, permeability changes, thermal stress development and material degradation are all governed by these properties. For this reason, assessing these properties separately does not provide a reliable evaluation. This issue was highlighted in the concept of functional zoning. Different parts of a dam are exposed to different loads and environmental conditions. Hence, each zone should have specific material design, testing, and monitoring.

One of the main conclusions of this review is the need for a life-cycle approach to quality management. Expected performance of concrete is acquired by laboratory testing. Construction-stage control ensures that design requirements are met. Changes in material during operations are observed by long-term monitoring, often using non-invasive methods. If these stages are considered together, negative trends can be detected at an early stage. Thus, preventive and performance-based maintenance method can be used. Such an approach is more effective than waiting to repair after damage has occurred.

➢ *Implications for Engineering*

The findings of this study have several practical implications for engineering practice:

• Designers should give priority to durability-related properties. These include permeability, thermal response, creep, and cracking pattern. Consideration of these factors as key design parameters is required. Functional zoning and long-term exposure conditions should be acknowledged.

• Periodic inspections should not be the only indicators for dam owners and operators. It is better to use monitoring systems that are continuous and integrated. Temperature, deformation, seepage, and non-destructive testing results should be directly linked to material performance.

• Quality control should be treated as a continuous process that should be regulated over the full life cycle of a dam. Laboratory data, construction records, and operational monitoring should be combined within one evaluation approach.

Turkey already benefits from strong regulatory alignment, experienced institutions, and advanced laboratory facilities. However, further improvements in long-term safety and reliability are still possible. Better data integration, more consistent monitoring, and clear interpretation of time-dependent material behavior under long-term and severe loading conditions can be one of the improvements needed.

➢ *Future Research Directions*

This review summarizes current practices in concrete dam engineering. Nevertheless, the management of longterm performance can be enhanced by additional research. Future studies might focus on several key areas:

• Integration of digital twins. This method allows to link numerical models with real-time monitoring data. By updating the models continuously, improved accuracy of safety assessment and performance prediction can be achieved.

• Data analysis carried out by AI. Monitoring systems generate large amounts of data. Artificial intelligence can be used to analyze these datasets. It can detect small anomalies and warn for unexpected deformation or material deterioration before it becomes late.

• Indicators of durability. To convert monitoring data into clear durability indicators, research needs to be conducted. These indicators should be easy to interpret and directly support engineering decisions.

• Consideration of uncertainty. From the very beginning, unpredictability should be considered in future design methodologies. This includes alterations in material properties, imposed loads, and deterioration over time. Accurate assessments of service life and related risks can be achieved by considering these parameters.

Usage of inverse analysis methodologies may provide additional benefits. By using long-term monitoring data, material properties can be determined, and structural behavior may be understood better.

Appendix A. Mathematical Background of CDA

This appendix presents the mathematical background of Conventional Deformation Analysis (CDA) used for geodetic monitoring of concrete dams. To ensure clarity and consistency, equations are presented. The main text's focus instead was on engineering interpretation and meaning of deformation in the material (Section 4.3).

CDA serves as a supporting tool that links material-related processes with overall structural behavior. These processes include creep, temperature effects, and changes in stiffness. Relevant mathematical expressions are placed in this appendix in order to show every derivation in a clear and understandable manner.

A.1. Observation Model and Network Adjustment

In CDA, for each observation period, the geodetic control network is adjusted specifically. Each adjustment is carried out as a free network. Such an approach allows for more reliable detection of deformation since it avoids biases caused by fixed reference limits.

For each epoch, the observation model is described using the Gauss–Markov model, which can be expressed as follows:

$$l_1 + V_1 = A_1 x_1 * C\ l_1 l_1 = \delta_0^2 P_1^{-1} \quad (2)$$

$$l_1 + V_i = A_i x_i * C\ l_i l_i = \delta_0^2 P_i^{-1} \quad (3)$$

Here, 1 refers to the first observation period, and i refers to later periods. A is the design matrix. x contains the unknown coordinates. l represents the measured values. V shows the remaining errors after adjustment. P is the weight matrix.

A.2. Displacement Vector and Statistical Analysis

The coordinates for each epoch are calculated using a least-squares method:

$$x_1 = (A_1^T P_1 A_1) + A_1^T P_1 l_1 \quad (4)$$

$$x_i = \left(A_{(i)}^T P_i A_i\right) + A_{(i)}^T P_I l_i \quad (5)$$

A null hypothesis is defined to check if there were a meaningful displacement two epochs:

$$\mathrm{H}_0 : E\ (x_1) = E(x_i) \quad (6)$$

$$H_0 : E\ (x_1) \neq E(x_i) \quad (7)$$

If the observation periods are considered independently, the displacement vector would be defined as:

$$d = x_i - x_l \quad (8)$$

and its cofactor matrix is given by:

$$Q_{dd} = Q_{xlxl} + Q_{xixi} \quad (9)$$

The quadratic form used for global statistical testing is expressed as:

$$R = d^T Q_{dd} + d \quad (10)$$

The test statistic is computed as:

$$T = \frac{R}{h s_0^2} \sim F_{h,f,a} \quad (11)$$

where h is the rank of the matrix Q_{dd}, f is the total degrees of freedom, a is the significance level, and $s_0^2$is the estimated variance factor:

$$S_0^2 = \frac{V_1^T P_1 V_1 + V_i^T P_i V_i}{f_1 + f_i} \quad (12)$$

A.3. Analysis of Local Displacement

If the computed test statistic exceeds the critical value of the Fisher distribution, the null hypothesis is rejected and a significant displacement is identified.

Following global testing, local displacement analysis is performed to identify individual points exhibiting significant movements. Horizontal displacement magnitudes and accuracy measures are calculated as:

$$dX_i = X_i - X_1; dY_i = Y_i - Y_1; dP_i = (dX_i^2 + dY_i^2)1/2 \quad (13)$$

$$m_i = (m_{xi}^2 + m_{yi}^2)^{1/2} \quad (14)$$

$$M_i = (m_1^2 + m_i^2)^{1/2} \quad (15)$$

Significant displacements are determined using the criterion:

$$T_i = 2{,}5 * (M_i)\sqrt{a^2 + b^2} \quad (16)$$

where a and b represent the confidence parameters defined according to established engineering practice.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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