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Delayed-Expansion MgO in mass concrete for Thermal-Stress control in arch dams: A comprehensive review and roadmap for Vietnam

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KEYWORDS

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ABSTRACT

Temperature cracking poses a major challenge in arch dams and other massive concrete structures. During cement hydration, heat accumulation followed by cooling creates tensile stresses that may exceed the material's tensile strength, leading to cracking and structural weakening. For arch dams, where compressive integrity is essential to transfer loads to abutments, even small thermal cracks can endanger global stability. Magnesium oxide (MgO) has been proven over decades to be an effective internal expansive agent for controlling thermal stress in mass concrete. Its delayed hydration to magnesium hydroxide [$Mg(OH)_2$] generates gradual expansion that compensates for thermal contraction during cooling. This review summarizes mechanisms, laboratory results, field experiences, and modeling of MgO expansion, emphasizing its application in arch dams. Studies from projects such as Baishan, Qingxi, and Three Gorges show that 3-6% MgO can reduce peak thermal stress by up to 40% and crack density by about 50%. Microstructural analyses confirm a denser matrix and improved durability, while numerical models indicate lower tensile stress and higher stability. For Vietnam's hydropower projects, this paper proposes applying MgO-based temperature-stress control through optimized dosage, particle-size refinement, and long-term validation to develop future TCVN standards for mass concrete in arch dams.

1. Introduction

Thermal cracking remains one of the most critical issues in the construction and operation of arch dams, where the curved geometry relies on compressive stress transfer to abutments. The high heat of cement hydration, combined with restrained deformation and complex three-dimensional stress conditions, makes arch dams particularly susceptible to cracking once the temperature begins to decline after placement. When tensile stress exceeds the concrete's tensile strength, cracks develop, jeopardizing watertightness, stiffness, and long-term safety of the structure [1], [2].

Conventional temperature-control techniques such as using low-heat cement, mineral admixtures, or embedded cooling pipes have been widely implemented in high dams, including the Hoa Binh and Son La projects in Vietnam. Although these methods effectively limit peak temperature and thermal gradients, they are costly, energy-intensive, and extend construction schedules, especially under remote mountainous conditions [3], [4].

To address these challenges, researchers since the 1960s have explored internal stress-compensation mechanisms that rely on controlled expansion rather than external cooling. Among these, the use of magnesium oxide (MgO) as a delayed expansive agent has proven highly effective. When moderately calcined MgO hydrates slowly to form magnesium hydroxide [$Mg(OH)_2$], it generates gradual, time-dependent expansion that compensates for thermal contraction during cooling, thereby maintaining compressive residual stress in the dam body [5], [6].

Extensive experimental and field-based studies in China and Japan have validated the effectiveness of MgO expansive concrete for thermal-stress control in hydraulic structures. For example, Mo, Deng, and Tang (2015) reported that MgO-bearing concrete applied in the Baishan Arch Dam effectively reduced peak temperature by approximately 10 °C and prevented post-cooling surface cracking through gradual autogenous expansion [7]. Similarly, numerical simulations and on-site monitoring of high-arch dams confirmed that MgO addition can reduce thermal tensile stress by 30-40% and maintain a compressive residual state during cooling. More recently, Nguyen et al. (2019) established and validated a quantitative model of autogenous volume deformation (AVD) for MgO-RCC systems, which has been successfully integrated into thermal-mechanical finite-element frameworks for dam design optimization [8].

Despite these proven successes abroad, the application of MgO expansive concrete in Vietnam remains limited. Domestic projects continue to depend primarily on imported low-heat cement and embedded cooling systems, which increase both cost and environmental impact. Moreover, Vietnam's tropical monsoon climate characterized by high humidity, pronounced diurnal temperature variations, and slow heat dissipation presents unique challenges that may alter MgO hydration kinetics and expansion behavior [9], [10].

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Accordingly, there is an urgent need to adapt and optimize MgO-based temperature-stress control for local conditions. This review therefore aims to (1) elucidate the chemical and microstructural mechanisms underlying MgO-induced delayed expansion; (2) summarize laboratory research, numerical modeling, and field experience from international projects; (3) evaluate the potential of MgO application under Vietnam's climatic and material environment; and (4) propose a practical research roadmap leading toward the establishment of a national technical standard (TCVN) for MgO expansive concrete in arch-dam construction.

Through this synthesis, the paper seeks to provide both a scientific foundation and an engineering framework for next-generation temperature-stress management in Vietnamese hydropower arch dams, contributing to safer, more durable, and more sustainable infrastructure development.

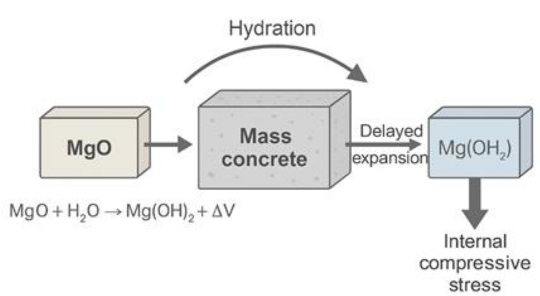
2. Mechanism and hydration kinetics of MgO in arch-dam concrete

2.1. Fundamental reaction

The expansive effect of MgO originates from its hydration to magnesium hydroxide (brucite):

$$MgO + H_2O \rightarrow Mg(OH)_2 + \Delta V \quad (1)$$

This transformation involves a volume increase of roughly 118%, generating internal compressive stress that counteracts thermal contraction if properly timed [11]. In arch dams, where temperature gradients are steepest near the upstream face and crown cantilever, this delayed expansion is particularly beneficial it restores compressive stress along the dam axis and reduces tensile zones that could otherwise initiate cracking [5].



Figue 1. Schematic illustration of MgO hydration and delayed-expansion mechanism in mass concrete.

Chao et al. [12] demonstrated that MgO hydration proceeds in two stages: an initial surface dissolution followed by diffusion through a brucite layer. This self-limiting behavior ensures stable, time-dependent expansion, particularly suitable for massive concrete structures with slow temperature decline.

Recent thermogravimetric and phase-field studies further reveal that the hydration rate follows an Arrhenius-type relationship:

$$r = Ae^{-Ea/RT} \quad (2)$$

where A is a material constant, Ea the activation energy, R the gas constant, and T the absolute temperature.

At internal dam temperatures of 40-60 ˚C, hydration proceeds slowly enough to develop delayed expansion during the cooling phase, a critical feature for arch-dam stability [13], [14].

2.2. Influence of calcination temperature

The activity of MgO is largely determined by its calcination temperature, as this parameter governs both the crystallinity and the specific surface area of the periclase phase [6,11]. When MgO is light-burned below 1000 ˚C, it possesses very high reactivity and hydrates too rapidly, leading to early expansion and possible instability in mass concrete. In contrast, hard-burned MgO, typically calcined between 1050 and 1150 ˚C, shows a delayed and moderate hydration rate that matches well with the cooling and contraction stage of arch dams. If the calcination temperature exceeds 1300 ˚C, the product becomes dead-burned and almost inert, exhibiting negligible expansion [11]. Mo et al. [2] verified that MgO fired at 1100 ˚C with a specific surface area of 2000–4000 cm^2/g demonstrates steady hydration and reliable volume stability. Furthermore, Chen et al. [15] observed that fine particles (<20 µm) hydrate rapidly, causing early expansion, whereas coarse particles (>75 µm) generate a more gradual, long-term expansion that helps relieve tensile stress in large dam blocks. By adjusting both calcination intensity and particle size, the reactivity of MgO can be precisely tuned to the thermal conditions of the dam. Considering that the internal temperature of arch-dam concrete can exceed 60 ˚C during early hydration, such control is essential to prevent premature expansion [14].

2.3. Environmental and Curing Conditions

The hydration behavior of MgO is greatly affected by the ambient temperature and humidity. When the relative humidity exceeds 90% and the curing temperature is maintained between 20 and 40 ˚C, the hydration reaction continues, resulting in stable and uniform expansion [2,16]. Inside the overall structure of the arch dam, the humidity is usually close to saturation, ensuring a stable hydration process. However, on the exposed surface, rapid evaporation and large temperature gradients may occur, resulting in uneven or localized expansion. Studies by Mo et al. [11] and Feng et al. [17] showed that at higher curing temperatures of 45 to 55 ˚C, the hydration rate of MgO increased sharply within the first month, resulting in premature expansion and reduced long-term compensation efficiency. In tropical regions such as northern Vietnam, where temperature and humidity fluctuate greatly, it is crucial to select MgO with appropriate reactivity to ensure that its delayed expansion is synchronized with the contraction caused by the cooling of the dam body [18]. Field studies of large hydropower projects have further confirmed that maintaining sufficient moisture and extending the curing time are essential to maintain stable MgO hydration and generate effective self-stress in large-volume concrete structures.

2.4. Interaction with Cement Hydration

In the composite Portland cement system, MgO participates in the hydration reaction in addition to the main reactions of calcium silicate (C_3S, C_2S) and aluminate (C_3A). Although the hydration reaction of MgO proceeds independently, the formation of $Mg(OH)_2$ contributes significantly to the densification of the microstructure because it can fill fine capillary pores and generate local compressive stress, thereby offsetting tensile deformation. Jiang et al. [19] and Zhou et al. [20] found through SEM and EDS that $Mg(OH)_2$ crystals are generally plate-shaped, interwoven with C-S-H gel, and bridge existing microcracks. This interaction leads to a significant reduction in total porosity, typically by 15% to 25%, and enhances the impermeability and stability of the interfacial transition zone (ITZ). In addition, Mg^{2+} reacts with aluminates to form small amounts of magnesium aluminate hydrates similar to the hydrotalcite phase, further enhancing the matrix strength and improving resistance to chloride ion attack [6], [20]. These coupled microstructural effects together explain the excellent volume stability and long-term durability of MgO-modified concrete properties that are particularly important for arch dams operating under cyclic thermal and hydrostatic loading conditions.

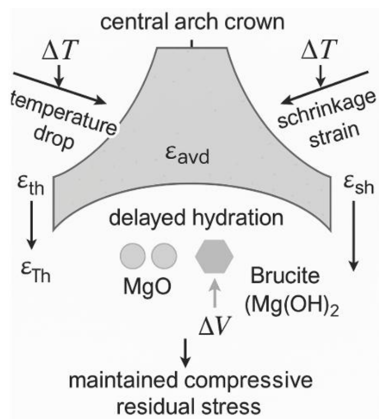
2.5. Microstructural evolution

The microstructural evolution of MgO expansive concrete presents a gradual densification process, as confirmed by SEM, XRD, and MIP observations. In the early stage (1–7 days), most MgO particles remain unhydrated and are finely dispersed within the C–S–H matrix. After approximately 28 days, brucite crystals begin to form as hexagonal plates, filling internal microvoids and sealing pores. Between 90 and 180 days, an interlocking network of $Mg(OH)_2$ develops, reducing total porosity by nearly 25% compared with ordinary concrete [6], [19]. Feng et al. [17] reported that such microstructural refinement produces residual compressive stresses of 0.2–0.4 MPa, effectively offsetting thermal tensile stresses during the cooling period. Moreover, Su et al. [21] demonstrated through thermal–mechanical coupling simulations that this densification process corresponds to fewer microcracks and improved impermeability. Therefore, MgO expansive concrete provides both temperature-stress compensation and durability enhancement, particularly suitable for arch dams in warm and humid regions.

3. Autogenous volume deformation and Finite-element modeling in Arch-Dam concrete

3.1. Concept of autogenous volume deformation (AVD)

The delayed hydration of MgO introduces a gradual volume increase that compensates for the volumetric contraction of concrete during cooling. This phenomenon, termed autogenous volume deformation (AVD), plays a pivotal role in predicting and controlling stress evolution in arch-dam structures [8]. The AVD of concrete depends not only on MgO reactivity but also on the thermal history of the dam body and the degree of external restraint [6].



Figue 2. Influence of calcination temperature on MgO reactivity and expansion rate.

In arch dams, the internal temperature field is non-uniform: the central arch crown tends to retain heat longer, while the surfaces cool faster. As cooling proceeds, tensile stress develops near the surface and abutments. The expansion generated by MgO hydration counteracts this tensile strain, maintaining compressive residual stress within the dam shell. Quantitatively, the total strain $\varepsilon(t)$ in the dam body can be expressed as:

$$\varepsilon(t) = \varepsilon_{th}(t) + \varepsilon_{th}(t) + \varepsilon_{avd}(t) \quad (3)$$

where: ε_{th}: thermal strain from temperature drop, ε_{sh}: shrinkage strain, ε_{avd}: compensating strain due to MgO expansion. By calibrating ε_{avd} from laboratory tests and embedding it in FE simulations, designers can select MgO dosages to minimize tensile regions; for arch dams, achieving a small compressive residual stress after cooling is the ideal target for structural stability [6], [8].

3.2. Experimental Determination and Model Application

To accurately predict the delayed expansion of MgO in mass and arch-dam concrete, Nguyen et al. [8] established a hyperbolic expansive model based on systematic laboratory experiments conducted on roller-compacted concrete (RCC) from the Linxihe Arch Dam project in China. The model captures the quantitative relationship among MgO content (M), curing temperature (T), and time (t), providing a physically realistic description of the autogenous volume deformation (AVD) process.

3.2.1. Experimental Background

In their study, Nguyen et al. [8] tested RCC specimens containing 3%, 4%, and 5% MgO under controlled curing temperatures of 20, 30, 40, and 50 ˚C for a period of 207 days. Each specimen's expansion was measured using a custom-built apparatus following the Chinese hydraulic concrete testing standard DL/T 5296-2013.

The results demonstrated that the AVD increased with both temperature and MgO content and gradually approached a stable plateau after approximately 200 days, corresponding to the completion of MgO hydration. Importantly, the AVD curves exhibited a distinct hyperbolic shape, indicating a rapid expansion phase at early ages followed by asymptotic stabilization.

To quantify the delayed expansive behavior of MgO in concrete, Nguyen et al. (2019) [8] proposed a hyperbolic expansive model derived from laboratory experiments on the Linxihe RCC arch dam. The model captures the relationship among MgO content (M), curing temperature (T), and time (t), providing a reliable basis for predicting autogenous volume deformation (AVD) in massive and arch-dam concrete.

The AVD is expressed as [8]:

$$G(t,T) = \frac{t}{\alpha_1 T \alpha_2 + k_1 T^{k_2 t}} c_1 T^{c_2} \times 10^{-6} \tag{3}$$

where $G(t,T)$ is the volumetric strain, and a_1, a_2, k_1, k_2, c_1, c_2 are empirical constants determined experimentally. These coefficients vary logarithmically with the MgO content M (% by binder mass):

$a_1 = 4.5933 \ln M - 3.5595$, $a_2 = -0.909 \ln M + 0.6788$,

$k_1 = -7.541 \ln M + 12.835$, $k_2 = 0.4024 \ln M - 2.0143$,

$c_1 = -0.174 \ln M + 1.0067$, $c_2 = 0.0334 \ln M + 0.0272$.

3.2.2. Model validation

The model was validated using experimental data from the Linxihe RCC arch-dam specimens. Simulated AVD curves showed excellent agreement with measured results across all MgO dosages and temperatures, with mean deviations below 10%. At higher temperatures (40-50 ˚C), expansion developed faster, reaching 70-80% of the final strain within 60 days, while at 20-30 ˚C, expansion was slower but more uniform. These results confirm that the model can reproduce both the rate and magnitude of AVD under varying environmental conditions.

3.2.3. Application in Finite-Element Analysis

Equation (3) enables direct incorporation of AVD into finite-element (FE) programs as a time- and temperature-dependent strain component $\varepsilon_{avd}(t, T)$. By defining $G(t, T)$ as an internal strain function in the constitutive model, designers can simulate the combined thermal-mechanical behavior of MgO-bearing arch-dam concrete. When applied to temperature-stress analysis of dam monoliths, the model demonstrates that MgO expansion can reduce peak tensile stresses by 20-40% and delay the onset of cracking by 7-15 days compared with conventional mixes. The results align closely with field observations from the Baishan, Longyangxia, and Linxihe projects. The AVD model not only describes the time-dependent expansion behavior but also provides a practical tool for predicting residual stress and optimizing MgO dosage under site-specific temperature regimes. Its integration into FEM-based dam design enhances predictive capability and supports performance-based control of thermal cracking.

3.2.4. Engineering Significance

The hyperbolic AVD model developed by Nguyen et al. [8] represents a substantial advancement over previous empirical formulations of expansion behavior in mass concrete.

Unlike earlier approaches, which treated delayed expansion as a constant or externally imposed strain, this model: Integrates the combined effects of MgO content, curing temperature, and time within a single, physically consistent equation; Accurately reproduces both early-age and long-term evolution of autogenous volume deformation (AVD); Is directly compatible with finite-element (FE)-based thermal-stress analysis of arch-dam concrete.

By embedding this model into FE simulations, the delayed MgO-induced expansion can be represented as an intrinsic material property, rather than an external adjustment.

Consequently, the model provides a quantitative design tool for optimizing MgO dosage and curing regimes, enabling engineers to predict and control the stress evolution of arch dams under realistic thermal and mechanical conditions.

This advancement bridges the gap between laboratory characterization and large-scale structural performance, offering a practical pathway toward performance-based thermal-stress management in modern arch-dam construction [8].

3.3. Field validation and case studies

Field validation of MgO expansive concrete has been carried out extensively in major arch dam and RCC dam projects over the past four decades. These case studies confirm the theoretical predictions and numerical models developed for autogenous volume deformation (AVD), demonstrating that properly dosed MgO can effectively control temperature-induced cracking and improve long-term structural stability.

3.3.1 Baishan Arch Dam

The Baishan Arch Dam, completed in 1982 in northeastern China, was among the earliest large-scale hydraulic structures to apply MgO expansive concrete for internal temperature-stress regulation. Despite exposure to severe climatic and thermal conditions, no visible cracking occurred after completion. Field observations and long-term monitoring revealed that the concrete exhibited slight micro-expansion, primarily attributed to the 4.3% MgO content in Fushun cement. Approximately 80% of the total expansion developed within 20 years, inducing beneficial compressive stresses of 0.2-0.4 MPa that compensated tensile stresses from thermal contraction. The 130 m-high structure achieved a reduction of about 10 °C in maximum temperature rise and effectively eliminated post-cooling surface cracks. Microstructural analyses confirmed a denser matrix and improved volumetric stability, demonstrating that properly controlled MgO expansion can serve as a passive stress-regulating mechanism, enhancing both structural durability and construction economy in massive arch dams [7], [8].

3.3.2 Qingxi Hydroelectric Station

The Qingxi Hydroelectric Station, situated on the Tingjiang River in Dapu District, Guangdong Province, lies within a humid subtropical region where natural cooling of mass concrete is highly limited. During early construction, the use of ice-mixed concrete failed to achieve the designed pouring temperature of 23 °C, leading to surface cracking. To address this problem, MgO expansive concrete technology was adopted. Specifically, MgO concrete was placed in the restricted foundation zone with a height of 7-8 m, equivalent to nearly half of the dam section, while the pouring temperature was increased to 31 °C and ice mixing was eliminated. Additionally, surface insulation was applied year-round to suppress thermal gradients. In total, about 500 tons of MgO (5% by binder mass) were incorporated into 50,000 m^3 of concrete, accounting for 36% of the total dam volume. Monitoring results showed autogenous deformation of $(80\text{-}100)\times10^{-6}$, compressive stress of 0.8-1.4 MPa, and compensatory stress up to 0.6 MPa, demonstrating excellent crack resistance and effective thermal stress control throughout operation [22].

3.3.3 Linxihe RCC Arch Dam

The Linxihe Roller-Compacted Concrete (RCC) Arch Dam, with a structural height of 120 m, served as an essential prototype for verifying the Autogenous Volume Deformation (AVD) model proposed by Nguyen et al. [8]. During construction, multiple RCC zones containing 3%, 4%, and 5% MgO were embedded with thermocouples and strain gauges to record thermal and deformation responses in real time. The observed AVD strains corresponded closely with the hyperbolic prediction, showing a maximum deviation of less than 10%. These results confirmed that the model could precisely describe both the early-age and long-term expansion characteristics of MgO concrete. Moreover, the delay period and magnitude of deformation were proven to be strongly dependent on MgO reactivity and the surrounding temperature field. Finite element simulations incorporating the AVD model further reproduced field-measured stress relaxation. Hence, the Linxihe project provided one of the most comprehensive and credible validations of the MgO-based AVD mechanism in both RCC and conventional arch dams.

3.3.4 Three Gorges projects

The Three Gorges Project, although designed mainly as a gravity dam, incorporated several arch-shaped spillway blocks using MgO expansive concrete to investigate its thermal stress control capability. Field data revealed that mixes containing 5-6% MgO by binder mass reduced the peak temperature gradient by approximately 20-25%, effectively preventing thermal cracking during the cooling phase. Long-term core samples extracted from the dam confirmed that the concrete maintained excellent volumetric stability, with no evidence of delayed harmful expansion or microcracking after more than a decade of operation. Microstructural analyses showed that finely dispersed brucite [$Mg(OH)_2$] and hydrotalcite-like phases contributed to pore refinement and sustained compressive self-stress, ensuring high durability under complex thermal-hydraulic conditions. These results, together with findings from the Xiangjiaba Project, demonstrate that properly calibrated MgO expansion provides a reliable and durable internal stress-regulating mechanism for massive hydraulic structures, offering both short- and long-term benefits in temperature-stress management [23], [24].

3.3.5 General findings

Across all these projects, several consistent conclusions emerge: Stress reduction: MgO expansion lowers peak tensile stress by 20-40% and maintains compressive residual stress after cooling. Crack mitigation: Crack density in MgO concrete is typically 50% lower than in ordinary mass concrete. Durability improvement: SEM and MIP data show a 15-25% reduction in porosity, enhancing watertightness.

Economic efficiency: Projects using MgO expansive concrete report a 15-25% reduction in temperature-control cost, mainly due to reduced cooling-pipe installation and shortened construction periods.

These case studies collectively validate the mechanistic and numerical models of MgO expansion and confirm their applicability to arch dams under complex thermal conditions.

They also highlight the need for region-specific calibration of MgO properties such as calcination temperature, particle-size distribution, and dosage to ensure that the delayed expansion aligns with the dam's thermal history and restraint conditions.

Table 1. Relationship between MgO content and reduction in thermal stress.

MgO content (% by binder)	Type of structure	Temperature reduction (°C)	Thermal stress reduction (%)	Source
3%	Gravity dam (Baishan)	8–10	25–30	[7]
4%	RCC arch dam (Linxihe)	10–12	30–35	[8]
5%	Arch dam (Qingxi)	12–15	35–45	[22]

Table 1 summarizes typical relationships between MgO dosage and thermal-stress reduction observed in large-scale dam projects. The results indicate an optimal dosage range of 3–6%, achieving 30–45% reduction in peak tensile stress without causing overexpansion.

3.4. Practical design implications

The field evidence and modeling results clearly demonstrate that the inclusion of MgO expansive agents provides a viable and cost-effective solution for thermal-stress control in arch-dam concrete. Translating these findings into practical design requires systematic consideration of material parameters, construction conditions, and long-term performance requirements.

3.4.1. Key design parameters

Three principal parameters govern the efficiency and stability of MgO-induced expansion in arch-dam concrete:

(1) MgO Content (3-6%) - The dosage directly determines the expansion magnitude and timing. Lower contents (<3%) often provide insufficient compensation for thermal contraction, while higher dosages (>6%) may cause over-expansion or localized microcracking. Field observations from the Baishan and Linxihe arch dams indicate that an optimum range of 4-5% MgO by binder mass achieves the best balance between stress compensation and dimensional stability [8], [10], [12], [25]. Within this range, expansion develops gradually during cooling and ceases once thermal equilibrium is reached, maintaining residual compressive stress without long-term distortion.

(2) Calcination Temperature (1050-1150 °C) - The firing temperature of MgO critically governs its hydration reactivity and the delay period of expansion. MgO calcined within 1050–1150 °C, commonly referred to as hard-burned MgO, exhibits a controlled and gradual hydration rate that aligns well with the post-cooling contraction phase of mass concrete in dams. Such thermal characteristics enable the generation of compensating expansion precisely when tensile stress begins to develop. In contrast, light-burned MgO (<1000 °C) hydrates too rapidly, causing premature expansion and early-age microcracking, whereas dead-burned MgO (>1300 °C) reacts extremely slowly and contributes negligible deformation. Experimental investigations and field evidence from large-scale projects confirm that regulating the calcination temperature within this optimal range ensures stable delayed expansion, effective thermal-stress compensation, and long-term volumetric stability of MgO-based hydraulic concrete [2], [10], [11].

(3) Placement Temperature and Thermal Regime - The initial placement temperature (10-20 °C) and controlled lift height are critical to minimizing thermal gradients during construction. Finite-element simulations incorporating the hyperbolic AVD model [Eq. (3)] demonstrate that when MgO-induced expansion is synchronized with the dam's temperature decline, the peak tensile stress in the crown block can be reduced by up to 40%. Optimized construction sequences and temperature management therefore allow MgO expansion to act as a self-regulating stress-compensation mechanism within the dam body. By balancing these three parameters MgO content, calcination temperature, and placement regime designers can ensure that the concrete maintains a residual compressive stress of 0.2-0.4 MPa after cooling, which is an essential prerequisite for the long-term structural stability of arch dams [8].

3.4.2. Integration into Finite-Element design workflow

The hyperbolic AVD model proposed by Nguyen et al. [8] can be conveniently integrated into numerical design procedures. In a typical finite element simulation for temperature–stress analysis, the thermal field is first calculated considering hydration heat, boundary cooling, and the thermophysical properties of the materials. The MgO-induced AVD function G(t, T) (Eq. 3) is then introduced as a time-dependent internal strain in the constitutive relationship. The resulting structural response is recalculated to identify tensile stress zones, residual compressive stresses, and possible cracking risks. This combined approach enables engineers to evaluate different MgO contents and placement temperatures prior to construction, thereby reducing design uncertainty. Such predictive capability represents an important advancement toward virtual prototyping of arch dams under realistic thermo-mechanical conditions.

3.4.3. Combination with supplementary materials

Combining MgO with mineral admixtures such as fly ash, ground granulated blast furnace slag (GGBFS), or silica fume further enhances performance. These pozzolanic materials lower hydration heat and delay early temperature rise, while MgO provides delayed expansion to compensate the subsequent contraction.

The synergy between low-heat cementitious systems and MgO-induced AVD creates a dual mechanism thermal moderation and stress compensation that is particularly advantageous for large arch dams constructed in tropical monsoon climates such as Vietnam's.

Experimental and numerical results indicate that the use of 5% MgO + 20% fly ash can lower peak temperature by 10-15 °C and reduce thermal stress by 35-45% compared with conventional mixes [8]. This dual-control approach enhances both crack resistance and sustainability by reducing cement consumption and construction energy demand.

3.4.4. Construction and quality control considerations

For successful application, MgO expansive concrete requires strict quality control during all stages of production and placement. During mixing, MgO must be evenly dispersed in the binder system to avoid localized excessive expansion; premixing with cement or fly ash is often recommended to ensure uniformity. Internal and surface temperatures should be continuously monitored to confirm that the expansion phase coincides with the cooling period of the structure. Curing conditions should maintain a relative humidity above 90% to promote complete hydration of MgO and achieve uniform expansion. Prior to large-scale deployment, laboratory calibration and pilot block testing are essential to confirm the predicted expansion properties and finite element simulation results. By strictly following these management procedures, the performance of MgO expansive concrete can be effectively stabilized, minimizing the risk of differential deformation between adjacent sections.

3.4.5. Economic and sustainability benefits

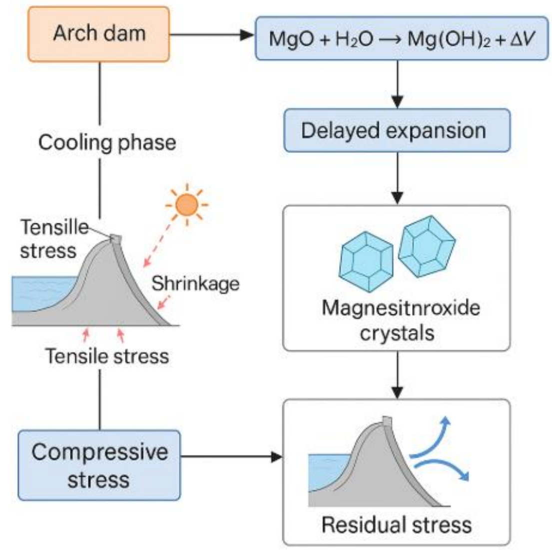
The application of the MgO expansion system has brought significant technical and economic benefits. Field experience has shown that the use of MgO concrete can reduce the demand for cooling pipe systems by approximately 15% to 25%, while eliminating the post-cooling process and significantly shortening the overall construction period. In addition, due to the improved structural integrity, maintenance and crack repair costs are also significantly reduced. When MgO is used in combination with supplementary cementitious materials, cement consumption and embodied CO_2 emissions are further reduced, contributing to environmental sustainability. From a full life cycle perspective, MgO-based thermal stress regulation technology provides a practical low-carbon alternative to traditional cooling-intensive construction methods. The system's proven performance in large-scale dam projects in China and internationally provides a valuable technical reference and lays a solid foundation for its future application in Vietnamese arch dams operating under tropical climate conditions.

3.4.6. Summary of design guidelines

Table 1. Key design parameters and target performance criteria for MgO expansive concrete in arch dams.

Parameter	Recommended Range	Design Objective
MgO dosage	3-6% of binder	Offset tensile stress (20-40% reduction)
Calcination temperature	1050-1150 °C	Delayed, stable expansion
Placement temperature	10-20 °C	Reduce thermal gradient
Curing humidity	≥ 90% RH	Ensure full MgO hydration
Residual compressive stress	0.2-0.4 MPa	Maintain arch-dam integrity

These guidelines provide practical reference values for future TCVN standard development and design adaptation of MgO expansive concrete in Vietnam's hydropower infrastructure.



Figue 3. Conceptual framework of MgO application for temperature-stress control in arch dams.

4. Vietnam application roadmap

Vietnam's hydropower infrastructure is dominated by medium- and large-scale arch and gravity dams located in mountainous regions of the North and Central Highlands. These structures are exposed to a tropical monsoon climate, characterized by high humidity (70-95%), daily temperature variations of 15-20 °C, and seasonal rainfall exceeding 2,000 mm. Such conditions complicate temperature control in mass concrete: conventional methods using embedded cooling pipes and staged pouring remain effective but economically inefficient.

The proven success of MgO expansive concrete in China and Japan suggests strong potential for adaptation in Vietnam. However, due to differences in local materials, climatic conditions, and construction practices, a phased implementation strategy is required.

4.1. Phase 1 - Laboratory characterization

The first step is to establish a baseline database of MgO materials and their hydration behavior under Vietnamese environmental conditions.

Key tasks include: Characterizing local MgO sources (magnesite, dolomite, serpentine) in terms of purity, calcination reactivity, and particle-size distribution; Conducting controlled hydration and expansion tests under various temperature-humidity regimes typical of northern Vietnam (20-45 °C, 80-95% RH); Determining the parameters of the AVD model [8] for locally produced MgO using the same methodology as Nguyen et al. (2019); Evaluating compatibility of MgO with domestic cement types (PCB40, PCB50) and supplementary cementitious materials (fly ash, slag). The outcomes of this phase will provide the necessary input for subsequent modeling and pilot applications.

4.2. Phase 2 - Numerical modeling and simulation

Validated laboratory data provided the foundation for finite element modeling (FEM) of the temperature-stress field in a representative dam section. A hyperbolic AVD function (Equation 3) can be used as a user-defined material model to simulate the delayed expansion of MgO concrete under specific thermal conditions. Comparative analysis of conventional and MgO-modified concrete allowed the identification of optimal parameters for the Vietnamese arch dam, such as MgO dosage, pouring temperature, and construction time. Furthermore, sensitivity analyses were performed to assess the impact of climate variables (including daily temperature variations, humidity fluctuations, and solar radiation) on the MgO hydration kinetics. This integrated modeling phase effectively combined material-level testing with engineering-scale application, ensuring that the predicted AVD behavior was consistent with actual construction and environmental conditions.

4.3. Phase 3 - Pilot-Scale field application

After model validation, pilot tests should be carried out on medium-scale arch dams (height 60-100 m) or spillway structures under construction.

Key objectives: Verify temperature evolution, strain development, and stress redistribution in MgO concrete compared to conventional mixes; Evaluate long-term durability indicators (water permeability, microcrack density, freeze-thaw resistance); Refine the AVD model coefficients using measured field data; The pilot study should include embedded thermocouples and strain gauges to monitor hydration heat and autogenous expansion. The results will form the basis for scaling up to national practice.

4.4. Phase 4 - Standardization and technology transfer

The final phase of this research roadmap aims to develop a national guideline, or TCVN standard, for the use of MgO expansive concrete in hydraulic structures. The proposed guideline should include standardized terms, symbols, and definitions; test methods for MgO reactivity, AVD determination, and constrained expansion; recommended dosage ranges and particle size requirements; acceptance criteria for FEM input parameters and residual compressive stresses; and quality assurance and construction monitoring procedures. Close collaboration between universities, research institutions, and major hydropower enterprises such as EVN, Song Da, and Lilama is essential for effective technology transfer. Successful completion of this framework will represent a significant advancement in the modernization of Vietnam's dam construction technology and the harmonization of national technical standards with international engineering practices.

5. Discussion and future prospects

The use of MgO expansive concrete represents a paradigm shift in temperature-stress control: from externally managed cooling to internally self-compensating expansion. Its potential benefits for arch dams especially under tropical conditions are substantial. However, several research and implementation challenges remain:

5.1. Key technical challenges

Vietnam’s climatic conditions present unique challenges for the practical application of MgO expansive concrete. High ambient humidity and frequent temperature fluctuations can accelerate the early hydration of MgO, thereby weakening the intended effect of retarding expansion. To address this issue, customized particle size grading and precise control of calcination temperature are required to ensure that the expansion phase coincides with the cooling process of the dam. In addition, the chemical composition and reactivity of locally produced MgO may differ from imported materials, necessitating comprehensive material testing and hydration kinetics calibration for each production batch. Although long-term field data from Chinese hydropower projects have shown stable performance over decades, the performance of MgO concrete under tropical environmental conditions is still lacking. Continuous stress-strain monitoring in pilot applications in Vietnam is essential to verify long-term reliability and support future standardization efforts.

5.2. Integration with emerging technologies

The implementation of Building Information Modeling (BIM) and digital twin systems in dam engineering provides new opportunities for real-time prediction and control.

Coupling MgO AVD models with digital construction management platforms could allow continuous adjustment of mix proportions, curing conditions, and construction sequence based on on-site thermal data.

Additionally, the integration of thermo-chemo-mechanical (TCM) models in FEM will enhance the accuracy of stress simulation and facilitate automated crack-risk evaluation.

5.3. Sustainability perspective

From an environmental standpoint, MgO expansive concrete supports Vietnam’s commitment to sustainable infrastructure: Reducing the need for cooling pipes and construction energy cuts CO_2 emissions; Partial substitution of clinker with MgO or supplementary materials decreases the carbon footprint of cement production; Improved durability extends service life, lowering life-cycle maintenance costs.

Together, these factors position MgO expansive concrete as a green and cost-effective solution for Vietnam's next-generation hydropower infrastructure.

6. Conclusions

This study comprehensively reviewed the mechanism, modeling, and practical application of delayed-expansion MgO in mass and arch-dam concrete. The findings confirm that the slow hydration of MgO to form $Mg(OH)_2$ produces a gradual, self-controlled expansion that compensates for thermal contraction and significantly reduces cracking risk during cooling. Experimental and field data from large hydropower projects demonstrate that an MgO content of 3–6% can lower thermal stress by up to 40% and improve long-term durability. The proposed hyperbolic autogenous volume deformation (AVD) model effectively predicts the time-dependent expansion behavior under different temperatures and MgO reactivities, offering a valuable design tool for engineers to optimize mix proportion and curing conditions. Beyond its mechanical benefits, MgO expansive concrete also supports sustainable construction by reducing the need for cooling pipes, shortening construction periods, and decreasing CO_2 emissions. To adapt this technology to Vietnam's tropical monsoon climate, a four-phase roadmap covering laboratory studies, numerical modeling, pilot applications, and TCVN standard development is recommended. Overall, the study establishes both a theoretical foundation and a practical framework for implementing MgO-based temperature-stress control in modern arch-dam construction.

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