PERSPECTIVE

Mitigating Thermal Cracking in Mass Concrete with Temperature Rise Inhibitor: A Sustainable and Efficient Strategy

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Abstract

Thermal cracking poses a significant threat to the structural integrity and service life of mass concrete. The starch-based Temperature Rise Inhibitor (TRI) emerges as a sustainable and efficient bio-based solution that directly addresses the root cause - the intense heat release during early-age cement hydration. Unlike conventional chemical admixtures, TRI features a special "controlled dissolution" mechanism in the high-pH environment of cement paste. This characteristic ensures a continuous release of organic molecules that selectively inhibit the nucleation of calcium silicate hydrates (C-S-H) gel, the primary hydrates of cement hydration. Consequently, TRI significantly slow down the heat release during the first 24 hours after casting without substantially delaying the setting time or compromising long-term strength gain. Here, we highlight the exceptional efficacy of TRI in regulating exothermic process of cement hydration, discussing mechanisms in cement and blended systems and the main challenges regarding their molecular-scale interaction with C-S-H nucleation. As discussed in this perspective, TRI exemplifies the potential of sustainable materials to address fundamental engineering challenges, bridging environmental responsibility with high performance in modern concrete.

Keywords: mass concrete, chemical admixture, starch, cement hydration.

Concrete is the most widely used man-made material on Earth, forming the backbone of critical national infrastructure including transportation networks, energy facilities, hydraulic structures, and urban systems [1]. Yet, the very nature of cement hydration poses a major durability challenge. As shown in Figure 1(a), owing to the low thermal conductivity of concrete, the large amount of heat released rapidly after mixing accumulates within the interior of concrete elements, creating steep temperature

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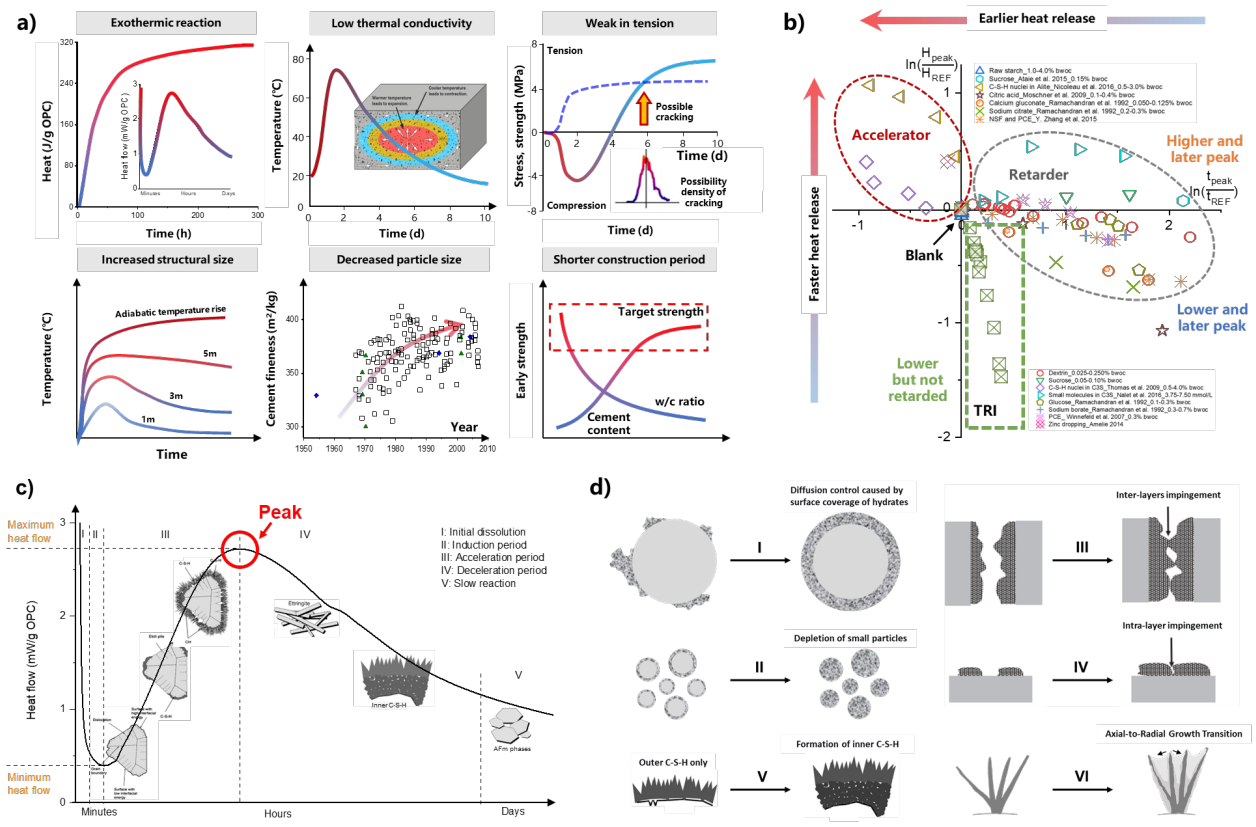

Figure 1. (a) Origin of thermal cracking. (b) Effect of set-controlling chemical admixtures on the exothermal process of cement hydration. (c) Heat flow curve of cement hydration. (d) Hypotheses regarding the rate controlling mechanism during the main hydration peak.

gradients and significant thermal stresses between the core and the surface [2]. These stresses frequently trigger thermal cracking, particularly in mass concrete, and increasingly in conventional structures as modern concretes employ higher cement contents and finer particle sizes [4] to achieve better early performance, initiating a progressive decline in both the structural capacity and functional lifespan of concrete.

For decades, engineers have worked around this issue with a combination of structural design refinement, low-heat binders, cooling systems, and chemical admixtures [6, 10]. These approaches help to mitigate the thermal cracking issue, but normally entail trade-offs in mechanical performance, construction efficiency, and/or project economics. Moreover, none of them, as shown in Figure 1(b), fundamentally change the intrinsic heat-evolution profile of cement hydration [8]. This context has catalyzed the development of novel chemical admixtures capable of modulating the hydration process itself, with starch-based Temperature Rise Inhibitor (TRI) representing a particularly promising bio-based innovation that targets the core of the thermal cracking issue without sacrificing long-term concrete properties.

A clear understanding of the rate-controlling mechanisms in early cement hydration is essential for the effective modulation of heat release. Recent advancements have established robust theoretical frameworks, including the dissolution theory [7] and the boundary nucleation and growth (BNG) model [11], to describe the hydration behavior until the appearance of the maximum heat flow. Nevertheless, the transition mechanism from the acceleration to the deceleration period remains a topic of debate, as hypotheses summarized in Figure 1(c). The needle model developed by Ouzia et al. [9] offers a quantitative perspective, demonstrating how C-S-H nucleation and growth dominate heat evolution from the onset of the acceleration stage to the end of the first

day. Therefore, targeted intervention in the ongoing nucleation and growth of C-S-H emerges as the critical strategy for regulating early-age heat release behavior.

Starch is an abundant, renewable polysaccharide made of glucose units linked by α-glycosidic bonds and exists mainly in two forms: amylose and amylopectin [15]. In its native state, starch has little influence on cement hydration because it is largely insoluble. Through controlled modification - such as acid hydrolysis, oxidation, or enzymatic treatment - it can be broken down into lower molecular weight, highly soluble dextrins, which are commonly used as intermediates in traditional retarders and water-reducing agents (Figure 2(a)). TRI is a more advanced use of this natural material in civil engineering. By carefully tuning the degree of acid hydrolysis and controlling the molecular weight distribution of final hydrolysate, TRI possesses a controlled dissolution profile in cement pore solution, releasing dextrin-like molecules mainly between 1,000 and 40,000 over several hours. This key feature ensures its continuous interaction with the ongoing hydration process, particularly during the critical acceleration period, distinguishing TRI fundamentally from conventional set-controlling admixtures that act within a minute-scale time window, leaving little influence on subsequent hydration.

Figure 2(b) illustrates the influence of TRI on the heat flow curve of ordinary Portland cement (OPC) hydration. Unlike conventional retarders that primarily shift the hydration curve in time, TRI significantly suppresses the maximum heat flow at an exceptionally low dosage (<0.2% by weight of cement), while leaving the timing of the main hydration peak largely unchanged [13]. Rather than blocking the dissolution of unreacted cement, TRI primarily interferes with the nucleation of C-S-H, thereby reducing the number of active nuclei formed during the induction period and acceleration period. This leads to a lower rate of hydrate formation, resulting in a gentler and more distributed heat evolution curve. Importantly, this effect is self-limiting. As hydration progresses, TRI molecules are progressively consumed through adsorption and interaction with highly charged aluminate phases such as ettringite. Once TRI is depleted, C-S-H nucleation restarts and hydration re-accelerates, giving rise to a broader secondary exothermic peak and a gradual recovery of cumulative heat toward the reference system.

Experimental evidence indicates that TRI has strong robustness across diverse binder systems [16]. Supplementary cementitious materials (SCMs), such as fly ash and ground granulated blast-furnace slag, are now widely incorporated into concrete to reduce hydration heat, improve durability, and lower carbon emissions. Despite the substantial changes SCMs introduce to hydration pathways, pore solution chemistry, and phase assemblage [12], TRI consistently retains its ability to depress maximum heat flow and redistribute hydration heat. TRI does not fundamentally change the hydration mechanisms of cement and SCMs; instead, it moderates their reaction rates following the original kinetic pathways. As a result, within reasonable ranges of SCM substitution rate and TRI dosage, TRI does not affect the long-term hydration degree or performance of either component. Such robustness reinforces TRI's broad application potential in modern blended concretes, supporting its role as a reliable and scalable solution for temperature control in increasingly complex cementitious systems.

Figure 2(c) presents a simplified schematic showing how TRI regulates hydration heat through limited yet continuous suppression of C-S-H nucleation. To achieve maximum efficiency, the active duration of TRI should closely match the timing of C-S-H nucleation. Conventional retarders act in an all-at-once manner, rapidly and completely suppressing nucleation shortly after addition, which shifts the entire nucleation process to later ages. From a heat-release perspective, this appears as an extended induction period and a delayed main hydration peak. To further improve TRI performance, recent efforts have focused on optimizing the composite structure of TRI particles [14]. The formation of a mulberry-like microstructure reshapes the dissolution behavior of TRI in alkaline cement paste by introducing an additional step - the gradual collapse of this composite structure. This delays the initial dissolution of TRI and reduces "ineffective dissolution" during the very early stage, when C-S-H nucleation has not yet begun. Such structural regulation not only improves current efficiency but also provides a clear pathway for next-generation TRI design, shifting hydration control from empirical dosage adjustment toward mechanism-based control with enhanced temporal precision. TRI has been implemented in projects such as the Taihu Lake Tunnel, where it contributed to a core temperature reduction exceeding 6.6 °C and significantly mitigated thermal cracking risk. Furthermore, in combination with expansion agents, this technology has been extended to other landmark

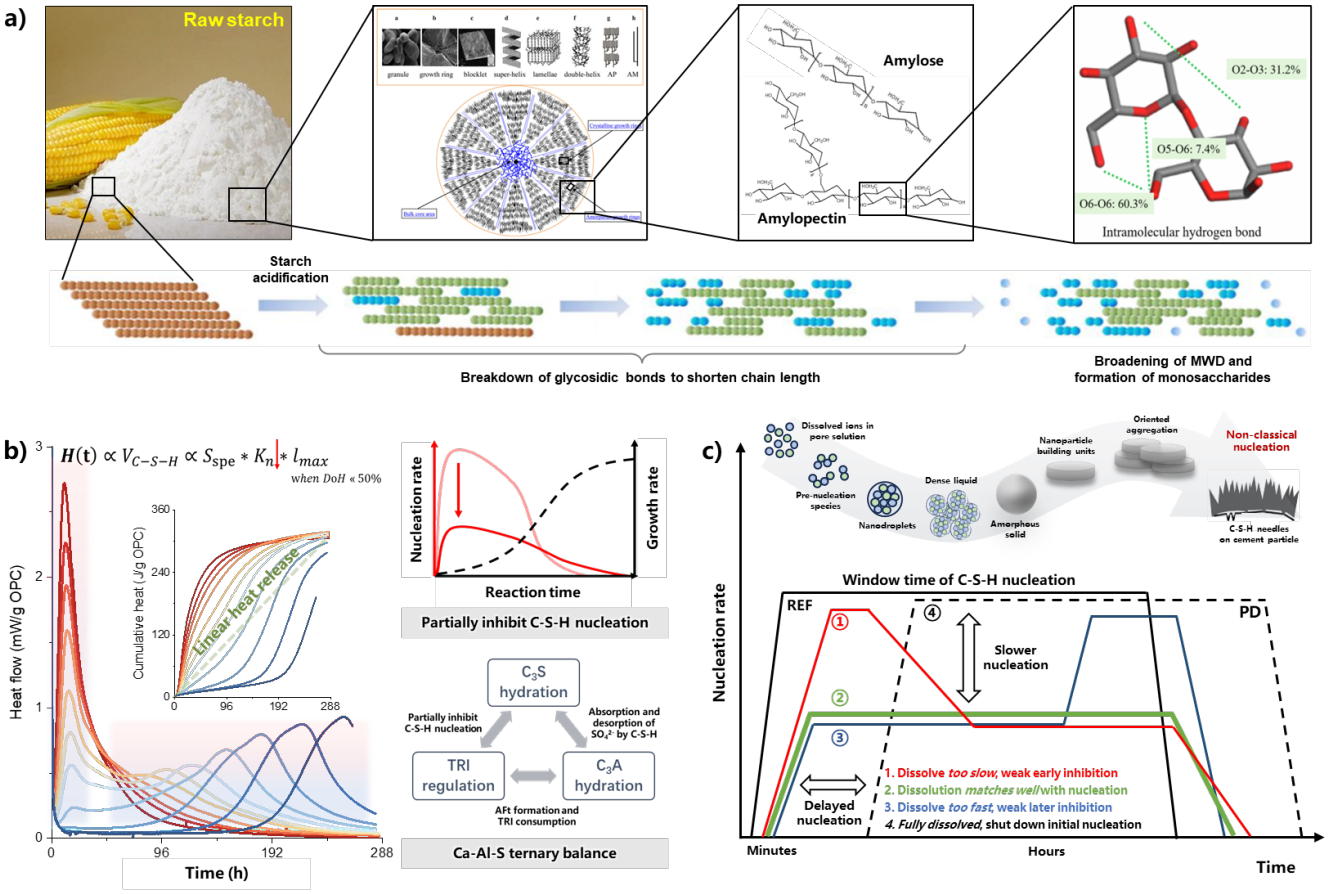

Figure 2. (a) From corn starch powder to hydrogen bonds in starch molecules. (b) Effect of starch-based Temperature Rise Inhibitor (TRI) on the exothermal process of cement hydration and the interaction mechanisms. (c) Relationship between TRI and C-S-H nucleation.

infrastructure projects including the Changtai Yangtze River Bridge and the Shenzhen-Zhongshan Link, ensuring the structural safety and long-term durability of mass concrete.

Despite the promising performance of TRI in regulating hydration heat, its molecular-scale interaction with the non-classical nucleation of C-S-H remains one of the most critical knowledge gaps. Current evidence suggests that TRI interferes with the formation and stabilization of early C-S-H precursors without disrupting their subsequent growth [13], yet the detailed mechanisms governing organic-inorganic interactions are still poorly understood. Direct experimental validation is challenging due to the transient nature of these processes and the technical limitations of in-situ observation within hydrating cement paste [3]. The precise nature of the organic-inorganic interaction, whether through specific adsorption, chelation of critical ions, or modification of solution thermodynamics, requires further clarification. In parallel, the success of starch-based TRI opens new opportunities for expanding hydration control toward other bio-based materials. The role of molecular structure, functional groups, chain flexibility, solubility, etc., on hydration kinetics remains largely unexplored. Systematic investigation of alternative bio-derived polymer/carrier and targeted molecular structure design for selective interaction with hydration species may enable the development of a new generation of sustainable admixtures with programmable performance [5]. Another important challenge lies in the compatibility between TRI and other chemical admixtures commonly used in concrete, such as superplasticizers and shrinkage-reducing agents. Synergistic or antagonistic interactions may significantly alter hydration pathways and performance stability, especially in complex,

multi-admixture systems. Therefore, comprehensive evaluation of these interactions is essential to ensure reliable performance in real engineering applications. Continued progress in this field will not only deepen our understanding of hydration control mechanisms but also support the development of bio-inspired materials for next-generation low-carbon and resilient concrete infrastructure.

Data Availability Statement

Not applicable.

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Conflicts of Interest

Wenbin Wang and Rui Wang are affiliated with the Jiangsu Sobute New Materials Co. Ltd., Nanjing 211103, China; Junhui He is affiliated with the Pinglu Canal Group Co., Ltd, Nanning 530022, China. The authors declare that these affiliations had no influence on the study design, data collection, analysis, interpretation, or the decision to publish, and that no other competing interests exist.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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