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Evaluation of Early-Age Compressive Strength in Winter Prefabrication: A Comparative Study

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Abstract: In the field of prefabrication, the timely demolding of concrete elements is crucial to prevent structural failures during panel lifting. This study investigates the early-age compressive strength of different concrete mixtures by simulating various prefabrication plant scenarios. Special attention is given to winter conditions, where concrete hydration tends to be slower, potentially compromising the minimum compressive strength requirement of 10 MPa. The first scenario (reference), set at an ambient temperature of 20 °C with raw materials at room temperature, establishes the baseline for comparison. Two alternative dispositions are explored: Scenario 2, with an external temperature of 8 °C and the water for mixing at 35 °C, and Scenario 3, with the same external temperature but utilizing a heating hood to maintain the concrete at 35 °C. The experimental results shed light on the effectiveness of different strategies in achieving the desired early-age compressive strength under winter conditions. The use of warm mixing water and heating hoods are evaluated as potential measures to counteract the hydration slowdown. The findings contribute valuable insights for optimizing prefabrication processes in cold weather, ensuring the structural integrity of precast concrete elements.

Keywords: precast concrete; early-age strength; cold-weather hydration

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1. Introduction

The continual evolution of the construction industry has been significantly characterized by the introduction of novel methodologies that prioritize efficiency, sustainability, and the reduction of construction timelines [1–3]. The precast concrete technique has established itself as an innovative approach, revolutionizing the traditional paradigms of structural development and execution. Based on the off-site manufacture of structural elements, this method represents an innovative alternative to conventional methods of pouring concrete on-site, underlining a shift in building methodologies [4].

At the heart of concrete prefabrication lies an innovative engineering process that facilitates the production of architectural and structural components within a controlled factory environment substantially distant from the actual site of construction. This prefabricated methodology has several advantages, ranging from unparalleled dimensional accuracy to the substantial acceleration of construction schedules. Concrete, known for its durability, is pivotal in this methodology, serving as the backbone that supports structural integrity and facilitates a wide range of architectural expressions [5–7].

The underlying efficiency of the prefabrication process is further enhanced by the standardization of components, which not only enables mass production but also makes construction requirements more cost-effective. Such a methodological transformation has not only changed the construction landscape but has also become a cornerstone in meeting the growing demand for sustainable and resilient construction practices [8].

This exposition lays the groundwork for an in-depth examination of the complexities inherent in concrete prefabrication, defining its qualities, the challenges it faces, and its transformative influence on contemporary construction methodologies [9].

Concrete prefabrication signifies a fundamental shift, redefining the traditional methodologies of constructing edifices. It encompasses the off-site manufacture of building components, marking a new era in construction characterized by superior precision, efficiency, and economic viability. Within this innovative framework, concrete is of essential importance, subjected to complex processes to ensure not just optimal strength but also lasting durability [10].

A critical aspect of prefabrication is the early demolding of concrete elements, a procedure that demands acute attention to the factors that influence compressive strength [11,12]. The industry norm suggests casting concrete on day 'd' and proceeding with demolding on day 'd + 1', or in some instances, as soon as 20 h after casting. However, this expedited process encounters notable challenges, especially under wintry conditions, where the concrete's hydration process, crucial for strength development, is impeded by low temperatures. This poses a significant risk to attaining the minimum compressive strength of 10 MPa required for the safe handling of prefabricated panels [13–17].

In addressing these challenges, a diverse array of strategies is employed, from the use of warm mixing water to the application of heating hoods, highlighting the dynamic approaches to optimizing prefabrication processes against winter-related challenges. This research focuses on the detailed examination of early-age compressive strength across concrete compositions, each designed to mirror the distinctive conditions prevalent in prefabrication factories.

This study looks at the complexities of winter-induced challenges with the aim of elucidating strategies to improve the prefabrication process. It provides new perspectives by systematically examining two industrial systems for mitigating winter-induced challenges, advancing current understanding, and offering practical solutions for improving the structural integrity of precast concrete elements. The ultimate aim is to preserve the structural integrity of precast concrete elements in adverse weather conditions. Through meticulous comparative analysis of different layouts, assessed using calorimetry to understand the internal reactions of concrete, this research seeks to provide a granular understanding and practical solutions to advance precast methodologies. As a result, this survey not only addresses the current challenges facing the sector but also seeks to pave the way for a more resilient and efficient future in prefabricated construction.

Despite extensive research into the prefabrication of concrete elements, there remains a significant gap in our understanding of how different environmental conditions, particularly winter conditions, affect the early strength development of precast concrete [13,18,19]. However, the specific challenges associated with cold weather accelerated curing processes are less explored, particularly with regard to the overall structural integrity and safety of precast concrete elements. Our study aims to fill this gap by systematically exploring the effectiveness of various industrial strategies designed to mitigate the negative effects of winter on the precasting process. Using advanced calorimetric analysis, we provide detailed information on concrete hydration kinetics, providing a nuanced understanding that can directly inform and improve cold-weather concreting practices.

2. Materials and Methods

2.1. Portland Cement

As part of this research, a comprehensive review of industrial references within the studied region revealed the predominance of three specific types of Portland cement: CEM I 52.5 N CE CP2 NF, CEM II/A-LL 52.5 N CE CP2 PM-CP2 NF and CEM II/A-LL 42.5 R CE [20–22]. It is imperative to highlight that each of these cement varieties has been subjected to meticulous conformity assessments in alignment with the standards stipulated by CE labeling. This ensures their adherence to the established quality specifications.

A comprehensive description of their chemical and physical properties is systematically presented in Tables 1 and 2, respectively.

Table 1. Chemical composition of different Portland cement types.

Chemical Characteristics [%]	CEM I 52.5 N CE CP2 NF	CEM II/A-LL 52.5 N CE CP2 PM-CP2 NF	CEM II/A-LL 42.5 R CE
PAF	2.4	-	6
CaO	64.0	63.0	64.5
SiO_2	19.3	19.0	17.9
Al_2O_3	4.8	4.6	4.4
Fe_2O_3	3.0	3.7	2.5
MgO	1.9	1.0	1.2
SO_3	3.2	2.5	2.4
K_2O	1.1	0.96	0.9
Na_2O	0.2	0.06	0.1
Na_2O equival. Actif	0.9	0.71	0.7
Cl^-	0.05	0.04	0.05

Table 2. Evolution of compressive strength in Portland cement variants.

Compressive Strength [MPa]	CEM I 52.5 N CE CP2 NF	CEM II/A-LL 52.5 N CE CP2 PM-CP2 NF	CEM II/A-LL 42.5 R CE
24 h	25	25	-
2 days	39	37	30
7 days	51	51	45
28 days	62	60	54

2.2. Limestone Filler

Due to its economic efficiency, limestone filler finds extensive application across the majority of pre-cast manufacturing factories within the local proximity. This preference is mainly influenced by financial feasibility while preserving the qualities essential for concrete production. To elucidate a thorough comprehension of the limestone filler's attributes utilized, an elaborate product characterization is systematically presented in Table 3.

Table 3. Characterization of limestone filler.

Component	$CaCO_3$	98.2%
	Cl^-	0.003%
	Sulfates	0.01%
	Total silica	0.02
	Others	≈1.77%
Particle size	Particles < 0.125 mm	98%
	Particles < 0.063 mm	90%
Density	2700 kg/m^3	

2.3. Sand

Sand constitutes an essential component within concrete formulations, significantly influencing the attributes and efficacy of the resultant concrete product. The sand incorporated in these mixtures is classified as a washed 0/4 sand. To provide a clear depiction of the material's composition, the physical characteristics of both fine and coarse particulates are delineated in Table 4.

Table 4. Characterization of mechanical and physical properties of washed 0/4 fine aggregate.

Properties	Washed 0/4 sand
Density	2630 kg/m^3
Water absorption	0.1%
Sand equivalent	81.3
Fineness modulus	2.3

2.4. Coarse Aggregate

The preparation of the concrete mix involves the use of semi-crushed, washed stones as the coarse aggregate, with a maximal aggregate dimension of 12.5 mm. Materials procured locally are selected and integrated into the mixture to conform to the agreed specifications. A comprehensive depiction of both the physical and mechanical characteristics of the fine and coarse aggregates is provided in Table 5.

Table 5. Physico-mechanical characterization of semi-crushed washed stones.

Properties	Semi-crushed washed stones
Density	2460 kg/m^3
Water absorption	2.4%
Freeze/thaw resistance	0.2
LOS Angeles	16.0

2.5. Additive

To increase the workability of self-compacting concrete, a superplasticizing additive is added. The superplasticizer used is a non-chlorinated, high water-reducing additive based on 30% solids polycarboxylate technology developed for the prefabrication industry. Furthermore, within the scope of the industrial manufacturing process, the application of an acceleration admixture is adopted to expedite the early-stage demolding process. The Set Accelerator used is a chlorine-free liquid admixture designed to accelerate concrete setting to 43% dry extract. This strategy is instrumental in enhancing the efficiency of production timelines while maintaining the structural and mechanical integrity of the concrete.

3. Experimental Methods

3.1. Mixture Proportioning and Preparation

This study meticulously designed its experimental approach for the effect due to varied environmental conditions while varying the cement types. The concrete mixes were systematically formulated on a constant basis, the main variable being the type of cement used. This variation yielded three distinct mix formulations, each subjected to a unique experimental scenario to investigate the interaction between cement composition, temperature conditions, and the resultant concrete properties.

3.1.1. First Experimental Scenario: Ambient Conditions

Storage of Materials: All the constituent materials, including the cement, were standardized by storing them at an ambient temperature of 20 °C in order to reduce the influence of temperature variability on the properties of the materials.

Mix Preparation and Sample Storage: The preparation of the concrete mix, along with the storage of the resulting samples, was consistently maintained at the ambient temperature of 20 °C. This condition aimed to replicate the standard environmental setting in which concrete is often produced and utilized.

3.1.2. Second Experimental Scenario: Controlled Cold Environment with Warm Mixing Water

Storage of Materials: In this scenario, all the components, with the exception of water, were subjected to a controlled cold environment at 8 °C in order to assess the impact of a reduced temperature on the performance of the concrete. This temperature represents mean temperature in Normandy, France. Conversely, the water was heated to 35 °C prior to mixing to emulate the conditions of warm mixing water typically employed in precast concrete manufacturing facilities, as depicted in Figure 1.

Figure 1. Regulated water temperature for concrete mixing in precast factory.

Mix Preparation and Sample Storage: Both the preparation of the concrete mix and the subsequent storage of samples were conducted within the same controlled environment at 8 °C, providing a consistent temperature setting for the duration of the experimental process.

3.1.3. Third Experimental Scenario: Simulating Post-Casting Heat Treatment

In this scenario, all components were subjected to a controlled cold environment maintained at 8 °C to simulate the application of a heating hood set at 35 °C, as illustrated in Figure 2. The preparation of the concrete mix and the storage of samples both took place within the heating hood, ensuring a uniform temperature environment throughout the experimental process.

In all scenarios, the samples were cured under highly controlled humidity conditions, maintained at 95% relative humidity, ensuring optimum moisture content for the concrete curing process. This rigorous control of the curing environment is crucial to the accurate assessment of the impact of cement under varying temperature conditions. The experimental framework, as described above, provides a comprehensive basis for understanding the behavior of the material under various conditions, reflecting real-world applications. The detailed examination of each scenario highlights the complex dynamics between cement composition, environmental conditions, and concrete mechanical properties, contributing to the body of knowledge essential to the advancement of concrete technology.

Figure 2. Heated hood system in precast factory.

Formulations and specific experimental conditions are represented in Table 6, with proprietary considerations preventing the disclosure of formulation specifics. This confidentiality is in observance of the proprietary rights of local manufacturing entities. For each experimental mix and scenario, three cylindrical specimens were prepared, along with calorimetric samples for in-depth analysis of thermal evolution, underlining the study's commitment to a systematic and rigorous examination of concrete performance characteristics.

Table 6. Overview of experimental scenarios and formulations for concrete mixes in diverse environmental.

	Scenario 1 T = 20 °C			**Scenario 2 Raw Material 8 °C Water Heated 35 °C Storage 8 °C**			**Scenario 3 Raw Material 8 °C Heat 35 °C**		
	Fi-1	**Fii-1**	**Fiii-1**	**Fi-2**	**Fii-2**	**Fiii-2**	**Fi-3**	**Fii3**	**Fiii-3**
CEM I 52.2N [kg/m^3]	370	-	-	370	-	-	370	-	-
CEM II/A 52.5N [kg/m^3]	-	370	-	-	370	-	-	370	-
CEM II/A-S 42.5R [kg/m^3]	-		370	-	-	370	-	-	370
Limestone filler [kg/m^3]	160	160	160	160	160	160	160	160	160
0/4 sand + 4/12.5 Coarse aggregate [kg/m^3]	1590	1590	1590	1590	1590	1590	1590	1590	1590
Superplasticizer + Accelerator [kg/m^3]	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Efficient Water [kg/m^3]	170	170	170	170	170	170	170	170	170

The mixing process utilized a 100-L rotary paddle mixer, adhering to the following steps to ensure consistency and optimal material properties:

Pre-Wetting: Prior to adding the materials, the mixer was pre-wetted to minimize additional water absorption from the mixer walls, which could otherwise affect the water-to-cement ratio and, consequently, the concrete's performance.

Adding Materials: Solid constituents were introduced in a specific order—first gravel, followed by sand, and finally cement. This sequence helps in achieving a more uniform distribution of the fine particles around the coarser aggregates before the cement coats and binds them.

Dry Mixing: The dry components were mixed for 30 s to ensure thorough blending of the aggregates with the cement, which is crucial for the homogeneity of the mix.

Water and additive: Water and additive were then added, and the mixture was blended for 60 s. This initial short mixing period with water allows for the beginning of the hydration process.

Final Mixing: Following the addition of water, the mixture was further mixed for an additional 60 s. This extended mixing time ensures a well-blended mixture, promoting consistency in hydration and performance across all samples.

3.2. Slump Test

In precast concrete applications, the slump test is a key procedure to ensure the concrete's workability matches the requirements for producing high-quality precast elements. The test is conducted by filling a slump cone with fresh concrete in three layers and then lifting the cone to allow the concrete to slump. The degree of slump, measured immediately after cone removal, indicates the concrete's workability. For precast purposes, measurements ranging from 660 to 750 mm classify the concrete as SF2 slump class, signifying a desirable fluidity and ease of mold filling. This classification, aligning with standards such as EN 12350-2, confirms the concrete's suitability for precast applications, ensuring optimal workability for mold filling and structural compactness.

3.3. Compressive Strength Test

Firstly, compressive strengths for Scenario 1 at 20 °C were evaluated to understand different formulations and cement effects in strict adherence to the guidelines specified in the NF EN 12390-3 standard. Subsequently, for the other two scenarios, the assessment of concrete compressive strength was conducted at a concrete age of 24 h. The decision to test at this specific time point was motivated by the need to evaluate early demolding characteristics in unfavorable conditions. In prefabrication factories, the challenge often lies in achieving early-age strength to facilitate rapid demolding, as opposed to the final strength, which typically presents fewer concerns.

The evaluation process involved the use of cylindrical samples measuring 11 $\times$ 22 cm, a dimension specified by the standard for assessing compressive strength. To ensure robust and representative results, three cylindrical samples were tested for each concrete mixture, and the average compressive strength was calculated.

3.4. Calorimetry Test

The study utilizes the calorimetry technique, specifically the calorimetry method conforming to the Langavant method and specifications of the NF EN 196-9 standard, to quantitatively assess the hydration heat evolution of cement across various experimental scenarios during the initial hydration stages. This methodological approach is critical for elucidating the thermal dynamics of cement hydration, an essential factor in understanding the setting and hardening processes of concrete.

3.4.1. Analytical Procedure and Experimental Setup

The calorimetry test is meticulously designed to capture the temperature evolution attributable to the exothermic reaction of cement hydration. By accurately measuring the heat released during this process, the test provides invaluable insights into the kinetics of cement hydration, offering a detailed understanding of the material's behavior under specific environmental conditions. The hydration heat of foamed concrete is measured during the first few hours using a calorimeter as per the NF EN 196-9 standard. This setup allows the determination of the amount of heat released by the cement from the temperature evolution.

3.4.2. Equipment and Calculations

Experiments are conducted using a calorimeter, which measures the temperature evolution and, thereby, the heat released by the cement during hydration. At a given time, the total heat of cement hydration, Q, is calculated as the sum of the heat accumulated $Qacc$ in the calorimeter and the heat dissipated to the outside $Qdis$, according to $Q = Qacc + Qdis$. Heat accumulated, $Qacc$, is determined using $\frac{c}{mc} \times \Delta T$, where c represents the total heat capacity of the calorimeter, mc is the mass of the cement in the test sample, and ΔT is the temperature difference between the test and reference calorimeters at time t. The heat dissipated, $Qdis$, is calculated from $\frac{1}{mc}\int_0^t \alpha \cdot \Delta T.dt$, where α is the total heat loss coefficient of the calorimeter.

3.4.3. Adaptation to Variable Experimental Conditions

To ensure the relevance and applicability of the calorimetric data to real-world scenarios, both the calorimeter setup and the raw materials are carefully adjusted to replicate the temperature and environmental conditions unique to each experimental scenario. This adaptation is essential for simulating the real conditions under which concrete products could be used, which enhances the validity of the results.

3.4.4. Significance and Implications of Findings

Through the calorimetry analysis, the study aims to derive a comprehensive profile of the thermal characteristics of cement hydration under varied conditions. The data acquired not only reveal the state of the material's heat output at an early age, but also enable concrete mixes and curing processes to be optimized. By understanding the factors influencing the rate and magnitude of heat release during cement hydration, concrete technologists can tailor mix formulations and curing environments to achieve desired performance characteristics, such as setting time and early strength development.

4. Results and Discussion

4.1. Slump Test

Self-compacting concrete is adopted for its ease of implementation. Results in Table 7 show a spread ranging from 660 to 750 mm, categorizing the concrete into the SF2 slump class [23,24]. This exposure class is commonly used for standard horizontal applications. These measurements on fresh concrete were taken before the concrete was placed in storage or subjected to any heating processes.

Table 7. Workability measurements of precast concrete using slump test.

	Scenario 1			Scenario 2			Scenario 3		
	Fi-1	**Fii-1**	**Fiii-1**	**Fi-2**	**Fii-2**	**Fiii-2**	**Fi-3**	**Fii-3**	**Fiii-3**
Slump flow [mm]	740	725	750	740	730	745	730	725	745

4.2. Compressive Strength Test

In the initial phase of the study, a comprehensive and quantitative evaluation was carried out on the cement formulations under standard test conditions of 20 °C, assessing compressive strength at 24 h, 7 days, and 28 days after mixing. Table 8 represents the outcomes, revealing a compressive strength progression that aligns with the anticipated classes of cement strength. Specifically, the CEM II 42.5 displayed a 28-day compressive strength of 56.1 MPa, which is lower than the 62.9 MPa and 65.8 MPa observed for CEM I 52.5 and CEM II 52.5, respectively. These results confirm the proportional relationship between early-age strength parameters and subsequent strength achievement, underlining the key industry standard of exceeding the 10 MPa threshold essential for demolding. (Table 8).

Table 8. Early-age and long-term compressive strength of cement formulations under standard conditions (20 °C) in scenario 1.

Compressive Strength [MPa]	**Scenario 1 T = 20 °C**		
	Fi-1	**Fii-1**	**Fiii-1**
24 h	32.3	31.8	24.3
7 days	55.9	54.3	46.9
28 days	62.9	65.8	56.1

Turning to the analysis of thermal effects on early compressive strength, Table 9 presents data from two divergent scenarios. Scenario 2 recorded a rapid decrease in compressive strength over 24 h, with values of 7.7 MPa, 9.3 MPa, and 3.2 MPa for Fi-2, Fii-2, and Fiii-2, respectively, falling below the demolding criterion despite increasing the initial mix temperature using hot water.

Table 9. Comparative analysis of compressive strength across different formulations and conditions.

	Scenario 1 T = 20 °C			**Scenario 2 Material 8 °C Water Heated 35 °C Storage 8 °C**			**Scenario 3 Material 8 °C Heat 35 °C**		
	Fi-1	**Fii-1**	**Fiii-1**	**Fi-2**	**Fii-2**	**Fiii-2**	**Fi-3**	**Fii-3**	**Fiii-3**
Compressive strength [MPa] 24 h	32.3 ± 1	31.8 ± 0.5	24.3 ± 0.7	7.7 ± 0.2	9.3 ± 0.5	3.2 ± 0.2	38.3 ± 1	39.8 ± 1.5	30.9 ± 0.7

This reduction in resistance led to major operational obstacles due to unexpected drops in temperature during the storage phase. In stark contrast, Scenario 3 implemented a sustained heating approach with a hood set to 35 °C. This intervention resulted in a significant improvement in the compressive strength of the early-age concrete, whose initial temperature, with recorded strengths of 38.3 MPa, 39.8 MPa, and 30.9 MPa for Fi-3, Fii-3, and Fiii-3, surpassing the Scenario 1 reference values. The initial material temperatures in this scenario denote a pronounced and beneficial response to the applied heating strategy [25,26]. The findings from these scenarios conclusively indicate the superiority of maintaining consistent temperature control throughout the concrete's setting phase, thus significantly bolstering the material's compressive strength and mechanical properties (Table 9).

4.3. Calorimetric Test

Merging the findings of Figures 3–5 and Table 10, we obtain a cohesive overview of the impact of environmental conditions and cement type on hydration kinetics and mechanical performance across three scenarios: standard ambient curing, cold storage with warm mixing water, and post-mixing heat treatment.

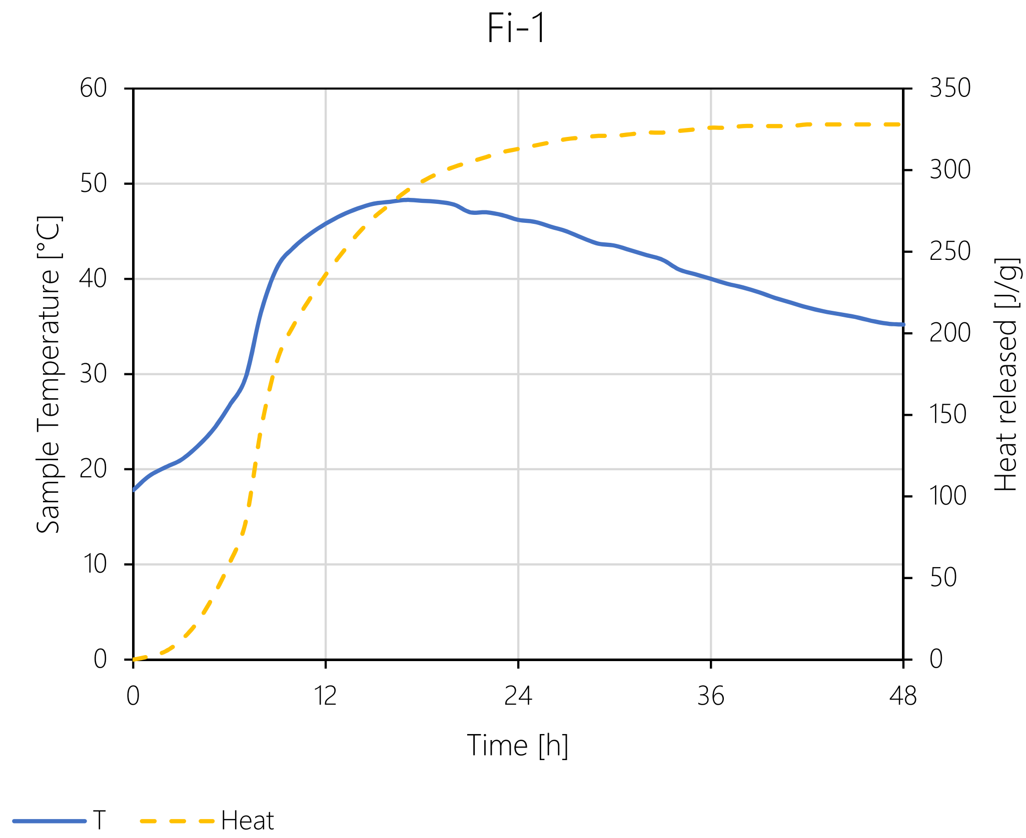

Figure 3. Calorimetric analysis of hydration in fi-1 cement: standard curing conditions.

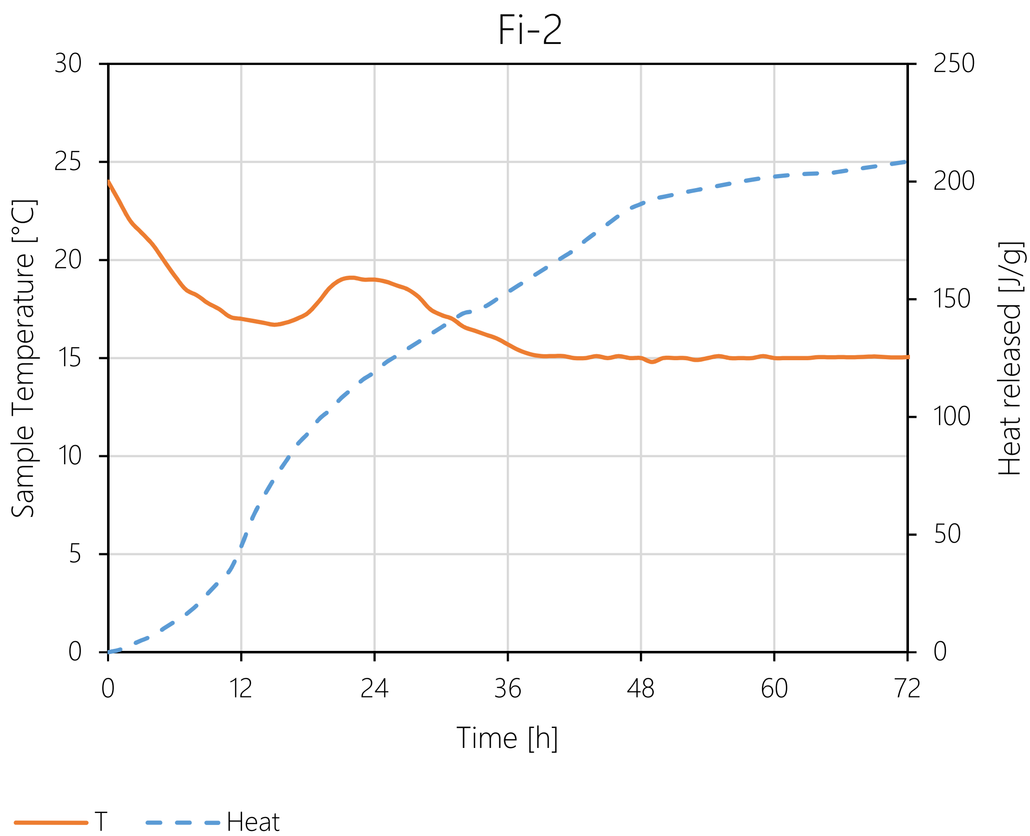

Figure 4. Calorimetric analysis of hydration in fi-2 cement: cold storage conditions.

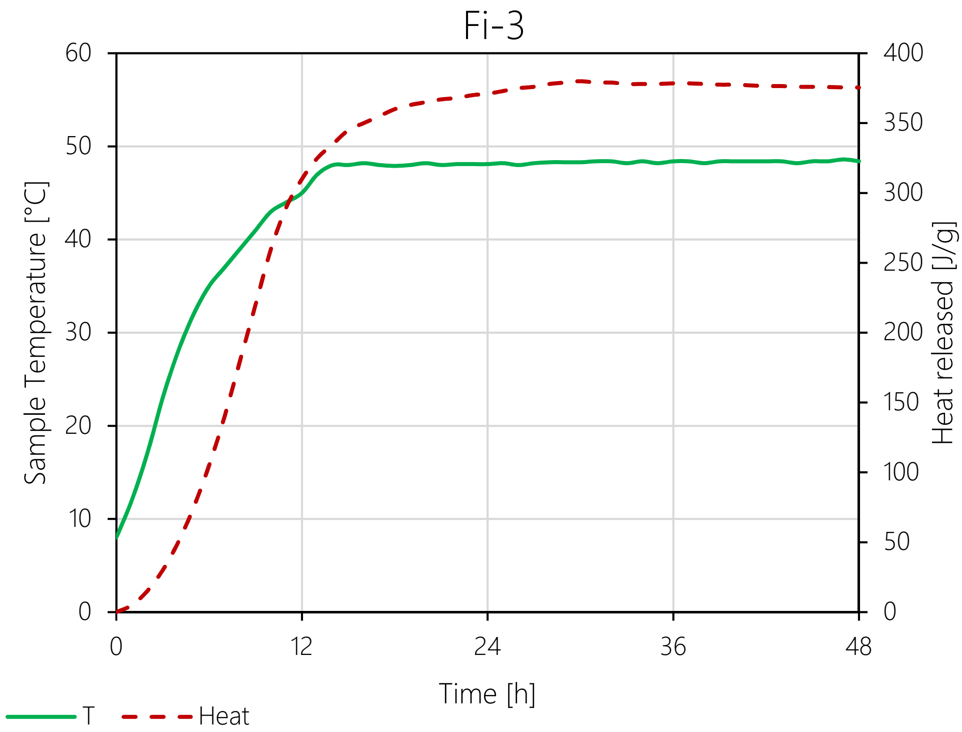

Figure 5. Calorimetric analysis of hydration in fi-3 cement: post-mixing heat treatment.

Table 10. Summary of heat release measurements for cement samples across three curing scenarios.

	Scenario 1 T = 20 °C			**Scenario 2 Material 8 °C Water Heated 35 °C Storage 8 °C**			**Scenario 3 Material 8 °C Heat 35 °C**		
	Fi-1	**Fii-1**	**Fiii-1**	**Fi-2**	**Fii-2**	**Fiii-2**	**Fi-3**	**Fii-3**	**Fiii-3**
Heat realized [J/g]	328	325	241	210	215	82	380	388	310

- Scenario 1: Standard ambient curing

Fi-1: Exhibits a sharp rise in temperature and heat released, indicative of rapid hydration kinetics, primarily due to the high reactivity of CEM I 52.2N. The early peak in temperature followed by a sustained heat release suggests an aggressive exothermic reaction typical of high-grade Portland cement. The calorimetric data reveal the highest heat release at 328 J/g, corresponding with a significant early-age compressive strength of 32.3 MPa.

Fii-1 and Fiii-1: Show moderated calorimetric profiles due to the inclusion of SCMs (Supplementary Cementitious Materials), with heat releases of 325 J/g and 241 J/g, respectively. This moderation is reflected in the slightly adjusted strength values of 31.8 MPa and 24.3 MPa, indicating the SCMs' effectiveness in tailoring the hydration kinetics and strength development path.

- Scenario 2: Cold Storage with warm mixing water

Fi-2: The rise in temperature is less marked, and the increase in heat released is more gradual, with a significant reduction in the heat released at 210 J/g due to cold storage conditions. This scenario highlights a delayed and prolonged dormant phase of hydration, leading to a markedly lower compressive strength of 7.7 MPa.

Fii-2 and Fiii-2: Reflect slightly higher total heat releases (215 J/g and 82 J/g, respectively) than Fi-2, showing the mitigating effect of SCMs on cold cure conditions. The resultant compressive strengths of 9.3 MPa and 3.2 MPa provide insight into the complex interactions between cement hydration and SCM reactivity under adverse temperature conditions.

- Scenario 3: Post-Mixing heat treatment

Fi-3: The calorimetric profile indicates a rapid temperature increase followed by a sharp rise in heat release, suggesting a highly accelerated hydration process facilitated by post-mixing heat treatment. This is evidenced by a pronounced heat release of 380 J/g, directly correlating with a significant increase in compressive strength to 38.3 MPa.

Fii-3 and Fiii-3: Also exhibit substantially higher heat releases (388 J/g and 310 J/g, respectively), indicating accelerated hydration kinetics due to elevated temperature curing. The observed compressive strengths (39.8 MPa and 30.9 MPa) highlight the potential of controlled heating to enhance both the rate and extent of cement hydration, significantly impacting mechanical performance.

The comprehensive analysis intertwining calorimetric data and mechanical performance across different curing scenarios unveils profound insights into the complex nature of cement hydration and its implications for concrete technology. By meticulously examining the interaction between environmental conditions, cement chemistry, and supplementary cementing materials, we gain a polyvalent understanding of concrete comportment [27–29].

- Enhanced understanding of hydration phases

Calorimetric profiles and mechanical data give a detailed insight into the hydration process:

Initial Reaction Phase: The pronounced temperature rise and heat release in the initial reaction phase, especially evident in Fi-1, underscores the high reactivity of CEM I 52.2N. This rapid onset of hydration highlights the sensitivity of this phase to cement composition, setting the stage for early strength development.

Dormant Period: The extended dormant period observed in Fi-2, marked by lower heat release and a flat temperature profile, illustrates how environmental conditions, specifically cold, can significantly delay the hydration process. This delay has critical implications for the curing of concrete in adverse conditions, underlining the need for appropriate curing practices.

Acceleration to Steady State: The swift transition to a steady-state phase in Fi-3, facilitated by post-mixing heat treatment, demonstrates an optimized environment for continuous hydration product formation. This phase is essential for achieving high strength and durability in the early stages of aging, as it ensures a sustained reaction that contributes to the development of the microstructure [30,31].

- Correlation of heat and temperature dynamics with mechanical properties

The analysis shows a direct correlation between the calorimetric data and the mechanical properties of the concrete [32,33]:

Heat-Temperature Lag: The observed lag between temperature peaks and maximum heat release, particularly in Fi-1, could be indicative of the timing in the formation of critical hydration products like calcium silicate hydrate (C-S-H), which is instrumental in strength development. This lag not only reflects the kinetics of chemical reactions but also the evolving microstructure of the concrete [34].

Temperature Stability: The stable temperature profile in the midst of increasing heat release, as seen in Fi-3, suggests a curing environment conducive to sustained hydration. This stability is essential for the development of a dense microstructure, which is essential for the durability and strength of the product [32,33,35–39].

- Strategic curing practices

The data support the use of strategic curing practices to enhance concrete performance:

Heat Treatment: The significant role of heat treatment in enhancing early-age strength, particularly in Scenario 3, points to its potential in precast concrete operations. This finding suggests that controlled thermal environments can substantially accelerate strength development, enabling more efficient production cycles [40,41].

Environmental and Material Considerations: The impact of cold curing conditions on hydration kinetics highlights the importance of managing ambient and material temperatures. Adjusting curing practices, such as employing heated mixing water or insulating forms, can mitigate the adverse effects of cold environments, highlighting the need for flexibility and adaptation in curing strategies.

5. Conclusions

This study summarizes the results of our detailed research into the impact of various environmental and thermal management strategies on the hydration kinetics and mechanical properties of cementitious formulations. It provides essential information with considerable implications for concrete technology.

In particular, under the challenging conditions that exist in cold weather precast concrete production, the research provides a convincing argument for the complex interactions between cement composition, supplementary cementitious materials (SCMs), and curing methodologies.

Quantitative assessments, including workability tests via slump measurements and compressive strength evaluations, as well as calorimetric analysis, form the experiential backbone of our discourse. These methodologies reveal a nuanced understanding of how strategic thermal management significantly influences the hydration process and, by extension, the structural and mechanical integrity of concrete.

Workability tests consistently place self-compacting concrete in slump class SF2, indicating consistently high workability in all scenarios. This quantitative evidence demonstrates the material's adaptability to standard horizontal applications, highlighting the critical nature of consistent workability to ensure efficient production and structural integrity of precast concrete elements, whatever the curing environment.

The study of compressive strength provides a remarkable illustration of the differences in performance under different curing conditions. Notably, under controlled heating conditions (Scenario 3), the concrete showed a remarkable increase in compressive strength at an early age—measurements such as 38.3 MPa, 39.8 MPa, and 30.9 MPa significantly exceeded those of standard ambient curing (Scenario 1) and interventions using warm mixing water (Scenario 2). These quantitative results not only illustrate the negative impact of cold weather on the early strength development of concrete but also support the effectiveness of sustainable heating approaches, such as fume hoods, in improving structural efficiency and durability.

In addition, calorimetric analysis provides a deeper understanding of concrete hydration kinetics, establishing a clear correlation between thermal management strategies and the hydration process. The acceleration of hydration kinetics demonstrated in the post-mix heat treatment scenario, marked by increased heat release and temperature stability, elucidates the optimization of the hydration process. This is essential to achieve a rapid gain in strength and improve the microstructural development of the concrete matrix, thus contributing to the durability and performance of the material.

In conclusion, our results argue for a strategic re-evaluation of curing practices in precast concrete production, highlighting the critical role of environmental and thermal management in mitigating the adverse effects of cold weather conditions. The superior performance of concrete under controlled heating conditions highlights the need for the construction industry to adopt innovative strategies that optimize structural and mechanical performance in a variety of climatic scenarios.

This study not only advances the field of concrete technology by providing a quantitative benchmark for future research but also highlights the imperative for actors in the construction industry to incorporate advanced hardening technologies and material innovations. This research is highly relevant to the precast concrete industry as it provides practical solutions and valuable insights to address the critical challenge of achieving adequate early-age compressive strength under adverse winter conditions, which is essential for the efficient and safe production of prefabricated concrete elements. The aim is to meet the industry's evolving challenges and lead the way in the development of resilient, durable, and high-performance concrete structures. The ideas gathered here provide the basis for new research and development efforts aimed at refining precast concrete methodologies to achieve an optimal balance between material performance, durability, and architectural versatility.

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