Article

An Overview of Smart Materials and Technologies for Concrete Construction in Cold Weather

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Abstract: Cold weather conditions pose significant challenges to the performance and durability of concrete materials, construction processes, and structures. This paper aims to provide a comprehensive overview of the material-related challenges in cold weather concrete construction, including slow setting, reduced curing rate, and slower strength development, as well as frost damage, early freezing, and freeze–thaw actions. Various innovative materials and technologies may be implemented to address these challenges, such as optimizing the concrete mix proportions, chemical admixtures, supplementary cementitious materials, and advanced construction techniques. The paper also examines the impact of weather-related challenges for personnel, equipment, and machinery in cold environments and highlights the importance of effective planning, communication, and management strategies. Results indicate that the successful implementation of appropriate strategies can mitigate the challenges, reduce construction time, and enhance the performance, durability, and sustainability of concrete structures in cold and freezing temperatures. The paper emphasizes the importance of staying updated about the latest advancements and best practices in the field. Future trends include the development of smart and functional concrete materials, advanced manufacturing and construction techniques, integrated design, and optimization of tools, all with a strong focus on sustainability and resilience.

Keywords: concrete; cold construction; engineering challenges; freezing; concrete setting; construction materials

1. Introduction

Concrete is a the most commonly used construction material [1,2]. It plays an important role in the development and construction of sustainable infrastructure, buildings, and various other structures. It is well known for its versatility, durability, and cost-effectiveness [3–7]. However, concrete construction in cold weather conditions presents numerous challenges that can significantly impact the performance, durability, and sustainability of the structures [8–12]. As cold weather construction becomes more prevalent due to expanding urbanization, expedited by rapid population growth [13,14] and the increased requirements for infrastructure development in colder regions, understanding the material-related challenges and identifying effective strategies and technologies to address these challenges is essential. Cold weather concrete construction has been an active area of research for several years, with numerous studies focusing on the challenges related to setting [15], curing [16], strength development [17], and drying [18], as well as frost damage [19], early freezing [20], and freeze–thaw cycles [21]. Despite these research efforts, there is still a need for a better understanding of the material-related challenges and technologies that can be employed to address them. This study contributes by filling the knowledge gap in the literature and providing a holistic understanding of the challenges, strategies, and performance enhancement opportunities for concrete construction. A comprehensive understanding of the challenges and strategies associated with concrete materials, construction processes, and structures, can be used to support construction...
professionals in making informed decisions and implementing effective solutions that improve the performance and sustainability of concrete structures in harsh environments.

The aim of this paper is to provide an in-depth analysis of the material-related challenges in cold weather concrete construction as well as explore innovative materials and the technologies to implement them, as illustrated in Figure 1. The study encompasses a comprehensive review of the existing literature, including research studies and case examples related to cold weather concrete construction. This review focuses on understanding the material-related challenges associated with slow setting, reduced curing rate, and slower strength development, as well as frost damage due to low temperatures, early freezing, and freeze–thaw actions. Furthermore, the paper explores innovative strategies and technologies that can be employed to address the various challenges, such as optimizing the concrete mix proportions [22], the use of chemical admixtures [23], supplementary cementitious materials [24], and advanced construction techniques [25]. The study emphasizes the emerging materials and technologies in the field, including the development of smart [26] and functional concrete materials [27], advanced manufacturing [28] and construction techniques [29], integrated design [30], and optimization of tools [31], all with a focus on sustainability and resilience. The study also highlights the potential impact of weather-related challenges on personnel, equipment, and machinery during construction. Furthermore, it emphasizes the importance of effective planning, communication, and management strategies to ensure successful completion of construction projects in low temperatures. As climate change continues to result in more unpredictable and extreme weather, understanding the challenges associated with cold weather construction and developing effective strategies and technologies to address them becomes increasingly important. This research not only contributes to the existing body of knowledge on this topic but also serves as a foundation for future research and development efforts in the field of concrete construction. The findings of this study are not limited to the specific challenges and strategies discussed but can also be extended to other construction materials and processes that may be affected by low temperatures. By fostering a culture of continuous learning and innovation, the construction industry can better adapt to the changing climate [32] and ensure the resilience and sustainability of infrastructure and buildings worldwide [33].

![Figure 1. Parts included in this review.](image)

### 2. Challenges in Cold Weather Concrete Construction

#### 2.1. Setting and Curing

Setting and curing are two critical processes that ultimately determine the strength growth, durability, and long-term performance of concrete materials. Low temperatures can
have a large negative effect on the development of concrete properties, as these processes can be significantly slowed down, leading to various material, structural, and management issues. The challenges of longer setting times and slower curing are discussed in the following sections, and counteracting engineering strategies are proposed in Section 2.1.3.

2.1.1. Setting

Setting refers to a specific time when concrete changes from a fluid, workable state to a solid, rigid state [34]. It involves the initial chemical reactions between cement [35] or other binders [36] and water, a process called hydration [37]. In cold conditions, the rate of hydration decreases due to the lower temperature, causing the concrete to set more slowly [38]. Slow setting can lead to problems affecting the construction procedure, the material properties, the durability of the structure, and the long-term sustainability. A longer setting time for concrete in cold and freezing temperatures can lead to various challenges and consequences, including increased construction time and costs [39]. As the concrete sets more slowly, the formwork and temporary supports must remain in place for a longer period to ensure the concrete can support its own weight and any applied loads [40]. This extended support time can cause delays in the construction schedule [41], as it may prevent other activities from taking place in parallel. The cost of formwork typically accounts for a major part of the total construction costs [42], and the prolonged need for supporting formwork can lead to high additional costs. Longer setting times may also necessitate more on-site personnel for a longer duration to monitor the concrete [43], maintain temperature control measures [44], and perform finishing tasks [45]. This increased labor requirement can lead to higher labor costs for the project. As the concrete sets more slowly in cold weather, it can be challenging to achieve a smooth, even surface finish [46]. This may also require additional effort and resources to rectify. Slower setting times may require the use of additional equipment, such as heated enclosures [11] or insulated formwork [47], to maintain optimal temperature conditions and accelerate the setting process. Any damage to the concrete due to the extended setting time may necessitate repairs or even replacement, which can further increase the complexity and add to the material and labor costs.

Construction projects often have strict deadlines, and any delays in the schedule can result in different types of financial penalties for the builder [48]. The longer setting time and its impact on the construction timeline may in the end lead to the activation of such penalties, increasing the overall cost of the project. With the extended setting time, the concrete also becomes more susceptible to damage from adverse weather conditions [49], such as rain, snow, or freezing temperatures, which can negatively affect its properties and structural performance. This may require additional measures to protect the concrete, adding to the overall cost and potentially causing further delays. If the slower setting time results in reduced strength or other undesirable properties in the concrete, it may be necessary to modify the structural design or add extra reinforcement, which will increase costs and extend the construction timeline. It is therefore important for the engineers to always consider the setting time and choose a concrete that fulfills the structural requirements in the ambient environment of the project.

2.1.2. Curing

Curing of concrete is the process of maintaining proper moisture and temperature conditions within the concrete after it has been placed and finished [50]. This process allows the concrete to develop its desired strength, durability, and long-term performance through the continued hydration of cement or other types of alternative binders [51]. Hydration is the chemical reaction between binders and water; it forms new compounds and crystalline structures, binding the aggregate particles together and giving concrete its strength. Adequate curing is essential to ensure that the hydration process continues for an extended period, allowing the concrete to reach its full potential in terms of strength and durability. By preventing the evaporation of water from the concrete, the curing process ensures that
there is enough water available for the hydration of cement, as illustrated in Figure 2 [52]. This can be achieved using various methods, such as applying curing compounds [53], covering the concrete with plastic sheets [54], or using wet coverings like burlap [55] or cotton mats [56]. Curing also involves maintaining a suitable temperature range within the concrete to facilitate the hydration process [57]. This is especially important in extreme weather conditions, such as cold or hot temperatures, where external measures may be required to regulate the concrete’s temperature. These measures may include using insulated blankets or enclosures [58], heated water [59], heating cables [60], or steam curing [61]. Curing helps reduce the potential for shrinkage and cracking in concrete by controlling the rate at which it dries and contracts [62]. Proper curing can minimize the development of microcracks, leading to improved durability and performance. Curing typically begins immediately after the concrete has been placed and finished, and it continues for a certain period, depending on the type of concrete, the intended use of the structure, and the environmental conditions. The curing duration can range from a few days to several weeks, with the most critical period being the first few days after placement [63]. By ensuring proper curing, contractors can optimize the performance, durability, and service life of concrete structures, making it a critical aspect of the overall construction process.

Figure 2. Hydration process of cement [52]: (a) Unhydrated cement particles (2000× magnification); (b) Partially hydrated cement particles (4000× magnification); (c) Hydrated cement particle (11,000× magnification).

A reduced curing rate in cold weather can lead to various challenges and consequences, including increased construction time, safety concerns, compromised durability, and increased costs [64]. Slower curing rates mean that it takes longer for the concrete to achieve its desired strength and be ready for subsequent construction stages, such as removing formwork, loading, or applying finishes. This can delay the overall construction schedule and affect the project timeline. If the concrete has not fully cured, it may not be able to support its self-weight or the loads applied during construction. This can lead to structural instability and increase the risk of accidents or failures on the construction site. Inadequate curing can result in incomplete hydration, which can cause the concrete to be more porous and susceptible to freeze–thaw damage, chemical attack, and other forms of deterioration [65]. This can compromise the long-term durability of the structure and lead to a reduced service life. Slower curing rates can result in higher labor and equipment costs, as additional resources are needed to maintain optimal curing conditions and monitor the concrete’s progress. Additionally, any damage or structural failures due to insufficient curing may require repairs or even replacement, which can further increase material and labor costs. To prevent curing-related issues, it is crucial to implement appropriate cold-weather concreting practices, such as maintaining optimal temperature conditions, using admixtures to accelerate the curing rate [66], and closely monitoring the concrete’s curing progress. By taking these measures, contractors can minimize the impact of reduced curing rates on construction time, safety, durability, and costs, while ensuring the quality and performance of concrete structures in cold and freezing temperatures.
2.1.3. Strategies to Prevent Setting and Curing Challenges

To prevent issues related to longer setting and slower curing of concrete in cold weather, various measures can be implemented to ensure the quality, performance, and durability. Chemical admixtures, such as accelerators, can be added to the concrete mix to accelerate the hydration process and reduce the setting time. These admixtures can help the concrete to achieve the desired strength faster, minimizing the impact of cold weather [67]. Maintaining the concrete temperature within an appropriate range is crucial to ensure proper setting and curing. This can be achieved through various methods, such as pre-heating [59], insulation, and heated enclosures [58]. Heating the water and/or aggregates before mixing can help maintain a suitable temperature for the concrete mix, ensuring a timely setting. Insulated formwork or blankets can be used to maintain the concrete’s temperature during setting and curing, protecting it from cold weather and reducing heat loss and rapid cooling. Temporary, heated enclosures can be built around the construction site to maintain a controlled environment with adequate temperature and humidity levels.

Employing appropriate curing techniques in cold weather is essential to maintain the moisture and temperature conditions necessary for the hydration process [50]. Insulated curing blankets can be placed over the concrete surface to minimize heat loss and maintain the desired curing temperature. Circulating heated water [59] through pipes embedded in the concrete can provide consistent and controlled heat to maintain the curing temperature. Steam can be introduced into an enclosed space to maintain the temperature and humidity required for curing. Modifying the concrete mix design to include more cement or incorporating supplementary cementitious materials (SCMs), such as fly ash or slag [51], can help increase the rate of strength development and counteract the effects of cold temperatures on setting time. Regularly or continuously monitoring the temperature and strength development of the concrete is crucial during cold weather construction. Field testing, such as the use of maturity meters or penetration resistance tests [68], can help ensure the concrete achieves the desired performance characteristics. Effective planning and scheduling of construction activities can help minimize the impact of cold weather on setting and curing times. Scheduling concrete placement during warmer periods of the day or coordinating with weather forecasts can help optimize the construction process. By implementing these preventing or proactive measures, contractors can mitigate the challenges associated with longer setting times in cold weather, ensuring the quality, durability, and performance of concrete structures.

2.2. Strength Development

Cold weather conditions can significantly affect the strength development of concrete [69], which is a critical aspect of its overall performance and durability. The setting, curing, and strength development processes of concrete are all temperature-dependent, and lower air temperatures can slow down these processes [70,71], leading to challenges in construction and potential long-term issues in the final structure. The rate of hydration, and consequently the rate of strength development, is heavily influenced by the concrete temperature [72]. As temperature decreases, the rate of hydration reduces, resulting in a slower strength gain. The rate of hydration is roughly reduced by half in 10 °C temperatures compared to 20 °C. Consequently, concrete placed and cured in cold conditions will exhibit a slower rate of strength development compared to concrete placed in warmer temperatures.

2.2.1. Factors Affecting the Strength Development in Cold Weather

The hydration process is highly dependent on temperature [69]. Low air temperatures can reduce the concrete temperature and hydration rate [70], ultimately affecting the material properties. The reduced hydration rate directly impacts the strength development, as it takes more time for the concrete to achieve its full potential strength in cold climates [73]. By understanding the factors affecting the material properties, contractors can take appropriate measures to prevent problems associated with slower strength development.
Cold weather prolongs the setting, which delays the strength development process. An extended setting time increases the vulnerability of concrete to external factors, such as harsh weather or mechanical damage, before it reaches an adequate level of strength. The curing process plays an important role in the strength development of concrete by maintaining appropriate moisture and temperature conditions [50]. The curing process takes more time in low temperatures, which can result in incomplete hydration and slower strength gain. If the curing process is not carefully managed in cold conditions, the concrete may be exposed to freezing temperatures, which can lead to freeze–thaw damage and significantly compromise the structure’s durability and performance.

The use of Supplementary Cementitious Materials, SCMs, such as fly ash or slag, is becoming more and more common in concrete mix designs. These materials can be used for several reasons, such as enhancing the concrete’s properties or reducing its environmental impact [74]. SCMs can also impact the hydration process and, consequently, the strength development. In cold weather, the pozzolanic reactions between SCMs and cement hydration products can be slower [75], further contributing to the reduced strength gain. Chemical admixtures, such as accelerators and water reducers, are often used to modify the properties of the concrete mix [76]. In cold weather, the effectiveness of some admixtures may be reduced due to the lower temperatures. During mixing and transportation, the concrete’s temperature can decrease [77], particularly in cold weather, and the effects can be significant when long distances separate concrete factories and construction sites, which is not uncommon in regions with cold climate. Delays in placing the concrete due to logistical challenges can exacerbate this issue, as the concrete may experience further temperature drops and reduced workability.

### 2.2.2. Consequences of Slow Strength Development

Understanding the potential consequences of slower strength development is essential to managing the challenges associated with cold weather concreting effectively. By implementing appropriate measures to mitigate these consequences, contractors can ensure the successful completion of their projects and maintain high quality, durability, and performance of the constructed concrete structures. Slow strength development can ultimately result in long construction times, as it takes more time for the concrete to achieve the required strength [77] for subsequent construction activities. This can lead to delays in the overall construction schedule, potentially causing a domino effect on the project timeline and increasing costs related to labor and equipment. A slow concrete is more susceptible to damage during construction, such as premature loading, weather exposure, or other construction activities [78]. Early-age damage can result in defects that compromise the structural integrity, require costly repairs, or even necessitate a complete replacement of the affected concrete elements [79]. If the concrete does not achieve its required strength within the expected timeframe, it may not be able to support the intended loads or perform as designed [80]. This can lead to potential safety concerns, a reduced service life, and increased likelihood of structural failures. This may, for example, be a major concern for deciding a safe time for form stripping, which typically requires a minimum strength of 5 MPa for vertical structural members and 70% of the final strength for horizontal members [81].

Slower strength development can lead to increased permeability and microcracking within the concrete [82], making it more susceptible to various forms of deterioration, such as freeze–thaw damage [83], alkali–silica reactions [84], and chloride-induced corrosion of reinforcing steel [85]. These forms of deterioration can compromise the long-term durability of the structure and result in increased maintenance and repair costs over the structure’s life. A reduced hydration rate can complicate the quality control process during construction. As the concrete takes longer to achieve its target strength, it becomes more difficult to accurately assess its performance characteristics and ensure it meets the project’s specifications. In some cases, this can lead to aesthetic issues [86], such as an uneven or poor-quality finish on the concrete surface. The longer the construction process takes, the
more resources are typically consumed, such as energy, water, and raw materials [87]. This can ultimately contribute to a larger environmental footprint for the construction project.

2.2.3. Measures to Mitigate Slow Strength Development

Understanding the impact of harsh weather on concrete strength development is essential for successful construction projects in such conditions. By implementing appropriate measures to mitigate the challenges associated with slow strength gain, contractors can ensure the quality, durability, and performance of concrete structures, even in cold and freezing temperatures. Proper planning, mix design adjustments [88], temperature control [89], and curing methods [50] can all contribute to a more efficient construction process and a more resilient final structure, ultimately leading to long-lasting and high-performing concrete structures.

Chemical admixtures [90], such as accelerators, can be added to the concrete mix to increase the rate of cement hydration and reduce the setting time, helping the concrete to achieve its desired strength more quickly. Modifying the concrete mix design to include more cement or incorporating supplementary cementitious materials [51], such as fly ash or slag, can help increase the rate of strength development and counteract the effects of low temperatures on the hydration process [57]. Some methods for temperature control include preheated materials [59], insulation, or heated enclosures [58]. Heating the water and/or aggregates before mixing can help maintain a suitable temperature for the concrete mix. Insulated formwork or blankets can be used to maintain the concrete’s temperature during setting and curing, protecting it from cold weather and reducing heat loss. Temporary enclosures can be built around the construction site to maintain a controlled environment with adequate temperature and humidity levels.

Employing appropriate curing techniques in cold weather is essential to maintain the moisture and temperature conditions necessary for the hydration process [62]. Some common cold weather curing methods include insulated curing blankets, heated water curing, and steam curing, as discussed in Section 2.1.3. Insulated curing blankets can be placed over the concrete surface to minimize the heat loss and maintain the desired curing temperature. Heated water curing implies circulating heated water through pipes embedded in the concrete, which can provide consistent and controlled heat to maintain the curing temperature. Steam curing can be introduced into an enclosed space to maintain the temperature and humidity required for curing.

Regularly or continuously monitoring the temperature and strength development of the concrete is crucial during cold weather construction [72]. By following the temperature history of the concrete, good estimations of the strength can be calculated using maturity equations [91]; see Equation (1). The equation shows that the maturity \( M(t, T) \) depends on the temperature \( T \) and the time \( t \). The reference temperature \( T_0 \) is typically 20 °C.

\[
M(t, T) = \sum (T - T_0) \Delta t, \tag{1}
\]

Field testing, including the use of maturity meters or penetration resistance tests, can also help to ensure that the concrete achieves the desired performance characteristics [92]. Effective planning of construction activities can help minimize the impact of cold weather on strength development.

2.3. Freezing of Concrete

Freezing temperatures pose significant challenges to the performance and durability of concrete structures. When concrete is subjected to cold conditions, it can experience different types of frost damage, which can lead to a reduction in the concrete’s strength, integrity, and service life. Early freezing and freeze–thaw actions can enhance and accelerate the negative effects of concrete freezing. The following sections will discuss these phenomena and their impacts on concrete and will detail some preventative measures that can be employed to mitigate the issues of concrete freezing. A wider analysis of preventive measures is presented in Sections 3 and 4.
2.3.1. Frost Damage

Frost-related deterioration and damage is a significant concern for concrete structures in cold climates, as it can lead to a decrease in strength, durability, and overall performance [93]. Frost damage occurs when water present in the concrete’s porous structure freezes and expands [94]. This expansion generates internal pressures that can exceed the tensile strength of the concrete, resulting in various forms of deterioration [95]. The primary factors that contribute to frost damage in concrete include aspects such as the water–cement ratio [96], air entrainment [97], permeability [98] and exposure to de-icing chemicals [99]. The water–cement ratio plays a critical role in determining the porosity and permeability of the concrete [100]. A higher water–cement ratio leads to increased porosity, which allows more water to infiltrate the concrete, raising the risk of frost damage. Air entrainment is the deliberate incorporation of microscopic air voids within the concrete mix. These voids provide space for the expansion of freezing water, helping to alleviate the internal pressures caused by ice formation. Insufficient air entrainment can increase the susceptibility of concrete to frost damage [101]. The permeability of concrete refers to its ability to allow water to penetrate its structure. Concrete with higher permeability is more prone to frost damage, as it permits a greater amount of water to enter and become trapped within the material [102]. The use of de-icing chemicals, such as salts, can exacerbate frost damage by increasing the saturation of water within the concrete and facilitating freeze–thaw cycles.

The primary consequences of frost damage in concrete include cracking, scaling, spalling, and a reduced overall durability [103]. The internal pressures generated by the expansion of freezing water can cause cracks to form and propagate in the concrete. These cracks can weaken the structure and provide pathways for further water ingress, leading to additional frost damage and other forms of deterioration. Scaling [104] is the flaking or peeling of the concrete surface; it occurs when the surface layer is subjected to frost damage. Scaling can result in an unsightly appearance and increased surface roughness, which can be particularly problematic in architectural concrete applications. Spalling [105] refers to the breaking away of large fragments of concrete, typically caused by the expansion of freezing water within the material. Spalling can compromise the structural integrity and aesthetics of the concrete. Frost can lead to a reduction in the durability of concrete structures, as the associated cracking, scaling, and spalling can expose the reinforcing steel to corrosion and facilitate other forms of deterioration, as seen in Figure 3. Understanding the causes and consequences of these damage processes is essential for designing, constructing, and maintaining resilient and long-lasting concrete structures [106]. By implementing appropriate mix designs, curing practices, and preventative measures, engineers and contractors can effectively manage the challenges associated with frost damage and ensure the successful completion of their projects. Regular inspection and maintenance of concrete structures exposed to freezing temperatures are also crucial in mitigating the risks of frost damage and extending the service life of the structures. Ultimately, a comprehensive understanding of frost damage and the application of appropriate mitigation strategies can help to maintain the structural integrity, performance, and aesthetics of concrete structures in cold weather conditions.
2.3.2. Early Freezing

Early freezing is a significant concern for concrete structures in cold climates, as it can lead to a reduction in strength, durability, and overall performance [108]. Early freezing occurs when the concrete is exposed to freezing temperatures before it has achieved sufficient strength, typically during the initial setting and curing stages [109]. Several concrete guidelines and research articles have defined threshold limits for the concrete compressive strength of 5–10 MPa [110] in terms of the necessity to avoid early freezing. When the ambient temperature falls below the freezing point, the water within the concrete mix can freeze, interrupting the cement hydration process and affecting the concrete’s strength development [111]. Insufficient protection of the concrete during the setting and curing stages, such as the use of inadequate insulating materials or heated enclosures, can expose the concrete to freezing temperatures and result in early freezing. A concrete mix design that does not consider the specific requirements for cold weather concreting, such as the use of admixtures designed to accelerate setting and hardening, can increase the risk of early freezing [112].

The implications of early freezing on concrete can be detrimental, with several potential consequences. When the cement hydration process is hindered due to early freezing, the concrete may not achieve its full potential strength [111]. This can result in a weaker structure that is unable to support the intended loads or perform as designed. The formation of ice lenses within the concrete during early freezing can lead to increased porosity and permeability [113]. This makes the concrete more susceptible to further freeze–thaw damage as well as other forms of deterioration [83]. Figures 4–6 show how early freezing can affect the material properties of concrete [114]. The figures show that the time when the concrete is first exposed to the freezing temperatures (frost onset time) is an important parameter, and that freezing within the first day has the biggest negative impact on the strength. The notation “Ref” in Figures 5 and 6 represents the unfrozen reference specimen.

Figure 3. Spalling of concrete due to cracking and corrosion in a cold climate [107].
Figure 4. Effect of early freezing with different frost onset times on concrete strength properties. The frost duration was 8 h, with a temperature of $-5 \, ^\circ C$. Reproduced with data from [114]. (a) Compressive strength of early frost affected concrete with onset times between 0.5 and 72 h, compared to unfrozen concrete (Ref). (b) Tensile strength of early frost affected concrete with onset times between 0.5 and 72 h, compared to unfrozen concrete (Ref).

Figure 5. Effect of early freezing with different frost onset times and temperatures on concrete strength properties. The frost duration was 8 h, and the temperatures were between $-1$ and $-9 \, ^\circ C$. Reproduced with data from [114]. (a) Compressive strength of early frost affected concrete with onset times between 0.5 and 8 h, compared to unfrozen concrete (Ref). (b) Tensile strength of early frost affected concrete with onset times between 0.5 and 8 h, compared to unfrozen concrete (Ref).
Freezing duration effect on compressive strength

![Graph 1](image1.png)

(a) Compressive strength of early frost affected concrete with onset times between 0.5 and 8 h, compared to unfrozen concrete (Ref).

Early freezing effect on porosity

![Graph 2](image2.png)

(b) Porosity of concrete affected by early freezing with onset times between 0.5 and 72 h, compared to unfrozen concrete (Ref).

Figure 6. Effect of early freezing with different frost onset times and durations on concrete strength properties. The frost duration was 8 h and the temperatures were between −1 and −9 °C. Reproduced with data from [114]. (a) Compressive strength of early frost affected concrete with onset times between 0.5 and 8 h, compared to unfrozen concrete (Ref). (b) Porosity of concrete affected by early freezing with onset times between 0.5 and 72 h, compared to unfrozen concrete (Ref).

The combination of reduced strength, increased permeability, and surface damage [115] caused by early freezing can compromise the long-term durability of the concrete structure, potentially leading to a shorter service life and increased maintenance and repair costs [116]. Early freezing poses a significant challenge to the performance and durability of concrete structures in cold climates [117]. Ongoing research and development in concrete technology, such as the introduction of new admixtures, materials, and construction techniques, can help improve the industry’s ability to manage early freezing and other related challenges [118]. This will ultimately contribute to the construction of more durable, resilient, and sustainable concrete structures, even in harsh and freezing environments.

2.3.3. Freezing and Thawing

Repeated freezing and thawing cycles can have significant adverse effects on the performance and durability of concrete structures in cold climates [119]. Freezing and thawing cycles occur when the concrete is exposed to fluctuating temperatures that repeatedly cause the water within its porous structure to freeze and thaw. The primary factors contributing to freezing and thawing in concrete include temperature fluctuations, water absorption, and inadequate air entrainment [120]. Frequent changes in temperature above and below the freezing point can lead to multiple freeze–thaw cycles, increasing the risk of damage to the concrete. The presence of water in the concrete is necessary for freeze–thaw damage to occur [121]. Concrete with high porosity and permeability is more likely to absorb water and be susceptible to freeze–thaw cycles [122]. Insufficient air entrainment in the concrete mix can lead to a lack of air voids, which serve as a relief mechanism for the pressures generated by freezing water [123].

The expansion of freezing water within the concrete can cause internal pressures that exceed the tensile strength of the material, leading to various forms of deterioration such as cracking, scaling, and spalling, as seen in Figure 7 [124]. The damage caused by freeze–thaw cycles can lead to a reduction in the compressive and tensile strength of the concrete, as well as reduced E-modulus, as shown in Figure 8, compromising its structural integrity.
and ability to support the intended loads. The cumulative effects of freezing and thawing can result in a decrease in the concrete’s durability, leading to a shorter service life and increased maintenance and repair costs [125]. Freeze–thaw cycles can also cause a loss of bond between the concrete and reinforcing steel, which may compromise the integrity and performance of the structure [126].

![Figure 7. Reduced E-modulus due to repeated freeze–thaw cycles [124].](image)

Figure 7. Reduced E-modulus due to repeated freeze–thaw cycles [124].

![Figure 8. Cracking caused by repeated freeze–thaw cycles [124]. (a) Uncracked reference concrete. (b) Cracking of concrete with damage level 1, i.e., 25% reduction of compressive strength. (c) Cracking of concrete with damage level 2, i.e., 50% reduction of compressive strength.](image)

Figure 8. Cracking caused by repeated freeze–thaw cycles [124]. (a) Uncracked reference concrete. (b) Cracking of concrete with damage level 1, i.e., 25% reduction of compressive strength. (c) Cracking of concrete with damage level 2, i.e., 50% reduction of compressive strength.

### 2.3.4. Preventive Measures

Implementing appropriate preventive measures and strategies can help mitigate the risks of frost damage, ensuring the durability, performance, and longevity of the concrete structures [93]. Regular inspection and maintenance of concrete structures are essential in identifying potential issues related to frost damage, early freezing, and freeze–thaw cycles [127]. Timely intervention can address these problems before they escalate and compromise the structure’s integrity [128]. Maintenance activities, such as repairing cracks, sealing joints, and applying protective coatings, can help maintain the durability and performance of the concrete structure. Educating engineers, contractors, and other stakeholders about the potential risks and consequences of frost-related problems is critical in ensuring the successful implementation of preventive measures and strategies. Preventing frost damage in concrete requires a comprehensive approach, including mix design optimization, cold weather concreting practices, protection and insulation, drainage and waterproofing, and regular inspection and maintenance [129]. By implementing these preventive measures and strategies, engineers and contractors can effectively manage the challenges associated
with cold weather concreting and ensure the successful completion of their projects. A detailed discussion on different preventive approaches is given in Section 3.

2.4. Weather-Related Challenges in Construction

Cold weather construction presents unique challenges to personnel, equipment, and site management, including low temperatures, snow, and wind [130]. These challenges can lead to increased costs, reduced productivity [131], and potential safety risks. By understanding and addressing these challenges, construction professionals can minimize their impact on project schedules, budgets, and outcomes.

2.4.1. Challenges for Personnel

Low temperatures can result in cold stress, frostbite, and hypothermia, posing significant risks to worker health and safety [132]. Cold weather can affect workers’ dexterity, coordination, and overall productivity [130]. Providing appropriate personal protective equipment (PPE), such as insulated clothing, gloves, and headgear, can help protect workers from cold-related illnesses and injuries. Snow and wind can reduce visibility on the construction site, making it difficult for workers to communicate and coordinate their efforts effectively [133]. Ensuring proper communication tools and establishing clear communication protocols can help mitigate this challenge. Proper training in cold weather construction practices is crucial in ensuring worker safety and productivity. Workers should be educated on the risks associated with cold weather construction and be provided with the necessary tools and resources to manage these risks effectively. A list of potential health challenges in cold weather is presented in Table 1.

2.4.2. Challenges for Equipment and Machinery

Low temperatures can affect the performance and efficiency of construction equipment and machinery. Engines may be more challenging to start, lubricants may become less effective, and hydraulic systems may become less responsive [134]. Regular maintenance and the use of cold-weather-specific lubricants and fluids can help minimize these performance issues. Cold temperatures can significantly reduce battery life for construction equipment and tools, affecting their performance and efficiency [135]. Ensuring proper battery storage and charging practices as well as using cold-weather-specific batteries can help mitigate this issue. Cold weather can also affect the properties of construction materials, making them more brittle and susceptible to damage [136]. Proper handling and storage techniques, such as protecting materials from moisture and temperature fluctuations, can help maintain their integrity and performance. Regular maintenance and inspection of construction equipment and machinery are crucial in cold weather conditions to prevent breakdowns and ensure efficient operation. Proper winterization applications, including engine block heaters, antifreeze, and cold-weather lubricants, can help protect equipment and machinery from the effects of low temperatures [137].

2.4.3. Challenges for Site Management

Accumulated snow and ice can pose significant safety risks and impede construction operations. Implementing a comprehensive snow and ice removal plan, including the use of snowplows, snow blowers, and de-icing agents, can help ensure a safe and efficient construction site [138]. Windy conditions on the construction site can create safety hazards, reduce worker productivity, and cause damage to structures and materials. Erecting wind barriers, such as windbreaks or temporary enclosures, can help protect the construction site and its occupants from the effects of strong winds [139]. Snow and ice can make access to and transportation within the construction site more difficult, leading to delays and increased costs. Ensuring proper site access and transportation planning, including snow removal and the use of appropriate vehicles, can help minimize these challenges. Cold weather conditions can result in construction delays and increased costs. Developing a comprehensive scheduling and contingency plan that accounts for potential weather-
related challenges can help ensure the project remains on track and within budget. Cold weather construction can have an impact on the surrounding environment, including the potential for erosion, sedimentation, and harm to wildlife habitats. Implementing appropriate environmental protection measures, such as sediment control and erosion prevention, can help minimize the environmental impact of construction activities in cold weather conditions [140]. A list of management strategies to ensure worker safety and prevent production interference is presented in Table 2.

Table 1. Physical health challenges for personnel on cold weather conditions [130].

<table>
<thead>
<tr>
<th>Physical Health Challenge</th>
<th>Cause</th>
<th>Symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numbness in exposed body parts</td>
<td>Exposed extremities in cold</td>
<td>Increased nerve pain</td>
</tr>
<tr>
<td>Increase in number of injuries</td>
<td>Continuous exertion in cold weather</td>
<td>Tiredness</td>
</tr>
<tr>
<td>Hobbling effect and uneasiness</td>
<td>Tight thermal clothing</td>
<td>Reduced ability to move</td>
</tr>
<tr>
<td>Physical fatigue</td>
<td>Performing for longer duration in cold weather</td>
<td>Tiredness</td>
</tr>
<tr>
<td>Hypothermia</td>
<td>Excessive loss of heat</td>
<td>Weak pulse, lack of consciousness</td>
</tr>
<tr>
<td>Vasoconstriction of blood vessels</td>
<td>Prolonged exposure to cold</td>
<td>Increase in blood pressure</td>
</tr>
<tr>
<td>Frostbite</td>
<td>Freezing of tissues</td>
<td>Long-term numbness in affected region</td>
</tr>
<tr>
<td>Necrosis</td>
<td>Lack of blood supply to tissue</td>
<td>Malfunctioning of cells</td>
</tr>
<tr>
<td>Upper and lower respiratory issues</td>
<td>Inhaling cold, dry air</td>
<td>Shortness of breath</td>
</tr>
<tr>
<td>Musculoskeletal disorders such as wrist, neck, back and overall body pain and inflammation</td>
<td>Increased muscular load</td>
<td>Carpal tunnel syndrome</td>
</tr>
<tr>
<td>Increase in number of accidents caused by slips and falls</td>
<td>Icy and slippery surfaces in workplace</td>
<td>Major and minor injuries in body parts</td>
</tr>
<tr>
<td>Trench foot</td>
<td>Performing activities in cold water</td>
<td>Blisters, blotchy skin</td>
</tr>
<tr>
<td>Increase in onset of fatigue due to personal protective clothing</td>
<td>Increase in metabolic energy</td>
<td>Tiredness, weakness in muscles</td>
</tr>
<tr>
<td>Reduced dexterity</td>
<td>Impaired response from hand receptors</td>
<td>Inability to handle tools and equipment</td>
</tr>
</tbody>
</table>

2.4.4. Additional Weather-Related Challenges

Freezing and thawing cycles can cause frost heave, leading to soil instability and potential damage to foundations and other structural elements. Ensuring proper site preparation, including soil stabilization techniques and the use of frost-protected shallow foundations, can help mitigate the risk of frost heave and soil instability [141]. Cold weather can also lead to increased condensation and moisture accumulation within buildings and structures, potentially resulting in mold growth and structural damage [142]. Implementing proper moisture control measures, such as vapor barriers and adequate ventilation, can help prevent condensation-related issues. Low temperatures often lead to increased energy consumption for heating, equipment operation, and other site activities. Implementing energy-efficient practices, such as using energy-efficient equipment and optimizing construction processes, can help reduce energy consumption and associated costs [143]. Cold weather construction may also involve additional permitting and regulatory requirements related to environmental protection, safety, and other factors [144]. Ensuring compliance
with all relevant regulations and obtaining the necessary permits can help prevent potential delays, fines, and other complications.

Table 2. Strategies for mitigating challenges of working in cold weather [130].

<table>
<thead>
<tr>
<th>Type of Control</th>
<th>Strategies for Cold Weather Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering control</td>
<td>Encourage the use of smart clothing inserted with infrared, humidity, and temperature sensors</td>
</tr>
<tr>
<td></td>
<td>Wear a Peltier-embedded cooling jacket</td>
</tr>
<tr>
<td></td>
<td>Heat exchange masks</td>
</tr>
<tr>
<td></td>
<td>Protective coverings and insulation</td>
</tr>
<tr>
<td></td>
<td>Anti-slip shoes</td>
</tr>
<tr>
<td></td>
<td>Provide workers with infrared heaters</td>
</tr>
<tr>
<td></td>
<td>Provide warming facilities/local shelters with heating mechanisms</td>
</tr>
<tr>
<td>Administrative control</td>
<td>Cold protection plan and cold management</td>
</tr>
<tr>
<td></td>
<td>Place warning signs on slippery surfaces</td>
</tr>
<tr>
<td>Personal protective equipment (PPE)</td>
<td>Ensure personal protective clothing (PPC) fits properly</td>
</tr>
</tbody>
</table>


Cold weather conditions can, as discussed in previous sections, have a significant impact on concrete construction and the performance of concrete structures, with challenges such as reduced setting time, slower strength development, and increased vulnerability to frost damage. However, technological advances and innovative construction strategies can help mitigate the challenges and improve the performance of concrete structures in cold weather [145]. By employing advanced concrete mix designs [146], appropriate concreting techniques [147], protective measures and insulation [107], accelerating admixtures and chemical additives [148], advanced monitoring and quality control systems [149], and prefabrication and modular construction [150], construction professionals can overcome the challenges associated with cold weather construction. Water is one of the biggest risks related to concrete construction in hazardous environments experiencing low and freezing temperatures; ensuring proper drainage and waterproofing is therefore extremely important to avoid water-related issues and risks, as discussed in Table 3.

Table 3. Drainage and waterproofing as damage-preventive strategies for concrete construction in cold weather.

<table>
<thead>
<tr>
<th>Drainage and Waterproofing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage</td>
</tr>
<tr>
<td>Ensuring proper drainage around the concrete structure can help prevent the accumulation of water and reduce the risk of freeze–thaw cycles [151]. Effective drainage systems, such as well-designed slopes, drains, and gutters, can help minimize water ingress and mitigate the risk of frost damage and early freezing [152].</td>
</tr>
<tr>
<td>Waterproofing and protective coatings</td>
</tr>
<tr>
<td>Applying waterproof membranes [153] or protective coatings [154] to the concrete surface can help prevent water absorption and reduce the risk of frost damage, early freezing, and freeze–thaw cycles. These treatments can improve the concrete’s resistance to moisture ingress [155] and thereby enhance its overall durability.</td>
</tr>
</tbody>
</table>

The following sections will discuss various technologies and construction strategies that can enhance the performance of concrete construction and concrete structures in cold weather conditions.
3.1. Advanced Concrete Mix Designs

Innovative concrete mix designs offer diverse opportunities to improve the performance of concrete in cold weather by addressing challenges such as slow setting, reduced strength development, and frost susceptibility [156]. Material measures that can be taken to mitigate frost-related problems are, for example, adjustments of the water–cement ratio, increasing the air content, and addition of supplementary cementitious materials, as discussed in Table 4. Some other important or recent advancements in concrete mix design include the development of new concrete materials such as ultra-high-performance concrete [157], self-consolidating concrete [158], fiber-reinforced concrete [159], and nanotechnologically enhanced concrete [160].

Table 4. Approaches for mix-design adjustments as damage-preventive strategies for concrete construction in cold weather.

<table>
<thead>
<tr>
<th>Adjusting the Mix Design</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water–cement ratio</td>
<td>Controlling the water–cement ratio is crucial to producing a dense and durable concrete mix with low permeability, reducing the risk of frost damage and freeze–thaw cycles [161]. A lower water–cement ratio reduces the porosity of the concrete, making it more resistant to water ingress and freezing [162].</td>
</tr>
<tr>
<td>Air entrainment</td>
<td>Incorporating air-entraining admixtures into the concrete mix creates small, evenly distributed air voids within the concrete [163]. These air voids provide space for the expansion of freezing water, reducing internal pressure and preventing frost damage, early freezing, and freeze–thaw deterioration [164].</td>
</tr>
<tr>
<td>Supplementary Cementitious Materials (SCMs)</td>
<td>The use of SCMs, such as fly ash, slag, or silica fume, can improve the concrete’s resistance to freezing and thawing cycles by increasing the water–binder ratio [165]. SCMs can thereby reduce the permeability of concrete and enhance its durability, making it less susceptible to frost damage and early freezing [166].</td>
</tr>
</tbody>
</table>

High-performance concrete (HPC) is a type of concrete with enhanced strength, durability, and resistance to environmental factors, including cold weather conditions [167]. The use of HPC or ultra-high-performance concrete (UHPC) can improve the performance of concrete structures by reducing permeability, increasing resistance to freeze–thaw cycles, and enhancing overall durability [157]. It may also offer enhanced cold weather opportunities such as faster setting and strength development, shorter times requirements for supportive formwork, and ultimately higher construction rates due to its rapid development of material and mechanical properties [168]. Self-consolidating concrete (SCC) is a type of concrete that flows and consolidates under its own weight, eliminating the need for mechanical consolidation [169]. SCC can be advantageous in cold weather construction, as it can be placed more quickly and with less labor, reducing the risk of early freezing and the need for additional heating and protection measures [170]. Additionally, it improves the working environment for construction workers as it eliminates the need for harsh work tasks such as vibration and enables the construction of complicated shapes and geometries that would not be possible to construct by using traditional vibrated concrete [171].

Fiber-reinforced concrete (FRC) is a type of concrete that incorporates fibers, such as steel or synthetic fibers, into the concrete mix [172]. The incorporation of fibers in concrete can improve the material’s tensile strength, ductility, and resistance to cracking, making it more resilient in cold weather conditions [173]. The increased cracking resistance is especially important in harsh environments where cracks must be avoided, for example, power plants, tunnels, marine structures, and dams [174]. Fiber-reinforced concrete can also help reduce the risk of frost damage and freeze–thaw deterioration due to the reduced crack
risk. Nanotechnologically enhanced concrete (NEC) refers to the use of nanotechnology and nanoparticles in the mix design of concrete [175]. This innovative material can help improve the performance of concrete in cold weather by enhancing its strength, durability, and resistance to environmental factors [176]. Nanoparticles, such as nano-silica or nanotitanium dioxide, can help reduce porosity, increase strength development, and improve resistance to freeze–thaw cycles [177].

3.2. Cold Weather Concreting Techniques

Innovative concreting techniques can help ensure the successful placement, setting, and curing of concrete in cold weather conditions. Some of these techniques include the use of precooled or preheated materials, accelerating admixtures, or real-time temperature monitoring for accurate strength estimations, as discussed in Table 5. Proper thermal management during concrete placement and curing is always crucial in low temperatures. Innovative methods for managing concrete temperature, such as the use of electric heating cables [18,60], hydronic heating systems [178], or insulated formwork [179], can help maintain the required temperature for optimal curing and strength development.

Table 5. Innovative concreting practices as damage-preventive strategies for concrete construction in cold weather.

<table>
<thead>
<tr>
<th>Cold Weather Concreting Practices</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preheated ingredients</td>
<td>Preheating the concrete ingredients, such as aggregates and water, can help maintain the concrete’s temperature during placement and reduce the risk of early freezing [180]. This practice ensures the proper setting and curing of the concrete in cold weather conditions [181]. The preheating technique can be useful in extreme cold conditions or when using mass concrete.</td>
</tr>
<tr>
<td>Accelerating admixtures</td>
<td>Chemical additives and accelerating admixtures can help improve the performance of concrete in cold weather by reducing setting time and shrinkage [182], promoting faster strength development, and enhancing the durability [183,184]. Non-chloride accelerators, such as calcium nitrate or calcium formate, can help speed up the setting and strength development of concrete in cold weather without the risk of corrosion associated with chloride-based accelerators [185].</td>
</tr>
<tr>
<td>Temperature monitoring and control</td>
<td>Monitoring and controlling the concrete temperature during placement and curing is critical in preventing early freezing and frost damage. Maintaining the concrete temperature within certain limits, typically between 5 and 35 °C, is recommended for proper curing and strength development [186]. Advanced temperature monitoring systems, such as wireless sensors or thermocouples, can provide real-time information on concrete temperature during placement and curing, helping the concrete to maintain the necessary temperature for optimal curing and strength development [187].</td>
</tr>
</tbody>
</table>

3.3. Protective Measures and Insulation

Innovative protective measures and insulation techniques can be used to protect concrete from the effects of low ambient temperatures and ensure proper curing and strength development, as explained in Table 6. Advances in insulation materials have led to the development of lightweight, reusable insulating boards, blankets, or covers that can provide better thermal performance and durability than traditional insulation methods [188]. These blankets can help the concrete maintain the required temperature...
and moisture levels for proper curing and strength development and can prevent early freezing [189].

Table 6. Insulation and protection techniques as damage-preventive strategies for concrete construction in cold weather.

<table>
<thead>
<tr>
<th>Protection and Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Insulating blankets or covers</strong></td>
</tr>
<tr>
<td><strong>Heated enclosures</strong></td>
</tr>
<tr>
<td><strong>Insulated concrete forms</strong></td>
</tr>
</tbody>
</table>

3.4. Advanced Monitoring and Quality Control

Innovative monitoring and quality control systems can help ensure the successful completion of concrete construction projects in cold weather by providing real-time information on critical factors, such as temperature, humidity, and strength development [193]. Advanced wireless sensor systems can provide real-time data on concrete temperature [194], humidity [195], and strength development [196], helping to ensure that the concrete maintains the necessary conditions for optimal curing and performance. These systems can also help identify potential issues early, allowing for timely corrective action [197]. Digital image correlation (DIC) techniques involve the use of high-resolution cameras and advanced image processing algorithms to measure the deformation and strain of concrete structures during curing and service life [198]. This information can be used to assess the performance of concrete in cold weather and identify potential issues related to cracking, shrinkage, or other forms of damage [199].

3.5. Prefabrication and Modular Construction

Prefabrication and modular construction techniques can help improve the efficiency and performance of concrete construction in cold weather by reducing the time and labor required for on-site placement and curing [200]. Some of the advantages of prefabrication and modular construction include the possibility of a controlled environment, faster construction, and improved quality control [201]. Prefabricated concrete elements can be produced in a controlled environment, ensuring optimal curing conditions, and reducing the risk of early freezing, frost damage, or other cold-weather-related issues. Prefabricated and modular elements can be assembled on site more quickly than traditional cast-in-place construction, reducing the time and labor required for concrete placement and curing in low temperatures [202]. The use of prefabrication and modular construction techniques can help improve quality control by allowing for more precise and consistent production of concrete elements.

As the construction industry continues to evolve in response to changing environmental conditions, new technologies, and increasing demand for energy-efficient and resilient infrastructure, the future of concrete materials, construction, and structures in cold weather environments is also expected to undergo significant changes. This section will discuss some of the key future trends and opportunities in the field of concrete materials, construction, and structures in cold weather, with a focus on enhancing their durability, performance, and sustainability.

4.1. Smart Concrete Materials and Their Production

The development and implementation of smart and functional concrete materials are expected to play a significant role in the future of cold weather construction. These advanced materials can provide enhanced performance, durability, and resilience in cold weather conditions, as well as offering new functionalities and capabilities [203]. Some potential smart and functional concrete materials include self-healing concrete [204] and phase change materials [205]. The sustainability can also be promoted in the production phase by adapting carbon capture, utilization, and storage technologies [206]. These technologies are discussed in Table 7.

Table 7. Smart concrete materials and production for improved sustainability.

<table>
<thead>
<tr>
<th>Smart Concrete Materials and Production Technologies</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-healing concrete</td>
<td>Self-healing concrete is an innovative type of building material that can autonomously repair cracks and damage, thereby improving the durability and longevity of concrete structures [207]. This technology typically relies on the use of bacteria or microcapsules containing healing agents, which are activated when cracks form, releasing the healing agent and promoting the formation of new concrete material [208].</td>
</tr>
<tr>
<td>Phase change materials</td>
<td>Phase change materials (PCMs) involve the incorporation of phase transitioning materials into concrete mixes, which can help improve the thermal performance of concrete structures in cold weather [209]. PCMs can store and release thermal energy as they undergo phase transitions, effectively acting as thermal batteries that help regulate the temperature of concrete structures and reduce the risk of frost damage or freeze–thaw deterioration [64].</td>
</tr>
<tr>
<td>Carbon capture, utilization, and storage technologies</td>
<td>Carbon capture, utilization, and storage (CCUS) technologies offer the potential to reduce the environmental impact of concrete production and use by capturing carbon dioxide emissions and incorporating them into concrete materials [210]. These technologies can help create more sustainable concrete materials and construction practices [211].</td>
</tr>
</tbody>
</table>

4.2. Advanced Manufacturing and Construction Technologies

The adoption of advanced manufacturing and construction techniques, such as additive manufacturing (3D printing) and robotics, is expected to transform the way concrete materials and structures are produced and constructed [212]. These techniques can improve the overall efficiency, reduce waste, and enhance the quality and performance of the structures. Some current trends and future opportunities in this area include 3D-printed concrete [213], robotic construction [214], and prefabrication [215], discussed in Table 8. These technologies offer possibilities for improved sustainability for all types of concrete construction, including work in harsh environments.
Table 8. Advanced manufacturing and construction technologies for sustainable concrete.

<table>
<thead>
<tr>
<th>Advanced Manufacturing and Construction Technologies for Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3D printing</strong></td>
</tr>
<tr>
<td><strong>Robotic construction</strong></td>
</tr>
<tr>
<td><strong>Modular and prefabricated construction</strong></td>
</tr>
</tbody>
</table>

4.3. Integrated Design and Optimization Technologies

The development and adoption of integrated design and optimization technologies, such as building information modeling (BIM) and artificial intelligence (AI), are expected to play a significant role in the future of concrete construction and structures [225]. These tools can help streamline design and construction processes [226], improve collaboration and communication between project stakeholders [227], and enhance the performance and durability of concrete structures, both in normal weather conditions and in cold environments [228]. Some integrated design and optimization technologies and their applications are shown in Table 9.

Table 9. Integrated design and optimization technologies for improved sustainability.

<table>
<thead>
<tr>
<th>Integrated Design and Optimization Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Building information modeling</strong></td>
</tr>
<tr>
<td><strong>Artificial intelligence and machine learning</strong></td>
</tr>
<tr>
<td><strong>Digital twins</strong></td>
</tr>
</tbody>
</table>
4.4. Sustainability and Resilience in Cold Weather Concrete Construction

As climate change and environmental concerns continue to drive the need for more sustainable and resilient infrastructure [238], the future of cold weather concrete construction is expected to focus increasingly on enhancing the sustainability and resilience of concrete materials, structures, and construction practices. The development and adoption of green concrete materials [239], such as those incorporating alternative binders like fly ash, slag, or geopolymers, can help reduce the environmental impact of concrete construction [240] while also improving the performance and durability of structures in cold weather environments [241]. These materials can offer enhanced material properties such as better resistance to freeze–thaw cycles [242], reduced permeability [243], and improved thermal performance [244].

Carbon capture, utilization, and storage technologies offer the potential to significantly reduce the carbon footprint of concrete production and use by capturing, storing, and utilizing carbon dioxide emissions [245]. These technologies can help create more sustainable and resilient concrete materials and structures while also addressing the global challenge of climate change [246]. As climate change leads to more extreme and variable weather conditions [247], the need for climate-adaptive design and construction practices is becoming increasingly important. In the context of cold weather concrete construction, this may involve designing and constructing structures that can withstand more frequent and severe freeze–thaw cycles [248], incorporating advanced materials and technologies to enhance resilience, and implementing construction practices that minimize the environmental impact. The future of concrete construction in cold weather environments is expected to be shaped by several key trends and opportunities, including the development of smart and functional concrete materials [249], the adoption of advanced manufacturing and construction techniques [250], the use of integrated design and optimization tools [251], and an increased focus on sustainability and resilience [252]. By staying informed about these trends and seeking to implement innovative solutions and best practices, construction professionals can continue to improve the overall performance, durability, and long-term sustainability of concrete structures in cold weather, ultimately benefiting the construction industry and society.

5. Conclusions

Various challenges, strategies, and performance enhancement techniques related to cold weather concrete construction were discussed in this paper. Cold weather conditions can significantly impact the setting, curing, and strength development of concrete, as well as increase the risk of frost damage, early freezing, and freeze–thaw deterioration. These challenges can lead to increased construction time, higher costs, and potential safety and durability concerns for concrete structures in cold weather environments. Several innovative materials and technologies can be employed to improve the performance and durability of concrete in cold and freezing temperatures. These strategies include adjusting and optimizing the concrete mix proportions, using chemical admixtures and supplementary cementitious materials, modifying the construction practices, and employing innovative materials and construction techniques. Weather-related problems and challenges in construction include the impact of low temperatures, snow, and wind, which affects personnel, equipment, and machinery. The implementation of effective planning, communication, and management strategies can help mitigate the weather-related challenges and ensure the successful completion of construction projects in cold weather environments. The future of cold weather concrete construction is expected to be shaped by several key trends and opportunities, including the development of smart and functional materials, the adoption of advanced manufacturing and construction techniques, the use of integrated design and optimization tools, and an increased focus on sustainability and resilience. These trends and opportunities offer a potential to further enhance the performance, durability, and sustainability of concrete structures in cold weather conditions.
The successful construction of durable, high-performing, and sustainable concrete structures in harsh environments requires a comprehensive understanding of the material-related challenges and the appropriate strategies and technologies to address them. By staying informed about the latest advancements and best practices in the field, construction professionals can continue to develop and implement more effective solutions to the unique challenges posed by cold weather concrete construction, ultimately benefiting both the construction industry and the end-users of these structures.

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