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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

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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].

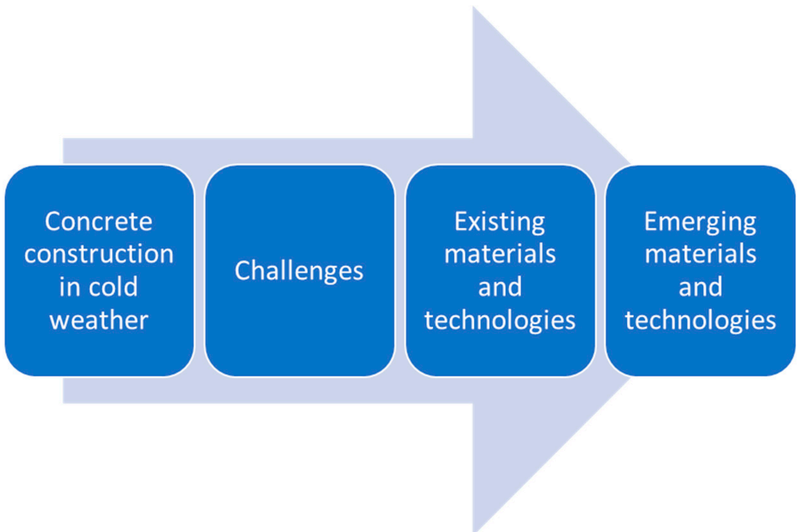


Figure 1. Parts included in this review.

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.

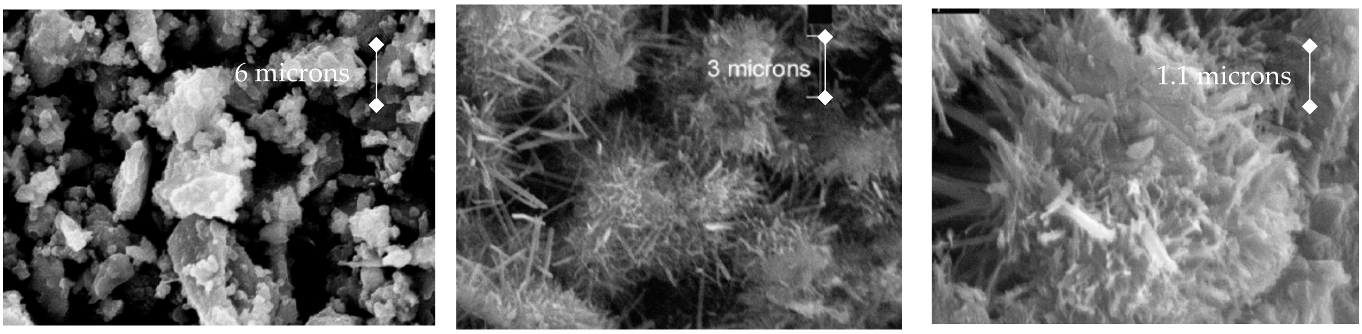
2.1.1. Setting

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.



(a) (b) (c)

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) 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.

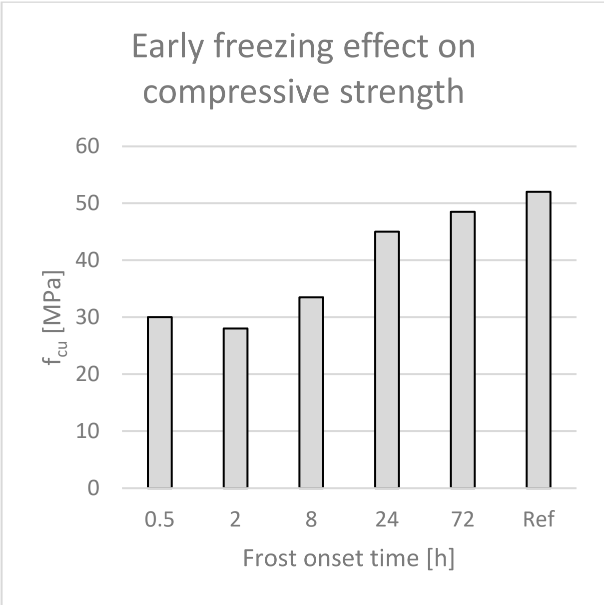
The primary consequences of frost damage in concrete include cracking, scaling, spalling, and a reduced overall durability [103]. The internal pressures generated by the expansion of freezing water can cause cracks to form and propagate in the concrete. These cracks can weaken the structure and provide 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.

Figure 3. Spalling of concrete due to cracking and corrosion in a cold climate [107].

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.



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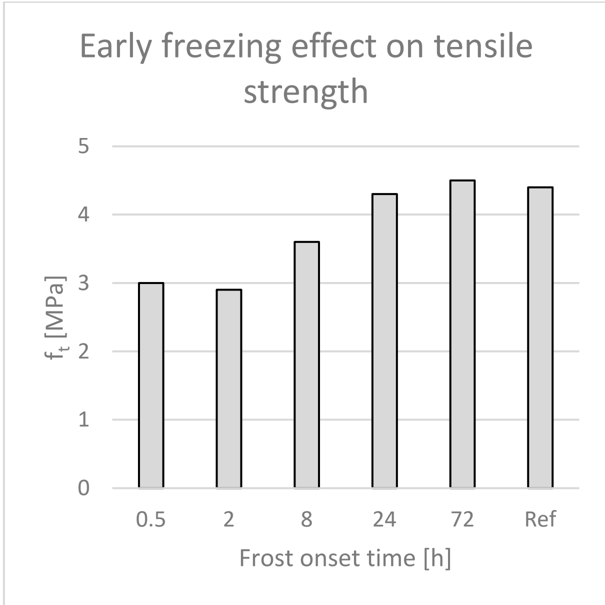

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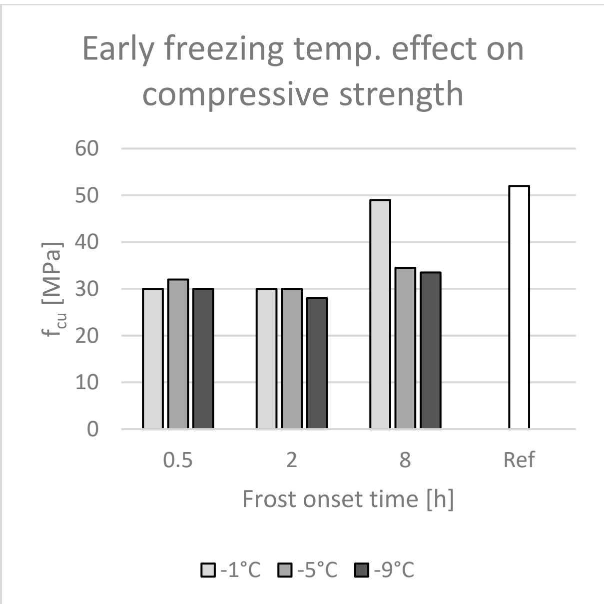
Figure 4. Effect of early freezing with different frost onset times on concrete strength properties. The frost duration was 8 h, with a temperature of −5 °C. Reproduced with data from [114]. (**a**) Compressive strength of early frost affected concrete with onset times between 0.5 and 72 h, compared 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).



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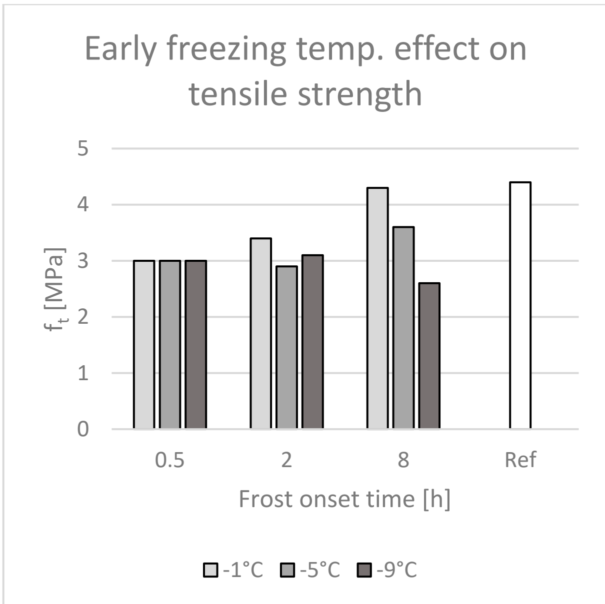


(**b**)

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 °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).

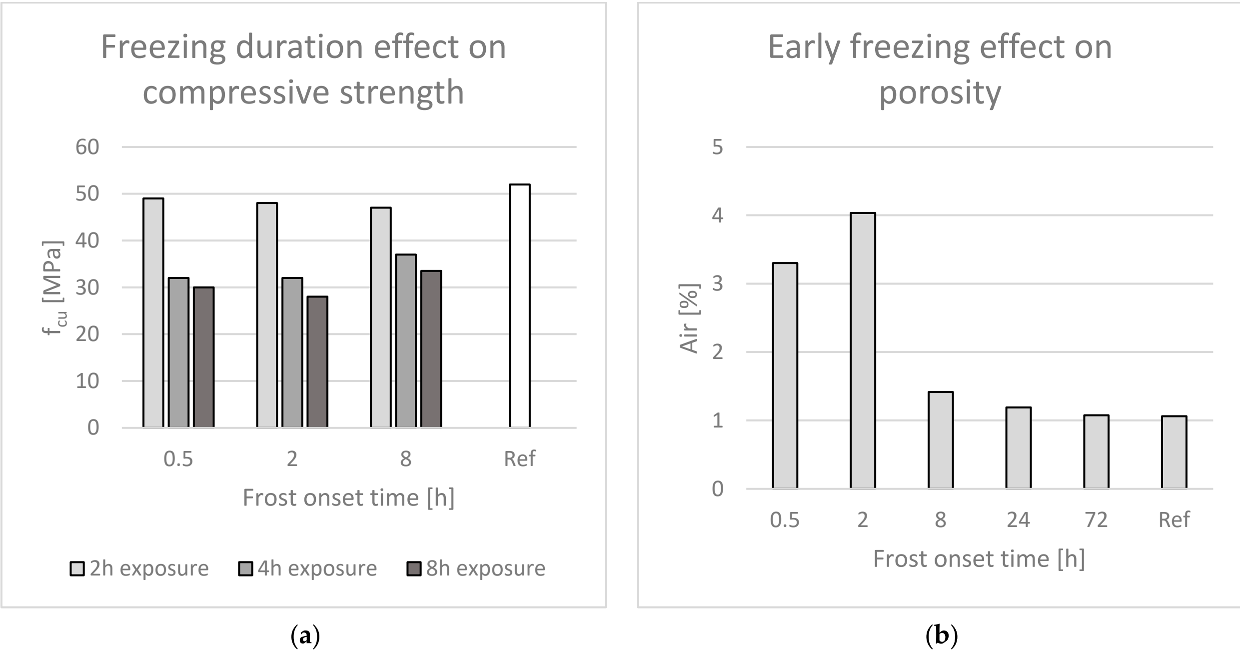


Figure 6. Effect of early freezing with different frost onset times and durations on concrete strength properties. The frost duration was 8 h and the temperatures were between −1 and −9 °C. Reproduced with data from [114]. (**a**) Compressive strength of early frost affected concrete with onset times 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].

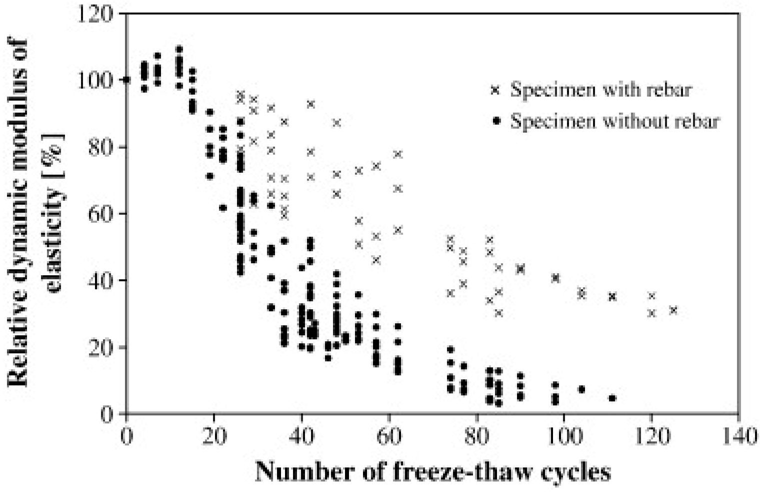
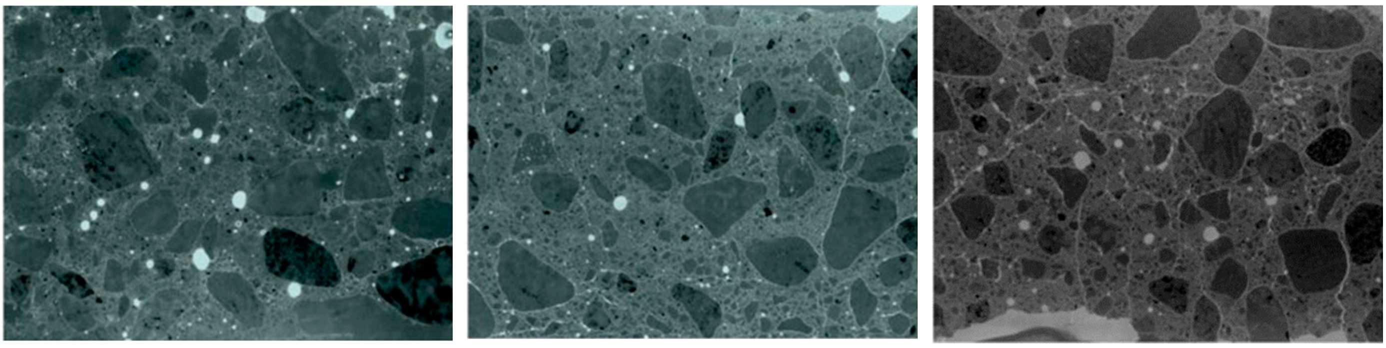


Figure 7. Reduced E-modulus due to repeated freeze–thaw cycles [124].



(**a**) (**b**) (**c**)

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].

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

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].

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

3. Materials, Technologies, and Strategies for Cold Weather

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.

Drainage and Waterproofing	
Drainage	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].
Waterproofing and protective coatings	Applying waterproofing 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.

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.

Adjusting the Mix Design	
Water–cement ratio	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].
Air entrainment	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].
Supplementary Cementitious Materials (SCMs)	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].

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 nano-titanium 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.

Cold Weather Concreting Practices	
Preheated ingredients	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.
Accelerating admixtures	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].
Temperature monitoring and control	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].

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.

Protection and Insulation	
Insulating blankets or covers	Providing adequate insulation for the concrete during setting and curing can help maintain the necessary temperature and moisture levels for optimal curing [189]. Insulating blankets or covers can protect the concrete from freezing temperatures, preventing early freezing and thereby preventing frost damage [188].
Heated enclosures	In very low, freezing temperatures, enclosures can be used to provide a controlled environment for concrete placement and curing [190]. The enclosures are typically equipped with heating systems, such as propane or electric heaters [191]. These enclosures can thereby maintain the temperature and humidity required for proper curing, minimizing the risk of frost-related problems.
Insulated concrete forms	Insulated formwork systems, such as insulated concrete forms (ICFs) or insulated sandwich panels, can provide a protective thermal barrier for concrete during placement and curing [192]. These systems can help maintain the necessary temperature for proper curing and strength development while also improving the energy efficiency of the finished structure.

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.

4. Emerging Materials, Technologies, and Strategies

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.

Smart Concrete Materials and Production Technologies	
Self-healing concrete	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].
Phase change materials	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].
Carbon capture, utilization, and storage technologies	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].

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.

Advanced Manufacturing and Construction Technologies for Concrete	
3D printing	3D printing technology offers the potential to revolutionize the production of concrete elements and structures [216]. By enabling precise and automated fabrication of complex or custom-designed components, 3D printing provides opportunities to reduce labor costs, minimize material waste, and improve the overall quality and performance of concrete structures [217].
Robotic construction	The use of robotic systems in the construction industry can help improve efficiency, reduce labor costs, and enhance quality and performance [218]. Robotic systems can be used for a range of construction tasks, such as concrete placement [219], reinforcement installation [220], and formwork assembly [221], helping to streamline construction processes and ensure consistent quality and performance.
Modular and prefabricated construction	Modular and prefabricated construction techniques involve the off-site production and assembly of concrete components [222]. These production techniques can help improve the efficiency and performance of concrete construction in low temperature environments [223]. By applying modular or prefabrication technologies, the construction industry can reduce on-site labor requirements, minimize weather-related delays, and ensure consistent quality and performance [224].

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.

Integrated Design and Optimization Technologies	
Building information modeling	Building information modeling (BIM) is a digital representation of the physical and functional characteristics of a building or infrastructure, enabling the integration of design, construction, and management processes [229]. BIM can help improve the efficiency, performance, and sustainability of concrete construction in cold weather by facilitating better coordination and communication among project stakeholders [227], optimizing material selection and construction techniques [229], and predicting potential issues related to frost damage, freeze–thaw cycles, or other cold weather-related challenges [230].
Artificial intelligence and machine learning	Artificial intelligence (AI) and machine learning technologies offer significant potential for improving the efficiency, performance, and durability of concrete construction and structures [231]. These technologies can help to optimize concrete mix designs [232], predict the performance of concrete materials and structures under various environmental conditions [233], and develop more efficient construction processes and techniques [234].
Digital twins	The digital twin technology involves the creation of a virtual replica of a physical asset or system [235], allowing for real-time monitoring, analysis, and optimization of its performance [236]. Digital twins can be used to model and predict the behavior of concrete structures in cold weather environments, enabling the use and development of more resilient and efficient construction techniques and materials [237].

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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References

1. Statista. Global Cement Production from 1995 to 2022. Available online: https://www.statista.com/statistics/219343/cement-production-worldwide/ (accessed on 27 April 2023).
2. Monteiro, P.J.; Miller, S.A.; Horvath, A. Towards sustainable concrete. *Nat. Mater.* **2017**, *16*, 698–699. [CrossRef]
3. Demissew, A. Comparative analysis of selected concrete mix design methods based on cost-effectiveness. *Adv. Civ. Eng.* **2022**, *2022*, 4240774. [CrossRef]
4. Tang, S.W.; Yao, Y.; Andrade, C.; Li, Z.J. Recent durability studies on concrete structure. *Cem. Concr. Res.* **2015**, *78*, 143–154. [CrossRef]
5. Mather, B. Concrete durability. *Cem. Concr. Compos.* **2004**, *26*, 3–4. [CrossRef]
6. Mathews, M.E.; Nandhagopal, M.; Anand, N.; Arulraj, G.P. Versatility at its best: An integrated review on development of self-compacting concrete. *Int. J. Sci. Tech. Res.* **2019**, *8*, 513–519.
7. Hegger, J.; Curbach, M.; Stark, A.; Wilhelm, S.; Farwig, K. Innovative design concepts: Application of textile reinforced concrete to shell structures. *Struct. Concr.* **2018**, *19*, 637–646. [CrossRef]
8. Kozikowski, R.L.; McCall, W.C.; Suprenant, B.A. Cold weather concreting strategies. *Concr. Internat.* **2014**, *36*, 45–49.
9. Korhonen, C. New developments in cold-weather concreting. In Proceedings of the 11th International Conference on Cold Regions Engineering, Anchorage, AK, USA, 20–22 May 2002.
10. Nmai, C.K. Cold weather concreting admixtures. *Cem. Concr. Compos.* **1998**, *20*, 121–128. [CrossRef]
11. Barna, L.A.; Seman, P.M.; Korhonen, C.J. Energy-efficient approach to cold-weather concreting. *J. Mater. Civ. Eng.* **2011**, *23*, 1544–1551. [CrossRef]
12. Chen, S.; Lu, W.; Olofsson, T.; Dehghanimohammadabadi, M.; Emborg, M.; Nilimaa, J.; Wang, Y.; Feng, K. Concrete Construction: How to Explore Environmental and Economic Sustainability in Cold Climates. *Sustainability* **2020**, *12*, 3809. [CrossRef]
13. Ritchie, H.; Roser, M. Urbanization. Available online: https://ourworldindata.org/urbanization (accessed on 29 April 2023).
14. Roser, M.; Ritchie, H.; Ortiz-Ospina, E.; Rodés-Guirao, L. World Population Growth. Available online: https://ourworldindata.org/world-population-growth (accessed on 29 April 2023).
15. Ryou, J.S.; Lee, Y.S. Properties of early-stage concrete with setting-accelerating tablet in cold weather. *Mater. Sci. Eng. A* **2012**, *532*, 84–90. [CrossRef]
16. Liu, Y.; Tian, W.; Ma, G. Electric activation curing behaviour of reinforced concrete beam under severely-cold environment: Breakthrough of rapid concrete manufacturing at cold region. *Constr. Build. Mater.* **2023**, *384*, 131443. [CrossRef]
17. Ortiz, J.; Aguado, A.; Agulló, L.; Garcia, T. Influence of environmental temperatures on the concrete compressive strength: Simulation of hot and cold weather conditions. *Cem. Concr. Res.* **2005**, *35*, 1970–1979. [CrossRef]
18. Nilimaa, J.; Zhaka, V. Material and Environmental Aspects of Concrete Flooring in Cold Climate. *Constr. Mater.* **2023**, *3*, 180–201. [CrossRef]
19. Şahin, Y.; Akkaya, Y.; Taşdemir, M.A. Effects of freezing conditions on the frost resistance and microstructure of concrete. *Constr. Build. Mater.* **2021**, *270*, 121458. [CrossRef]
20. Sang, Y.; Yang, Y. Assessing the freezing process of early age concrete by resistivity method. *Constr. Build. Mater.* **2020**, *238*, 117689. [CrossRef]
21. Wang, R.; Hu, Z.; Li, Y.; Wang, K.; Zhang, H. Review on the deterioration and approaches to enhance the durability of concrete in the freeze–thaw environment. *Constr. Build. Mater.* **2022**, *321*, 126371. [CrossRef]

22. Chen, H.; Cao, Y.; Liu, Y.; Qin, Y.; Xia, L. Enhancing the durability of concrete in severely cold regions: Mix proportion optimization based on machine learning. *Constr. Build. Mater.* **2023**, *371*, 130644. [CrossRef]
23. Demirboğa, R.; Karagöl, F.; Polat, R.; Kaygusuz, M.A. The effects of urea on strength gaining of fresh concrete under the cold weather conditions. *Constr. Build. Mater.* **2014**, *64*, 114–120. [CrossRef]
24. Kothari, A.; Habermehl-Cwirzen, K.; Hedlund, H.; Cwirzen, A. A Review of the Mechanical Properties and Durability of Ecological Concretes in a Cold Climate in Comparison to Standard Ordinary Portland Cement-Based Concrete. *Materials* **2020**, *13*, 3467. [CrossRef]
25. Qu, Z.; Yu, Q.; Ong, G.P.; Cardinaels, R.; Ke, L.; Long, Y.; Geng, G. 3D printing concrete containing thermal responsive gelatin: Towards cold environment applications. *Cem. Concr. Compos.* **2023**, *140*, 105029. [CrossRef]
26. Han, B.; Wang, Y.; Dong, S.; Zhang, L.; Ding, S.; Yu, X.; Ou, J. Smart concretes and structures: A review. *J. Intell. Mater. Syst. Struct.* **2015**, *26*, 1303–1345. [CrossRef]
27. Golroo, A.; Tighe, S.L. Pervious concrete pavement performance modeling: An empirical approach in cold climates. *Can. J. Civ. Eng.* **2012**, *39*, 1100–1112. [CrossRef]
28. Provost-Smith, D.J.; Elsayed, M.; Nehdi, M.L. Effect of early-age subfreezing temperature on grouted dowel precast concrete wall connections. *Constr. Build. Mater.* **2017**, *140*, 385–394. [CrossRef]
29. Shlyakhtina, T.F.; Ivankova, E.A.; Popov, N.A. Winter concrete: Problems and solutions. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *75*, 012081. [CrossRef]
30. Sakai, K.; Banthia, N. Integrated Design of Concrete Structures and Technology Development. In *Concrete Technology for a Sustainable Development in the 21st Century*; E&FN Spon: London, UK, 2000; pp. 14–26.
31. Shelehov, I.J.; Dorofeeva, N.L.; Shelehov, M.I.; Dorofeev, I.A. Optimization of concrete works technological process in the winter period. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *751*, 012080. [CrossRef]
32. Sanz-Valle, R.; Naranjo-Valencia, J.C.; Jiménez-Jiménez, D.; Perez-Caballero, L. Linking organizational learning with technical innovation and organizational culture. *J. Knowl. Manage.* **2011**, *15*, 997–1015. [CrossRef]
33. Santiago, P. Achieving Sustainability in Construction Through Digitally Informed Decisions. In *Industry 4.0 for the Built Environment: Methodologies, Technologies and Skills*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 247–269. [CrossRef]
34. Schindler, A.K. Prediction of concrete setting. In Proceedings of the RILEM International Symposium on Advances in Concrete through Science and Engineering, Evanston, IL, USA, 25 March 2004.
35. Hu, J.; Ge, Z.; Wang, K. Influence of cement fineness and water-to-cement ratio on mortar early-age heat of hydration and set times. *Constr. Build. Mater.* **2014**, *50*, 657–663. [CrossRef]
36. Yang, K.H.; Moon, G.D.; Jeon, Y.S. Implementing ternary supplementary cementing binder for reduction of the heat of hydration of concrete. *J. Clean. Product.* **2016**, *112*, 845–852. [CrossRef]
37. Schindler, A.K. Concrete Hydration, Temperature Development, and Setting at Early-Ages. Ph.D. Thesis, The University of Texas at Austin, Austin, TX, USA, May 2002.
38. Wade, S.A.; Nixon, J.M.; Schindler, A.K.; Barnes, R.W. Effect of temperature on the setting behavior of concrete. *J. Mater. Civ. Eng.* **2010**, *22*, 214–222. [CrossRef]
39. Chen, Y.; Okudan, G.E.; Riley, D.R. Sustainable performance criteria for construction method selection in concrete buildings. *Autom. Constr.* **2010**, *19*, 235–244. [CrossRef]
40. Lee, T.; Lee, J.; Kim, Y. Effects of admixtures and accelerators on the development of concrete strength for horizontal form removal upon curing at 10 C. *Constr. Build. Mater.* **2020**, *237*, 117652. [CrossRef]
41. Carette, J.; Staquet, S. Monitoring the setting process of eco-binders by ultrasonic P-wave and S-wave transmission velocity measurement: Mortar vs concrete. *Constr. Build. Mater.* **2016**, *110*, 32–41. [CrossRef]
42. Li, W.; Lin, X.; Bao, D.W.; Xie, Y.M. A review of formwork systems for modern concrete construction. *Structures* **2022**, *38*, 52–63. [CrossRef]
43. Krawczyńska-Piechna, A. Comprehensive approach to efficient planning of formwork utilization on the construction site. *Proc. Eng.* **2017**, *182*, 366–372. [CrossRef]
44. Schindler, A.K.; Frank McCullough, B. Importance of concrete temperature control during concrete pavement construction in hot weather conditions. *Transp. Res. Rec.* **2002**, *1813*, 3–10. [CrossRef]
45. Liu, J.; Lee, Y.C.; Bard, J. Material characterization of workability and process imaging for robotic concrete finishing. *Constr. Robotics* **2021**, *5*, 73–85. [CrossRef]
46. Karagöl, F.; Demirboğa, R.; Kaygusuz, M.A.; Yadollahi, M.M.; Polat, R. The influence of calcium nitrate as antifreeze admixture on the compressive strength of concrete exposed to low temperatures. *Cold Reg. Sci. Tech.* **2013**, *89*, 30–35. [CrossRef]
47. Aslani, A.; Hachem-Vermette, C. Energy and environmental assessment of high-performance building envelope in cold climate. *Energy Build.* **2022**, *260*, 111924. [CrossRef]
48. Lin, M.C.; Tserng, H.P.; Ho, S.P.; Young, D.L. Developing a construction-duration model based on a historical dataset for building project. *J. Civ. Eng. Managem.* **2011**, *17*, 529–539. [CrossRef]
49. Saravanan, T.J.; Balamonica, K.; Priya, C.B.; Reddy, A.L.; Gopalakrishnan, N. Comparative performance of various smart aggregates during strength gain and damage states of concrete. *Smart Mater. Struct.* **2015**, *24*, 085016. [CrossRef]
50. Taylor, P.C. *Curing Concrete*; CRC Press: Boca Raton, FL, USA, 2013.

51. Hassan, A.; Arif, M.; Shariq, M. Effect of curing condition on the mechanical properties of fly ash-based geopolymer concrete. *SN Appl. Sci.* **2019**, *1*, 1694. [CrossRef]
52. Hover, K.C. The influence of water on the performance of concrete. *Constr. Build. Mater.* **2011**, *25*, 3003–3013. [CrossRef]
53. Chyliński, F.; Michalik, A.; Kozicki, M. Effectiveness of Curing Compounds for Concrete. *Materials* **2022**, *15*, 2699. [CrossRef]
54. Al-Gahtani, A.S. Effect of curing methods on the properties of plain and blended cement concretes. *Constr. Build. Mater.* **2010**, *24*, 308–314. [CrossRef]
55. Raheem, A.A.; Soyingbe, A.A.; Emenike, A.J. Effect of curing methods on density and compressive strength of concrete. *Int. J. Appl. Sci. Technol.* **2013**, *3*, 55–64.
56. Huo, X.S.; Wong, L.U. Experimental study of early-age behavior of high performance concrete deck slabs under different curing methods. *Constr. Build. Mater.* **2006**, *20*, 1049–1056. [CrossRef]
57. Tang, Y.; Su, H.; Huang, S.; Qu, C.; Yang, J. Effect of curing temperature on the durability of concrete under highly geothermal environment. *Adv. Mater. Sci. Eng.* **2017**, *2017*, 7587853. [CrossRef]
58. Kodur, V.K.R.; Bhatt, P.P.; Soroushian, P.; Arablouei, A. Temperature and stress development in ultra-high performance concrete during curing. *Constr. Build. Mater.* **2016**, *122*, 63–71. [CrossRef]
59. Li, W.; Huang, Z.; Hu, G.; Duan, W.H.; Shah, S.P. Early-age shrinkage development of ultra-high-performance concrete under heat curing treatment. *Constr. Build. Mater.* **2017**, *131*, 767–774. [CrossRef]
60. Nilimaa, J.; Hösthagen, A.; Emborg, M. Thermal Crack Risk of Concrete Structures: Evaluation of Theoretical Models for Tunnels and Bridges. *Nordic Concr. Res.* **2017**, *56*, 55–69. Available online: http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-64967 (accessed on 16 May 2023).
61. Zeyad, A.M.; Tayeh, B.A.; Adesina, A.; de Azevedo, A.R.; Amin, M.; Hadzima-Nyarko, M.; Agwa, I. SReview on effect of steam curing on behavior of concrete. *Clean. Mater.* **2022**, *3*, 100042. [CrossRef]
62. Duan, Y.; Wang, Q.; Yang, Z.; Cui, X.; Liu, F.; Chen, H. Research on the effect of steam curing temperature and duration on the strength of manufactured sand concrete and strength estimation model considering thermal damage. *Constr. Build. Mater.* **2022**, *315*, 125531. [CrossRef]
63. Otieno, M.; Ikotun, J.; Ballim, Y. Experimental investigations on the effect of concrete quality, exposure conditions and duration of initial moist curing on carbonation rate in concretes exposed to urban, inland environment. *Constr. Build. Mater.* **2017**, *246*, 118443. [CrossRef]
64. Yu, K.; Jia, M.; Yang, Y.; Liu, Y. A clean strategy of concrete curing in cold climate: Solar thermal energy storage based on phase change material. *Appl. Ener.* **2021**, *331*, 120375. [CrossRef]
65. Jana, D. Concrete scaling—A critical review. In Proceedings of the 29th Conference on Cement Microscopy, Quebec City, QC, Canada, 20–24 May 2007.
66. Wang, W.C.; Duong, H.T.H.; Zhang, C.H. Influence of accelerating admixtures on high early strength cement performance using heat curing method. *Case Stud. Constr. Mater.* **2023**, *18*, e01746. [CrossRef]
67. Ren, G.; Tian, Z.; Wu, J.; Gao, X. Effects of combined accelerating admixtures on mechanical strength and microstructure of cement mortar. *Constr. Build. Mater.* **2021**, *304*, 124642. [CrossRef]
68. Tan, K.; Gjorv, O.E. Performance of concrete under different curing conditions. *Cem. Concr. Res.* **1996**, *26*, 355–361. [CrossRef]
69. Bagheri-Zadeh, S.H.; Kim, H.; Hounsell, S.; Wood, C.R.; Soleymani, H.; King, M. Field study of concrete maturity methodology in cold weather. *J. Constr. Eng. Manage.* **2007**, *133*, 827–835. [CrossRef]
70. Pushpalal, D.; Danzandorj, S.; Bayarjavkhlan, N.; Nishiwaki, T.; Yamamoto, K. Compressive strength development and durability properties of high-calcium fly ash incorporated concrete in extremely cold weather. *Constr. Build. Mater.* **2022**, *316*, 125801. [CrossRef]
71. Wang, D.; Shi, C.; Wu, Z.; Xiao, J.; Huang, Z.; Fang, Z. A review on ultra high performance concrete: Part II. Hydration, microstructure and properties. *Constr. Build. Mater.* **2015**, *96*, 368–377. [CrossRef]
72. Huang, H.; Huang, T.; Yuan, Q.; Zhou, D.; Deng, D.; Zhang, L. Temperature dependence of structural build-up and its relation with hydration kinetics of cement paste. *Constr. Build. Mater.* **2019**, *201*, 553–562. [CrossRef]
73. El-Mir, A.; Assaad, J.J.; Nehme, S.G.; El-Hassan, H. Correlating strength and durability to time-temperature profiles of high-performance mass concrete. *Case Stud. Constr. Mater.* **2022**, *16*, e01055. [CrossRef]
74. Alqarni, A.S. A comprehensive review on properties of sustainable concrete using volcanic pumice powder ash as a supplementary cementitious material. *Constr. Build. Mater.* **2022**, *323*, 126533. [CrossRef]
75. Wang, T.; Ishida, T.; Gu, R.; Luan, Y. Experimental investigation of pozzolanic reaction and curing temperature-dependence of low-calcium fly ash in cement system and Ca-Si-Al element distribution of fly ash-blended cement paste. *Constr. Build. Mater.* **2021**, *267*, 121012. [CrossRef]
76. Shobeiri, V.; Bennett, B.; Xie, T.; Visintin, P. A comprehensive assessment of the global warming potential of geopolymer concrete. *J. Cleaner Prod.* **2021**, *297*, 126669. [CrossRef]
77. Hooton, R.D. Future directions for design, specification, testing, and construction of durable concrete structures. *Cem. Concr. Res.* **2019**, *124*, 105827. [CrossRef]
78. Asamoto, S.; Kurashige, I.; Chun, P.J. Effect of high temperature at early ages on drying shrinkage and creep of concrete focusing on microcracking damage. *Mater. Struct.* **2023**, *56*, 67. [CrossRef]

79. Alexander, M.; Beushausen, H. Durability, service life prediction, and modelling for reinforced concrete structures–review and critique. *Cem. Concr. Res.* **2019**, *122*, 17–29. [CrossRef]
80. Zheng, Y.; Yang, J.; Liao, B.; Ma, S.; Zhong, H.; Lei, J. Investigation on the concrete strength performance of underlying tunnel structure subjected to train-induced dynamic loads at an early age. *Constr. Build. Mater.* **2022**, *337*, 127622. [CrossRef]
81. Lee, T.; Lee, J. Setting time and compressive strength prediction model of concrete by nondestructive ultrasonic pulse velocity testing at early age. *Constr. Build. Mater.* **2020**, *252*, 119027. [CrossRef]
82. Bui, D.C.; Nakarai, K.; Nishikawa, H. Effects of early-age thermal microcracking on material properties and structural performance of limestone aggregate concrete. *Cem. Concr. Res.* **2021**, *124*, 104267. [CrossRef]
83. Zheng, X.; Wang, Y.; Zhang, S.; Xu, F.; Zhu, X.; Jiang, X.; Zhou, L.; Shen, Y.; Chen, Q.; Yan, Z.; et al. Research progress of the thermophysical and mechanical properties of concrete subjected to freeze-thaw cycles. *Constr. Build. Mater.* **2022**, *330*, 127254. [CrossRef]
84. Figueira, R.B.; Sousa, R.; Coelho, L.; Azenha, M.; de Almeida, J.M.; Jorge, P.A.S.; Silva, C.J.R. Alkali-silica reaction in concrete: Mechanisms, mitigation and test methods. *Constr. Build. Mater.* **2019**, *222*, 903–931. [CrossRef]
85. Zhang, F.; Hu, Z.; Dai, L.; Wen, X.; Wang, R.; Zhang, D.; Song, X. Study on Corrosion Mechanism of Different Concentrations of Na_2SO_4 Solution on Early-Age Cast-In-Situ Concrete. *Materials* **2021**, *14*, 2018. [CrossRef]
86. Chen, Y.; Matalkah, F.; Rankothge, W.; Balachandra, A.; Soroushian, P. Improvement of the surface quality and aesthetics of ultra-high-performance concrete. *Proc. Inst. Civ. Eng. Constr. Mater.* **2019**, *172*, 246–255. [CrossRef]
87. Zhang, Y.; Yan, D.; Hu, S.; Guo, S. Modelling of energy consumption and carbon emission from the building construction sector in China, a process-based LCA approach. *Energy Policy* **2019**, *134*, 110949. [CrossRef]
88. Sharifi, E.; Sadjadi, S.J.; Aliha, M.R.M.; Moniri, A. Optimization of high-strength self-consolidating concrete mix design using an improved Taguchi optimization method. *Constr. Build. Mater.* **2020**, *236*, 117547. [CrossRef]
89. Nguyen, D.H.; Nguyen, V.T.; Lura, P.; Dao, V.T. Temperature-stress testing machine–A state-of-the-art design and its unique applications in concrete research. *Cem. Concr. Res.* **2019**, *102*, 28–38. [CrossRef]
90. Choi, H.; Inoue, M.; Choi, H.; Kim, J.; Sudoh, Y.; Kwon, S.; Lee, B.; Yoneyama, A. Physicochemical Study on the Strength Development Characteristics of Cold Weather Concrete Using a Nitrite–Nitrate Based Accelerator. *Materials* **2019**, *12*, 2706. [CrossRef]
91. Nandhini, K.; Karthikeyan, J. The early-age prediction of concrete strength using maturity models: A review. *J. Build. Rehabil.* **2021**, *6*, 1–10. [CrossRef]
92. Nepomuceno, M.C.S.; Bernardo, L.F.A. Evaluation of Self-Compacting Concrete Strength with Non-Destructive Tests for Concrete Structures. *Appl. Sci.* **2019**, *9*, 5109. [CrossRef]
93. Kurihashi, Y.; Konno, H.; Hama, Y. Effects of frost-damaged reinforced concrete beams on their impact resistance behavior. *Constr. Build. Mater.* **2020**, *274*, 122089. [CrossRef]
94. Wang, Z.; Gong, F.; Ueda, T. Modeling and simulation on static and fatigue behaviors of intact and frost damaged concrete with ice-strengthening effects. *J. Adv. Concr. Technol.* **2021**, *19*, 346–358. [CrossRef]
95. Mao, J.; Jia, H.; Wu, K.; Wang, Q.; Li, S.; Qian, W.; Xiong, F. A novel method to prevent frost cracking of perforated concrete components in cold regions. *Cold Reg. Sci. Technol.* **2023**, *211*, 103848. [CrossRef]
96. Wang, Z.; Gong, F.; Zhang, D.; Wang, Y.; Ueda, T. RBSM based analysis on mechanical degradation of non-air entrained concrete under frost action–A general prediction with various water cement ratio, lowest temperatures and FTC numbers. *Constr. Build. Mater.* **2019**, *211*, 744–755. [CrossRef]
97. Deng, X.; Gao, X.; Wang, R.; Gao, M.; Yan, X.; Cao, W.; Liu, J. Investigation of microstructural damage in air-entrained recycled concrete under a freeze–thaw environment. *Constr. Build. Mater.* **2021**, *268*, 121219. [CrossRef]
98. Wang, Y.; Liu, Z.; Fu, K.; Li, Q.; Wang, Y. Experimental studies on the chloride ion permeability of concrete considering the effect of freeze–thaw damage. *Constr. Build. Mater.* **2020**, *236*, 117556. [CrossRef]
99. Yuan, J.; Du, Z.; Wu, Y.; Xiao, F. Freezing-thawing resistance evaluations of concrete pavements with deicing salts based on various surfaces and air void parameters. *Constr. Build. Mater.* **2019**, *204*, 317–326. [CrossRef]
100. Liu, R.; Xiao, H.; Liu, J.; Guo, S.; Pei, Y. Improving the microstructure of ITZ and reducing the permeability of concrete with various water/cement ratios using nano-silica. *J. Mater. Sci.* **2019**, *54*, 444–456. [CrossRef]
101. Zhi, D.; Gong, F.; Wang, Z.; Zhao, Y.; Ueda, T. RBSM-based mesoscale study of frost deterioration for recycled concrete considering air-entrainment in old and new mortar. *J. Build. Eng.* **2023**, *68*, 106210. [CrossRef]
102. Yan, W.; Wu, Z.; Niu, F.; Wan, T.; Zheng, H. Study on the service life prediction of freeze–thaw damaged concrete with high permeability and inorganic crystal waterproof agent additions based on ultrasonic velocity. *Constr. Build. Mater.* **2020**, *259*, 120405. [CrossRef]
103. Zhang, G.; Yu, H.; Li, H.; Yang, Y. Experimental study of deformation of early age concrete suffering from frost damage. *Constr. Build. Mater.* **2019**, *215*, 410–421. [CrossRef]
104. Konzilia, J.; Egger, M.; Feix, J. Experimental investigation on salt frost scaling of textile-reinforced concrete. *Struct. Concr.* **2022**, *23*, 954–969. [CrossRef]
105. Zeiml, M.; Leithner, D.; Lackner, R.; Mang, H.A. How do polypropylene fibers improve the spalling behavior of in-situ concrete? *Cem. Concr. Res.* **2006**, *36*, 929–942. [CrossRef]

106. Rosenqvist, M. Frost-Induced Deterioration of Concrete in Hydraulic Structures: Interactions between Water Absorption, Leaching and Frost Action. Ph.D. Thesis, Lund University, Lund, Sweden, 14 September 2016. Available online: https://lup.lub.lu.se/record/dfac7b31-229a-4d1d-a02e-43258ce060f4 (accessed on 27 April 2023).
107. Adachi, Y.; Hirakawa, H.; Fukushima, A.; Uematsu, T.; Kikuta, K.; Taniguchi, M. Investigation of the Deterioration of Medium-Rise-Wall Type Reinforced Concrete Buildings with External Insulation in Snowy Cold Districts. *Buildings* **2022**, *12*, 2048. [CrossRef]
108. Wang, R.; Zhang, Q.; Li, Y. Deterioration of concrete under the coupling effects of freeze–thaw cycles and other actions: A review. *Constr. Build. Mater.* **2022**, *319*, 126045. [CrossRef]
109. Zhang, L.; Ma, R.; Lai, J.; Ruan, S.; Qian, X.; Yan, D.; Qian, K.; Wang, S. Performance buildup of concrete cured under low-temperatures: Use of a new nanocomposite accelerator and its application. *Constr. Build. Mater.* **2022**, *335*, 127529. [CrossRef]
110. Yuan, J.; Huang, X.; Chen, X.; Ge, Q.; Zhang, Z. Early-age mechanical properties and hydration degrees of magnesium phosphate cement paste in freezing winter of cold regions. *Constr. Build. Mater.* **2022**, *345*, 128337. [CrossRef]
111. Jamolovich, T.U. Modern methods for controlling the strength of concrete in the structures of monolithic buildings. *Acad. Globe Indersci. Res.* **2022**, *3*, 588–595. [CrossRef]
112. Wang, Y.; Lei, L.; Liu, J.; Ma, Y.; Liu, Y.; Xiao, Z.; Shi, C. Accelerators for normal concrete: A critical review on hydration, microstructure and properties of cement-based materials. *Cem. Concr. Compos.* **2022**, *134*, 104762. [CrossRef]
113. Zhang, C.; Liu, T.; Jiang, C.; Chen, Z.; Zhou, K.; Chen, L. The Freeze-Thaw Strength Evolution of Fiber-Reinforced Cement Mortar Based on NMR and Fractal Theory: Considering Porosity and Pore Distribution. *Materials* **2022**, *15*, 7316. [CrossRef] [PubMed]
114. Hu, X.; Peng, G.; Niu, D.; Zhao, N. Damage study on service performance of early-age frozen concrete. *Constr. Build. Mater.* **2019**, *210*, 22–31. [CrossRef]
115. Regan, E.E.; O'Brien, S.M. Exposing Exposed Concrete—Design, Construction, and Maintenance Considerations for Success. In Proceedings of the Ninth Congress on Forensic Engineering, Denver, CO, USA, 4–7 November 2022; pp. 111–120. [CrossRef]
116. Guler, S.; Akbulut, Z.F. Effect of freeze-thaw cycles on strength and toughness properties of new generation 3D/4D/5D steel fiber-reinforced concrete. *J. Build.Eng.* **2022**, *51*, 104239. [CrossRef]
117. Xu, Y.; Ye, H.; Yuan, Q.; Shi, C.; Gao, Y.; Fu, Q. The durability of concrete subject to mechanical load coupled with freeze–thaw cycles: A review. *Arch. Civ. Mech. Eng.* **2022**, *22*, 47. [CrossRef]
118. Al-Rashed, R.; Al-Jabari, M. Managing Thermal Effects in Waterproofed Concrete with Multi-Crystallization Enhancer. *Cement* **2022**, *10*, 100050. [CrossRef]
119. Qiu, W.L.; Teng, F.; Pan, S.S. Damage constitutive model of concrete under repeated load after seawater freeze-thaw cycles. *Constr. Build. Mater.* **2020**, *236*, 117560. [CrossRef]
120. Lu, Z.; Feng, Z.G.; Yao, D.; Li, X.; Ji, H. Freeze-thaw resistance of Ultra-High performance concrete: Dependence on concrete composition. *Constr. Build. Mater.* **2021**, *293*, 123523. [CrossRef]
121. Al-Kheetan, M.J.; Al-Tarawneh, M.A.; Ghaffar, S.H.; Chougan, M.; Jweihan, Y.S.; Rahman, M.M. Resistance of hydrophobic concrete with different moisture contents to advanced freeze–thaw cycles. *Struct. Concr.* **2021**, *22*, E1050–E1061. [CrossRef]
122. Santana Rangel, C.; Amario, M.; Pepe, M.; Martinelli, E.; Toledo Filho, R.D. Durability of Structural Recycled Aggregate Concrete Subjected to Freeze-Thaw Cycles. *Sustainability* **2020**, *12*, 6475. [CrossRef]
123. Ma, H.; Yu, H.; Da, B.; Tan, Y. Study on failure mechanism of concrete subjected to freeze-thaw condition in airport deicers. *Constr. Build. Mater.* **2021**, *313*, 125202. [CrossRef]
124. Hanjari, K.Z.; Utgenannt, P.; Lundgren, K. Experimental study of the material and bond properties of frost-damaged concrete. *Cem. Concr. Res.* **2011**, *41*, 244–254. [CrossRef]
125. Song, H.; Yao, J.; Xiang, J. The role of aggregate and cement paste in the deterioration of the transitional interface zone of pervious concrete during freeze-thaw cycles. *Case Stud. Constr. Mater.* **2022**, *16*, e01086. [CrossRef]
126. Jiang, J.; Yang, H.; Deng, Z.; Li, Z. Bond performance of deformed rebar embedded in recycled aggregate concrete subjected to repeated loading after freeze–thaw cycles. *Constr. Build. Mater.* **2022**, *318*, 125954. [CrossRef]
127. Suzuki, T.; Nishimura, S.; Shimamoto, Y.; Shiotani, T.; Ohtsu, M. Damage estimation of concrete canal due to freeze and thawed effects by acoustic emission and X-ray CT methods. *Constr. Build. Mater.* **2020**, *245*, 118343. [CrossRef]
128. Faheem, A.; Hasholt, M.T. The effect of temperature distribution in mortar on frost scaling. *Cem. Concr. Res.* **2022**, *157*, 106824. [CrossRef]
129. Liu, Z.; Li, L.; Gao, J.; Li, Y.; Lou, B.; Maria Barbieri, D.; Ye, T.; Sha, A. Frost-Related Damage of Portland Cement Pastes at Early Age. *J. Mater. Civ. Eng.* **2023**, *35*, 04023020. [CrossRef]
130. Karthick, S.; Kermanshachi, S.; Pamidimukkala, A.; Namian, M. A review of construction workforce health challenges and strategies in extreme weather conditions. *Int. J. Occup. Safety Ergo.* **2023**, *29*, 773–784. [CrossRef]
131. Ballesteros-Pérez, P.; Rojas-Céspedes, Y.A.; Hughes, W.; Kabiri, S.; Pellicer, E.; Mora-Melià, D.; del Campo-Hitschfeld, M.L. Weather-wise: A weather-aware planning tool for improving construction productivity and dealing with claims. *Autom. Constr.* **2017**, *84*, 81–95. [CrossRef]
132. Karthick, S.; Kermanshachi, S.; Ramaji, I. Health and safety of construction field workforce active in extreme weather conditions. In Proceedings of the Construction Research Congress, Arlington, TX, USA, 9–12 March 2022; pp. 737–747. [CrossRef]
133. Apipattanavis, S.; Sabol, K.; Molenaar, K.R.; Rajagopalan, B.; Xi, Y.; Blackard, B.; Patil, S. Integrated framework for quantifying and predicting weather-related highway construction delays. *J. Constr. Eng. Mana.* **2010**, *136*, 1160–1168. [CrossRef]

134. Raymond, D.L. A Synopsis of Cold Weather Operation Problems of Engine Powered Equipment Experienced in the Northern States and Border Areas of Canada. *SAE Tech. Paper* **1965**, 650935. [CrossRef]
135. Jaguemont, J.; Boulon, L.; Dubé, Y. A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures. *Appl. Energy* **2016**, *164*, 99–114. [CrossRef]
136. Edwards, K.L. Selecting materials for optimum use in engineering components. *Mater. Design* **2005**, *26*, 469–473. [CrossRef]
137. Huang, D.; Chen, Z.; Zhou, S. Self-powered heating strategy for lithium-ion battery pack applied in extremely cold climates. *Energy* **2022**, *239*, 122095. [CrossRef]
138. Rahman, M.L.; Malakooti, A.; Ceylan, H.; Kim, S.; Taylor, P.C. A review of electrically conductive concrete heated pavement system technology: From the laboratory to the full-scale implementation. *Constr. Build. Mater.* **2022**, *329*, 127139. [CrossRef]
139. Shin, Y.S.; Kim, G.H. A comparison of the economic feasibility of the protecting tent method and SCSFM method for heat curing of cold-weather concrete. *Appl. Mech. Mater.* **2014**, *651*, 1311–1314. [CrossRef]
140. Harbor, J. Engineering geomorphology at the cutting edge of land disturbance: Erosion and sediment control on construction sites. *Geomorphology* **1999**, *31*, 247–263. [CrossRef]
141. Nan, J.; Liu, J.; Chang, D.; Li, X. Mechanical characteristics and microstructure study of saline soil stabilized by quicklime after curing and freeze-thaw cycle. *Cold Reg. Sci. Tech.* **2022**, *201*, 103625. [CrossRef]
142. Brambilla, A.; Sangiorgio, A. Mould growth in energy efficient buildings: Causes, health implications and strategies to mitigate the risk. *Renew. Sust. Energy Rev.* **2020**, *132*, 110093. [CrossRef]
143. Pokhrel, S.; Amiri, L.; Poncet, S.; Sasmito, A.P.; Ghoreishi-Madiseh, S.A. Renewable heating solutions for buildings; a techno-economic comparative study of sewage heat recovery and solar borehole thermal energy storage system. *Energy Build.* **2022**, *259*, 111892. [CrossRef]
144. Tsagarakis, K.P.; Efthymiou, L.; Michopoulos, A.; Mavragani, A.; Anđelković, A.S.; Antolini, F.; Bacic, M.; Bajare, D.; Baralis, M.; Bogusz, W.; et al. A review of the legal framework in shallow geothermal energy in selected European countries: Need for guidelines. *Renew. Energy* **2020**, *147*, 2556–2571. [CrossRef]
145. Patil, M.; Boraste, S.; Minde, P. A comprehensive review on emerging trends in smart green building technologies and sustainable materials. *Mater. Today Proc.* **2022**, *65*, 1813–1822. [CrossRef]
146. Akeed, M.H.; Qaidi, S.; Ahmed, U.; Faraj, R.H.; Majeed, S.S.; Mohammed, A.S.; Emad, W.; Tayeh, B.A.; Azevedo, A.R. Ultra-high-performance fiber-reinforced concrete. Part V: Mixture design, preparation, mixing, casting, and curing. *Case Stud. Constr. Mater.* **2022**, *17*, e01363. [CrossRef]
147. Ikumi, T.; Salvador, R.P.; Aguado, A. Mix proportioning of sprayed concrete: A systematic literature review. *Tunnel. Undergr. Space Tech.* **2022**, *124*, 104456. [CrossRef]
148. Zhu, Z.G.; Hou, K.P.; Sun, H.F.; Cheng, Y.; Yang, B.J.; Sun, W. Research on the Effect of Curing Temperature, Steel Fiber, and Admixture Content on Concrete Performance Based on Orthogonal Test in Cold Region. *Adv. Mater. Sci. Eng.* **2022**, *2022*, 3671823. [CrossRef]
149. Fu, X.; Zhao, G.; Wang, M.; Wang, J.; Xu, Y.; Gu, C. Comprehensive evaluation method for structural behavior of concrete dams in cold regions. *Eng. Struct.* **2023**, *278*, 115435. [CrossRef]
150. Pan, W.; Zhang, Z. Benchmarking the Sustainability of Concrete and Steel Modular Construction for Buildings in Urban Development. *Sus. Cities Soc.* **2023**, *90*, 104400. [CrossRef]
151. Kia, A.; Wong, H.S.; Cheeseman, C.R. Freeze–thaw durability of conventional and novel permeable pavement replacement. *J. Transp. Eng. B Pavem.* **2022**, *148*, 04022051. [CrossRef]
152. Huang, W.; Wang, H. Multi-aspect engineering properties and sustainability impacts of geopolymer pervious concrete. *Compos. B Eng.* **2022**, *242*, 110035. [CrossRef]
153. Kavitha, R.; Vivekananthan, M.R.; Dhanagopal, K.; Divyabharathi, P.; Prabhakaran, M.; Ramprathap, M. An overview of water proofing system in concrete structures. *Mater. Today Proc.* 2023; *in press*. [CrossRef]
154. Yin, B.; Xu, H.; Fan, F.; Qi, D.; Hua, X.; Xu, T.; Liu, C.; Hou, D. Superhydrophobic coatings based on bionic mineralization for improving the durability of marine concrete. *Constr. Build. Mater.* **2023**, *362*, 129705. [CrossRef]
155. Ayyoob, S.; Zaki, M.; Khan, M.S.; Khan, S.A.; Kamal, M.A. The Efficiency of Waterproofing Agents in Concrete: Assessment of Compressive Strength and Permeability. *Amer. J. Civ. Eng. Arch.* **2022**, *10*, 137–146. [CrossRef]
156. Tang, C.W.; Cheng, C.K.; Ean, L.W. Mix Design and Engineering Properties of Fiber-Reinforced Pervious Concrete Using Lightweight Aggregates. *Appl. Sci.* **2022**, *12*, 524. [CrossRef]
157. Lu, J.X.; Shen, P.; Ali, H.A.; Poon, C.S. Mix design and performance of lightweight ultra high-performance concrete. *Mater. Design* **2022**, *216*, 110553. [CrossRef]
158. Sharbaf, M.; Najimi, M.; Ghafoori, N. A comparative study of natural pozzolan and fly ash: Investigation on abrasion resistance and transport properties of self-consolidating concrete. *Constr. Build. Mater.* **2022**, *346*, 128330. [CrossRef]
159. Ganapathy, G.P.; Keshav, L.; Ravindiran, G.; Razack, N.A. Strength prediction of self-consolidating concrete containing steel fibre with different fibre aspect ratio. *J. Nanomater.* **2022**, *2022*, 7604383. [CrossRef]
160. Liu, X.; Liu, L.; Lyu, K.; Li, T.; Zhao, P.; Liu, R.; Zuo, J.; Fu, F.; Shah, S.P. Enhanced early hydration and mechanical properties of cement-based materials with recycled concrete powder modified by nano-silica. *J. Build. Eng.* **2022**, *50*, 104175. [CrossRef]
161. Liu, Y.; Yang, S.; Li, J.; Wang, F.; Hu, S. Effect of w/c ratio and antifreeze admixture on the frost damage of sulfoaluminate cement concrete at −20 °C. *Const. Build. Mater.* **2022**, *347*, 128457. [CrossRef]

162. Wang, Z.; Wang, X.; Zhu, P.; Liu, H.; Yan, X.; Wei, D. Mix-Proportion Design Methods and Sustainable Use Evaluation of Recycled Aggregate Concrete Used in Freeze–Thaw Environment. *J. Mater. Civ. Eng.* **2023**, *35*, 04022401. [CrossRef]
163. Mardani, A.; Emin, A. Utilization of high-range water reducing admixture having air-entraining agents in cementitious systems. *J. Build. Eng.* **2022**, *64*, 105565. [CrossRef]
164. Zeng, H.; Lai, Y.; Qu, S.; Yu, F. Exploring the effect of graphene oxide on freeze–thaw durability of air-entrained mortars. *Constr. Build. Mater.* **2022**, *324*, 126708. [CrossRef]
165. Zhang, D.; Zhang, T.; Yang, Q. Mechanical Properties and Damage Layer Thickness of Green Concrete under a Low-Temperature Environment. *Materials* **2022**, *15*, 7409. [CrossRef] [PubMed]
166. Zhang, S.; Chen, B.; Tian, B.; Lu, X.; Xiong, B. Effect of Fly Ash Content on the Microstructure and Strength of Concrete under Freeze–Thaw Condition. *Buildings* **2022**, *12*, 2113. [CrossRef]
167. Wu, X.; Zheng, S.; Feng, Z.; Chen, B.; Qin, Y.; Xu, W.; Liu, Y. Prediction of the frost resistance of high-performance concrete based on RF-REF: A hybrid prediction approach. *Constr. Build. Mater.* **2022**, *333*, 127132. [CrossRef]
168. Ullah, R.; Qiang, Y.; Ahmad, J.; Vatin, N.I.; El-Shorbagy, M.A. Ultra-High-Performance Concrete (UHPC): A State-of-the-Art Review. *Materials* **2022**, *15*, 4131. [CrossRef] [PubMed]
169. Kanaan, D.; Safhi, A.e.M.; Suleiman, A.R.; Soliman, A.M. Fresh, Hardened, and Microstructural Properties of Ambient Cured One-Part Alkali-Activated Self-Consolidating Concrete. *Sustainability* **2023**, *15*, 2451. [CrossRef]
170. Prithiviraj, C.; Saravanan, J.; Ramesh Kumar, D.; Murali, G.; Vatin, N.I.; Swaminathan, P. Assessment of Strength and Durability Properties of Self-Compacting Concrete Comprising Alccofine. *Sustainability* **2022**, *14*, 5895. [CrossRef]
171. Bhuva, P.; Bhogayata, A. A review on the application of artificial intelligence in the mix design optimization and development of self-compacting concrete. *Mater. Today Proc.* **2022**, *65*, 603–608. [CrossRef]
172. Zhang, P.; Wang, C.; Gao, Z.; Wang, F. A review on fracture properties of steel fiber reinforced concrete. *J. Build. Eng.* **2023**, *67*, 105975. [CrossRef]
173. Behnia, B.; Askarinejad, P.; LaRussa-Trott, N. Investigating Low-Temperature Cracking Behavior of Fiber-Reinforced Asphalt Concrete Materials. *Int. J. Pavement Res. Tech.* **2023**, 1–12. [CrossRef]
174. Cao, Y.; Bao, J.; Zhang, P.; Sun, Y.; Cui, Y. A state-of-the-art review on the durability of seawater coral aggregate concrete exposed to marine environment. *J. Build. Eng.* **2022**, *60*, 105199. [CrossRef]
175. Saleh, A.N.; Khalil, O.A.; Attar, A.A. An overview of mechanical and thermal properties of nano concrete. *AIP Conf. Proc.* **2022**, *2398*, 020025. [CrossRef]
176. Eissa, A.; Yasien, A.M.; Bassuoni, M.T.; Alfaro, M. Performance of treated soft clay with nano-modified cementitious binders at reference and cold temperatures. *Int. J. Geosynth. Ground Eng.* **2022**, *8*, 52. [CrossRef]
177. Vijayan, D.S.; Devarajan, P.; Sivasuriyan, A. A review on eminent application and performance of nano based silica and silica fume in the cement concrete. *Sust. Energy Tech. Ass.* **2023**, *56*, 103105. [CrossRef]
178. Hurley, M.; Habibzadeh-Bigdarvish, O.; Lei, G.; Yu, X. Laboratory study of a hydronic concrete deck heated externally in a controlled sub-freezing environment. *Energy Built Environ.* 2022, *in press*. [CrossRef]
179. Kildashti, K.; Nash, S.; Samali, B. In-plane lateral behaviour of PVC modular concrete form squat walls: Experimental and numerical study. *J. Build. Eng.* **2022**, *52*, 104494. [CrossRef]
180. Mazumder, E.A.; Prasad, M.L.V. Performance Enhancement of Fly Ash-Based Self Compacting Geopolymer Concrete Using Pre-heating Technique. *Iran. J. Sci. Tech. Trans. Civ. Eng.* **2023**, 1–13. [CrossRef]
181. Eren, F.; Keskinateş, M.; Felekoğlu, B.; Felekoğlu, K.T. The role of Pre-Heating and mineral additive modification on Long-Term strength development of calcium aluminate cement mortars. *Constr. Build. Mater.* **2022**, *340*, 127720. [CrossRef]
182. Zhan, P.M.; He, Z.H. Application of shrinkage reducing admixture in concrete: A review. *Constr. Build. Mater.* **2019**, *201*, 676–690. [CrossRef]
183. Abubakri, S.; Lomboy, G.R.; Kennedy, D.; Watts, B. Development of Electrically Conductive Cold Weather Cement Concrete. *J. Cold Reg. Eng.* **2023**, *37*, 04022016. [CrossRef]
184. Su, Y.; Luo, B.; Luo, Z.; Huang, H.; Li, J.; Wang, D. Effect of Accelerators on the Workability, Strength, and Microstructure of Ultra-High-Performance Concrete. *Materials* **2022**, *15*, 159. [CrossRef]
185. Reddy, P.N.; Naqash, J.A. Development of high early strength in concrete incorporating alccofine and non-chloride accelerator. *SN Appl. Sci.* **2019**, *1*, 1–11. [CrossRef]
186. Hamada, H.; Alattar, A.; Tayeh, B.; Yahaya, F.; Almeshal, I. Influence of different curing methods on the compressive strength of ultra-high-performance concrete: A comprehensive review. *Case Stud. Constr. Mater.* **2022**, *17*, e01390. [CrossRef]
187. Taheri, S. A review on five key sensors for monitoring of concrete structures. *Constr. Build. Mater.* **2019**, *204*, 492–509. [CrossRef]
188. Abu-Jdayil, B.; Mourad, A.H.; Hittini, W.; Hassan, M.; Hameedi, S. Traditional, state-of-the-art and renewable thermal building insulation materials: An overview. *Constr. Build. Mater.* **2019**, *214*, 709–735. [CrossRef]
189. Surahyo, A.; Surahyo, A. Hot and cold weather concreting. *Concr. Constr. Pract. Prob. Sol.* **2019**, 257–272. [CrossRef]
190. Jun, H.; Ke, G. Analysis on Energy Saving Potential of Residential Building Enclosure Based on Orthogonal Experimental Analysis. *J. Civ. Eng. Urb. Plan.* **2022**, *4*, 27–33.
191. Viegas, G.M.; Jodra, J.I.; San Juan, G.A.; Díscoli, C.A. Heat storage wall made of concrete and encapsulated water applied to mass construction social housing in temperate climates. *Energy Build.* **2018**, *159*, 346–356. [CrossRef]

192. Ekrami, N.; Garat, A.; Fung, A.S. Thermal analysis of insulated concrete form (ICF) walls. *Energy Proc.* **2015**, *75*, 2150–2156. [CrossRef]
193. Zuo, Z.; Huang, Y.; Pan, X.; Zhan, Y.; Zhang, L.; Li, X.; Zhu, M.; Zhang, L.; De Corte, W. Experimental research on remote real-time monitoring of concrete strength for highrise building machine during construction. *Measurement* **2021**, *178*, 109430. [CrossRef]
194. Afzal, J.; Yihong, Z.; Afzal, U.; Aslam, M. A complex wireless sensors model (CWSM) for real time monitoring of dam temperature. *Heliyon* **2023**, *9*, e13371. [CrossRef]
195. Zhang, H.; Li, J.; Kang, F. Real-time monitoring of humidity inside concrete structures utilizing embedded smart aggregates. *Constr. Build. Mater.* **2022**, *331*, 127317. [CrossRef]
196. John, S.T.; Roy, B.K.; Sarkar, P.; Davis, R. IoT enabled real-time monitoring system for early-age compressive strength of concrete. *J. Constr. Eng. Mana.* **2020**, *146*, 05019020. [CrossRef]
197. Gamil, Y.; Nilimaa, J.; Najeh, T.; Cwirzen, A. Formwork pressure prediction in cast-in-place self-compacting concrete using deep learning. *Auto. Constr.* **2023**, *151*, 104869. [CrossRef]
198. Gehri, N.; Mata-Falcón, J.; Kaufmann, W. Refined extraction of crack characteristics in Large-scale concrete experiments based on digital image correlation. *Eng. Struct.* **2022**, *251*, 113486. [CrossRef]
199. Kinda, J.; Bourdot, A.; Charpin, L.; Michel-Ponnelle, S.; Benboudjema, F. Investigation of drying shrinkage of cement-based materials assisted by digital image correlation. *J. Mater. Civ. Eng.* **2022**, *34*, 04021477. [CrossRef]
200. Wong, R.W.; Loo, B.P. Sustainability implications of using precast concrete in construction: An in-depth project-level analysis spanning two decades. *J. Clean. Prod.* **2022**, *378*, 134486. [CrossRef]
201. Yang, S. The Development and Application of Prefabricated Buildings. *High. Sci. Eng. Tech.* **2022**, *18*, 162–167. [CrossRef]
202. Bischof, P.; Mata-Falcon, J.; Kaufmann, W. Fostering innovative and sustainable mass-market construction using digital fabrication with concrete. *Cem. Concr. Res.* **2022**, *161*, 106948. [CrossRef]
203. Li, Z.; Zhou, X.; Ma, H.; Hou, D. *Advanced Concrete Technology*, 2nd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2022.
204. Onyelowe, K.C.; Ebid, A.M.; Riofrio, A.; Baykara, H.; Soleymani, A.; Mahdi, H.A.; Jahangir, H.; Ibe, K. Multi-Objective Prediction of the Mechanical Properties and Environmental Impact Appraisals of Self-Healing Concrete for Sustainable Structures. *Sustainability* **2022**, *14*, 9573. [CrossRef]
205. Sawadogo, M.; Benmahiddine, F.; Hamami, A.E.A.; Belarbi, R.; Godin, A.; Duquesne, M. Investigation of a novel bio-based phase change material hemp concrete for passive energy storage in buildings. *Appl. Therm. Eng.* **2022**, *212*, 118620. [CrossRef]
206. Monteiro, J.; Roussanaly, S. CCUS scenarios for the cement industry: Is CO_2 utilization feasible? *J. CO2 Util.* **2022**, *61*, 102015. [CrossRef]
207. Hossain, M.R.; Sultana, R.; Patwary, M.M.; Khunga, N.; Sharma, P.; Shaker, S.J. Self-healing concrete for sustainable buildings. A review. *Environ. Chem. Lett.* **2022**, *20*, 1265–1273. [CrossRef]
208. Amran, M.; Onaizi, A.M.; Fediuk, R.; Vatin, N.I.; Muhammad Rashid, R.S.; Abdelgader, H.; Ozbakkaloglu, T. Self-Healing Concrete as a Prospective Construction Material: A Review. *Materials* **2022**, *15*, 3214. [CrossRef] [PubMed]
209. Wu, D.; Rahim, M.; El Ganaoui, M.; Bennacer, R.; Liu, B. Multilayer assembly of phase change material and bio-based concrete: A passive envelope to improve the energy and hygrothermal performance of buildings. *Energy Conv. Mana.* **2022**, *257*, 115454. [CrossRef]
210. Hargis, C.W.; Chen, I.A.; Devenney, M.; Fernandez, M.J.; Gilliam, R.J.; Thatcher, R.P. Calcium Carbonate Cement: A Carbon Capture, Utilization, and Storage (CCUS) Technique. *Materials* **2021**, *14*, 2709. [CrossRef]
211. Kong, Y.K.; Ruan, S.; Kurumisawa, K. Recycling of calcined carbonated cement pastes as cementitious materials: Proposed CCUS technology for calcium looping. *J. Environ. Chem. Eng.* **2022**, *10*, 108247. [CrossRef]
212. Guimarães, A.S.; Delgado, J.M.P.Q.; Lucas, S.S. Advanced Manufacturing in Civil Engineering. *Energies* **2021**, *14*, 4474. [CrossRef]
213. Classen, M.; Ungermann, J.; Sharma, R. Additive Manufacturing of Reinforced Concrete—Development of a 3D Printing Technology for Cementitious Composites with Metallic Reinforcement. *Appl. Sci.* **2020**, *10*, 3791. [CrossRef]
214. Xiao, H.; Muthu, B.; Kadry, S.N. Artificial intelligence with robotics for advanced manufacturing industry using robot-assisted mixed-integer programming model. *Intell. Serv. Robot.* **2020**, 1–10. [CrossRef]
215. Gunawardena, T.; Mendis, P. Prefabricated Building Systems—Design and Construction. *Encyclopedia* **2022**, *2*, 70–95. [CrossRef]
216. El Inaty, F.; Baz, B.; Aouad, G. Long-term durability assessment of 3D printed concrete. *J. Adh. Sci. Tech.* **2022**, 1–16. [CrossRef]
217. Bazli, M.; Ashrafi, H.; Rajabipour, A.; Kutay, C. 3D printing for remote housing: Benefits and challenges. *Aut. Constr.* **2023**, *148*, 104772. [CrossRef]
218. Dörfler, K.; Dielemans, G.; Lachmayer, L.; Recker, T.; Raatz, A.; Lowke, D.; Gerke, M. Additive Manufacturing using mobile robots: Opportunities and challenges for building construction. *Cem. Concr. Res.* **2022**, *158*, 106772. [CrossRef]
219. Meisel, N.A.; Watson, N.; Bilén, S.G.; Duarte, J.P.; Nazarian, S. Design and system considerations for construction-scale concrete additive manufacturing in remote environments via robotic arm deposition. *3D Print. Add. Manuf.* **2022**, *9*, 35–45. [CrossRef]
220. Momeni, M.; Relefors, J.; Khatry, A.; Pettersson, L.; Papadopoulos, A.V.; Nolte, T. Automated fabrication of reinforcement cages using a robotized production cell. *Aut. Constr.* **2022**, *133*, 103990. [CrossRef]
221. Ou, Y.; Bao, D.W.; Zhu, G.Q.; Luo, D. Additive Fabrication of Large-Scale Customizable Formwork Using Robotic Fiber-Reinforced Polymer Winding. *3D Print. Add. Manuf.* **2022**, *9*, 109–121. [CrossRef]
222. Han, Y.; Yan, X.; Piroozfar, P. An overall review of research on prefabricated construction supply chain management. Engineering. *Constr. Arch. Mana.* 2022; *in press*. [CrossRef]

223. Aurier, L.; Hassan, M.; Jaworski, J.; Guizani, L. Review of Accelerated Bridge Construction Systems for Bridge Superstructures and Their Adaptability for Cold Weather. *CivilEng* **2023**, *4*, 83–104. [CrossRef]
224. Zhao, X.; Cao, L. Application Strategy of BIM Technology in Virtual Construction of Prefabricated Buildings. *J. Arch. Res. Dev.* **2022**, *6*, 40–46. [CrossRef]
225. Jiang, J.; Xiong, Y.; Zhang, Z.; Rosen, D.W. Machine learning integrated design for additive manufacturing. *J. Intel. Manuf.* **2022**, *33*, 1073–1086. [CrossRef]
226. Anane, W.; Iordanova, I.; Ouellet-Plamondon, C. BIM-driven computational design for robotic manufacturing in off-site construction: An integrated Design-to-Manufacturing (DtM) approach. *Auto. Constr.* **2023**, *150*, 104782. [CrossRef]
227. Ng, M.S.; Graser, K.; Hall, D.M. Digital fabrication, BIM and early contractor involvement in design in construction projects: A comparative case study. *Arch. Eng. Design Mana.* **2023**, *19*, 39–55. [CrossRef]
228. Liu, Y.; Cao, Y.; Wang, L.; Chen, Z.S.; Qin, Y. Prediction of the durability of high-performance concrete using an integrated RF-LSSVM model. *Constr. Build. Mater.* **2022**, *356*, 129232. [CrossRef]
229. Sherif, M.; Nassar, K.; Hosny, O.; Safar, S.; Abotaleb, I. Automated BIM-based structural design and cost optimization model for reinforced concrete buildings. *Sci. Rep.* **2022**, *12*, 21616. [CrossRef]
230. Mousavi, M.; TohidiFar, A.; Alvanchi, A. BIM and machine learning in seismic damage prediction for non-structural exterior infill walls. *Auto. Constr.* **2022**, *139*, 104288. [CrossRef]
231. Baduge, S.K.; Thilakarathna, S.; Perera, J.S.; Arashpour, M.; Sharafi, P.; Teodosio, B.; Shringi, A.; Mendis, P. Artificial intelligence and smart vision for building and construction 4.0: Machine and deep learning methods and applications. *Auto. Constr.* **2022**, *141*, 104440. [CrossRef]
232. Sadrossadat, E.; Basarir, H.; Karrech, A.; Elchalakani, M. Multi-objective mixture design and optimisation of steel fiber reinforced UHPC using machine learning algorithms and metaheuristics. *Eng. Comput.* **2022**, *38*, 2569–2582. [CrossRef]
233. Moein, M.M.; Saradar, A.; Rahmati, K.; Mousavinejad, S.H.G.; Bristow, J.; Aramali, V.; Karakouzian, M. Predictive models for concrete properties using machine learning and deep learning approaches: A review. *J. Build. Eng.* **2022**, *63*, 105444. [CrossRef]
234. Zabin, A.; González, V.A.; Zou, Y.; Amor, R. Applications of machine learning to BIM: A systematic literature review. *Adv. Eng. Inf.* **2022**, *51*, 101474. [CrossRef]
235. Opoku, D.G.J.; Perera, S.; Osei-Kyei, R.; Rashidi, M.; Famakinwa, T.; Bamdad, K. Drivers for Digital Twin Adoption in the Construction Industry: A Systematic Literature Review. *Buildings* **2022**, *12*, 113. [CrossRef]
236. Madubuike, O.C.; Anumba, C.J.; Khallaf, R. A review of digital twin applications in construction. *J. Inf. Tech. Constr.* **2022**, *27*, 145–172. [CrossRef]
237. Hosamo, H.H.; Nielsen, H.K.; Kraniotis, D.; Svennevig, P.R.; Svidt, K. Digital Twin framework for automated fault source detection and prediction for comfort performance evaluation of existing non-residential Norwegian buildings. *Energy Build.* **2023**, *281*, 112732. [CrossRef]
238. Ying, J.; Zhang, X.; Zhang, Y.; Bilan, S. Green infrastructure: Systematic literature review. *Econ. Res.* **2022**, *35*, 343–366. [CrossRef]
239. Coffetti, D.; Crotti, E.; Gazzaniga, G.; Carrara, M.; Pastore, T.; Coppola, L. Pathways towards sustainable concrete. *Cem. Concr. Res.* **2022**, *154*, 106718. [CrossRef]
240. Das, S.; Saha, P.; Jena, S.P.; Panda, P. Geopolymer concrete: Sustainable green concrete for reduced greenhouse gas emission—A review. *Mater. Today Proc.* **2022**, *60*, 62–71. [CrossRef]
241. Coffetti, D.; Cabrini, M.; Crotti, E.; Gazzaniga, G.; Lorenzi, S.; Pastore, T.; Coppola, L. Durability of Mortars Manufactured with Low-Carbon Binders Exposed to Calcium Chloride-Based De-Icing Salts. *Key Eng. Mater.* **2022**, *919*, 151–160. [CrossRef]
242. Alhassan, M.; Alkhawaldeh, A.; Betoush, N.; Alkhawaldeh, M.; Huseien, G.F.; Amaireh, L.; Elrefae, A. Life Cycle Assessment of the Sustainability of Alkali-Activated Binders. *Biomimetics* **2023**, *8*, 58. [CrossRef] [PubMed]
243. Manjunatha, M.; Seth, D.; Balaji, K.V.G.D.; Bharath, A. Engineering properties and environmental impact assessment of green concrete prepared with PVC waste powder: A step towards sustainable approach. *Case Stud. Constr. Mater.* **2022**, *17*, e01404. [CrossRef]
244. Forero, J.A.; Bravo, M.; Pacheco, J.; de Brito, J.; Evangelista, L. Thermal Performance of Concrete with Reactive Magnesium Oxide as an Alternative Binder. *Sustainability* **2022**, *14*, 5885. [CrossRef]
245. Roy, S.; Roy, S. Carbon Dioxide Capture—A Challenge for Green Economy. *Amer. J. Appl. Bio-Tech. Res.* **2022**, *3*, 30–49. [CrossRef]
246. Guo, Y.; Luo, L.; Liu, T.; Hao, L.; Li, Y.; Liu, P.; Zhu, T. A review of low-carbon technologies and projects for the global cement industry. *J. Environ. Sci.* **2023**, *136*, 682–697. [CrossRef]
247. Clarke, B.; Otto, F.; Stuart-Smith, R.; Harrington, L. Extreme weather impacts of climate change: An attribution perspective. *Environ. Res. Clima.* **2022**, *1*, 012001. [CrossRef]
248. Zaqout, T.; Andradóttir, H.Ó.; Arnalds, Ó. Infiltration capacity in urban areas undergoing frequent snow and freeze–thaw cycles: Implications on sustainable urban drainage systems. *J. Hydr.* **2022**, *607*, 127495. [CrossRef]
249. Zhang, H.; Li, J.; Kang, F.; Zhang, J. Monitoring and evaluation of the repair quality of concrete cracks using piezoelectric smart aggregates. *Constr. Build. Mater.* **2022**, *317*, 125775. [CrossRef]
250. Katman, H.Y.B.; Khai, W.J.; Bheel, N.; Kırgız, M.S.; Kumar, A.; Benjeddou, O. Fabrication and Characterization of Cement-Based Hybrid Concrete Containing Coir Fiber for Advancing Concrete Construction. *Buildings* **2022**, *12*, 1450. [CrossRef]

251. Azam, R.; Riaz, M.R.; Farooq, M.U.; Ali, F.; Mohsan, M.; Deifalla, A.F.; Mohamed, A.M. Optimization-Based Economical Flexural Design of Singly Reinforced Concrete Beams: A Parametric Study. *Materials* **2022**, *15*, 3223. [CrossRef] [PubMed]
252. Junaid, M.F.; Rehman, Z.U.; Kuruc, M.; Medveď, I.; Bačinskas, D.; Čurpek, J.; Čekon, M.; Ijaz, N.; Ansari, W.S. Lightweight concrete from a perspective of sustainable reuse of waste byproducts. *Constr. Build. Mater.* **2022**, *319*, 126061. [CrossRef]