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Formwork Engineering for Sustainable Concrete Construction

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Abstract: This study provides a comprehensive review of the engineering challenges of formwork in concrete construction. The paper investigates different formwork systems, their design based on form pressure, and the difficulties of form stripping. Alternative binders are gaining more and more interest by opening new opportunities for sustainable concrete materials and their impact on form pressure and concrete setting is also investigated in this paper. The discussion involves several engineering challenges such as sustainability, safety, and economy, while it also explores previous case studies, and discusses future trends in formwork design. The findings pinpoint that choosing an appropriate formwork system depends significantly on project-specific constraints and that the development of innovative materials and technologies presents significant benefits but also new challenges, including the need for training and regulation. Current trends in formwork design and use show promising possibilities for the integration of digital technologies and the development of sustainable and 'smart' formwork systems. Continued research within the field has the possibility to explore new formwork materials and technologies, which will contribute to the implementation of more effective and sustainable practices in concrete construction.

Keywords: formwork systems; concrete construction; form pressure; form stripping; alternative binders; sustainability; formwork design; digital technologies

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1. Introduction

Formwork is a temporary or permanent mold which can be contained and shaped while wet until it hardens, and can support itself and all additional loads during construction [1]. The temporary formwork is removed when the concrete has gained sufficient strength, while the permanent types are integrated as permanent parts of the structure [2]. Formwork is a crucial aspect of concrete construction, representing a significant proportion of the total cost and is required for a major part of the time during cast-in-place projects [3]. According to Kreiger et al., the material and labor costs for formwork can be as high as 35–60% of the total costs [4]. The choice and execution of formwork can greatly influence the surface quality and finish, as well as the strength development and durability of the concrete structures being built [5]. Understanding the wide range of engineering aspects of formwork is therefore essential for construction professionals seeking to optimize their work in terms of cost effectiveness and quality. This paper aims to provide a comprehensive review of these aspects, including types and materials used for formwork, design of formwork based on form pressure, form stripping considerations, and the impact of alternative binders on the setting of concrete.

Formwork has been used for concrete construction for centuries, and the technological aspects and understanding has also developed over time to meet the changing demands of the construction industry [5]. The Romans used wooden formwork to shape their concrete structures [6], and some of these structures, for example Pantheon, remain after almost 2000 years, demonstrating the incredible durability of concrete as a construction material. The roman concrete mix contained natural pozzolans from volcanic ash, burnt lime, pumice aggregates, and water, demonstrating the sustainability and potential to produce concrete without additional CO_2 emissions [7]. As construction methodologies and formwork systems advanced, new materials and designs were incorporated to improve the efficiency, safety, and quality of concrete construction. A variety of formwork types are used today, including different materials such as timber, steel, plywood, aluminum, and plastic, each with its unique advantages and disadvantages [8]. The form systems can also be distinguished as temporary forms, which are removed after the concrete has hardened, or permanent forms which remain after the concrete has hardened, forming a composite structure [9].

Form stripping, or the process of removing the formwork after the concrete has hardened, is another essential aspect for constructors as they usually prefer to remove it as early as possible for increased productivity and reduced costs [10]. The timing and method of form stripping can have a significant impact on the quality of the finished concrete surface, as well as the structural integrity [5]. Form stripping too early can lead to unsafe situations, and cause damage or deformation to the structure. Leaving the formwork in place too long, on the other hand, can make the form removal difficult and increase construction time and costs considerably [11]. Formwork design is a complex engineering task that requires a deep understanding of several factors such as concrete hydration, strength development, and form pressure [12,13]. The pressure exerted by the fresh concrete on the formwork can significantly affect the stability and safety of the formwork system. The form pressure is influenced by several factors such as the rate of concrete placement, the internal and ambient temperatures, the characteristics of the concrete mix, and the use of chemical admixtures [14,15]. Designing formwork to withstand the pressure, as well as additional construction loads, without compromising the quality of the finished concrete is an important concern for engineers, especially for high structures like walls and columns, which are naturally exposed to higher pressures [15].

The use of alternative binders in concrete mixtures is becoming more common as the construction industry seeks to reduce its environmental footprint and improve the properties of concrete [16–21]. The cement industry accounts for about 7–8% of the global CO_2 emissions and there is an urgent need to find more sustainable alternatives for material production as well as construction procedures [22]. Alternative binders may offer opportunities to reduce the environmental impacts considerably, but they can also affect the material processes of concrete, such as setting and hardening [23,24]. This, in turn, influences the early material properties such as the concrete strength, and leads to engineering concerns regarding form pressure, form stripping, and the overall design and use of formwork [25]. A comprehensive understanding of how these binders interact with concrete and formwork is therefore crucial for effective formwork design and use.

This paper investigates the current knowledge regarding these concerns and other critical aspects of formwork for concrete construction. Despite the extensive use of formwork in concrete construction, there is a lack of comprehensive review papers addressing its engineering aspects. Most existing literature focuses on specific aspects, such as a particular type of formwork, or a single aspect of formwork design or use. This paper aims to fill the gap by providing a comprehensive overview of different engineering aspects of formwork for concrete construction. In the following sections, the paper will explore the types of formworks, investigate different approaches for formwork design, and discuss the process and requirements for form stripping. It will also examine how the use of alternative binders affects the setting of concrete and thereby the form pressure. Finally, it will discuss different issues related to sustainability, cost, and safety, and explore future trends and technologies in formwork design and use.

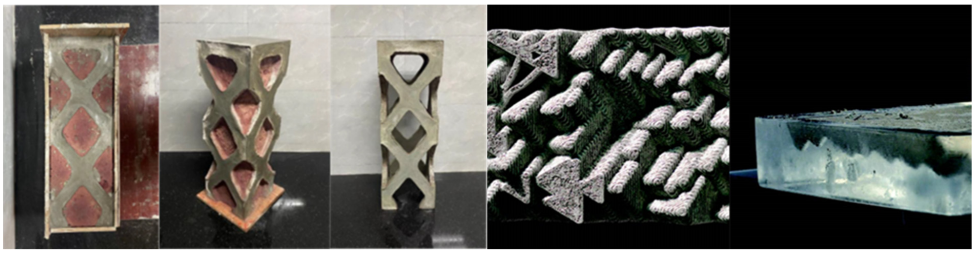
2. Formwork Types

The choice of formwork is an important aspect of concrete construction as it can greatly influence the quality, finish, and durability of the final structure [8]. Several types of formwork have been developed over the years, each having unique properties and thereby providing opportunities for the engineers to match their choice of formwork for different project requirements. This section will review different formwork materials and types, including temporary, permanent, and insulated concrete forms (ICF), and explore how they affect the concrete.

Timber is one of the traditional materials for formwork and is still widely used in construction projects all over the world [26]. It is typically made from a combination of timber and plywood, making it cost effective, lightweight, highly flexible, and easy to produce and handle on site [5]. Timber formwork is suitable for complex designs due to its adaptability and can be reused multiple times if properly maintained [27]. The timber material is, however, susceptible to water damage and decay, and requires skilled labor for assembly and disassembly [28]. The rough texture of timber can imprint on the concrete surface, affecting the finish, and is therefore often used in combination with plywood. Timber forms can, however, be used to design and create architecturally appealing patterns on the surface of a concrete structure. The advantage of plywood is that it can easily be bent to create curved forms and it leaves a smoother finish on the concrete compared to timber. The disadvantage is that it is also prone to water damage and fast decay, limiting the reusability of plywood forms [29]. The quality and cost of different plywood materials varies, and high-quality, water-resistant types are available, but more expensive [5].

Formwork made of steel is robust and durable, which is highly advantageous as it offers the potential to reuse the form many times [5]. The material properties and characteristics of steel forms ensure that they do not adhere to concrete very easily, thereby enabling easy form stripping and providing a smooth finish on the concrete surface [30]. The strength of steel allows it to withstand high pressures, making it suitable for large construction projects [31]. However, steel formwork can be expensive to buy, prone to corrode, and heavy to handle on site, requiring machinery for movement and placement. It also requires specialized labor and is less adaptable to complex designs compared to timber formwork [32]. Aluminum formwork is gaining popularity due to its lightweight, high strength-to-weight ratio, and resistance to corrosion and decay. Like steel, it leaves a smooth finish on the concrete surface and can be reused many times [33]. Aluminum formwork is typically prefabricated and modular, making it easy to handle and quick to assemble and disassemble [34]. However, it can be more expensive and less adaptable to complex designs compared to timber formwork.

Plastic formwork is a relatively new type that offers advantages such as lightweight, corrosion resistance, and easy handling [35]. It also leaves a smooth finish on the concrete surface, like steel and aluminum forms [5]. Plastic formwork is typically modular and can be reused multiple times, making it cost effective over time [36]. However, it may not be suitable for heavy, high-pressure concrete applications. Recent studies have focused much attention on developing economical and environmentally friendly materials and systems for formwork. For example, Gericke et al. proposed a formwork system based on frozen and CNC-milled sand [37,38], and a 3D-printed, resin-bonded sand formwork was developed by Meibodi et al. [39,40]. Ice is another material that has recently been investigated by Sitnikov for formwork applications [41–43]. Ice formwork can for example be CNC-milled into a variety of shapes, or 3D printed, and does not require any demolding as it melts as the temperature increases [44–46]. However, a frost-resistant concrete may be required due to the low temperatures and for this reason Sitnikov developed a special high-performance concrete for his studies [47]. Figure 1 shows the application of frozen sand formwork, ice formwork and timber formwork, while a comparison between different formwork materials and systems is presented in Table 1.



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

(**c**)

Figure 1. Different types of formwork materials. (**a**) Frozen sand formwork [48]; (**b**) ice formwork [47]; (**c**) timber formwork.

Table 1. Comparison of various formwork systems. Adapted from [5].

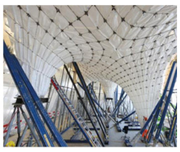
Formwork Type		Labor Cost	Material Cost	Speed of Construction	Geometries	Surface Quality	Reusability
Timber		High	Medium	Low	Mostly regular shapes	Medium	Yes
Metal		Medium	High	Low	Mostly orthogonal shapes	High	Yes
Fabric formwork		Medium	Low	High	Flexible	High	Limited

Table 1. *Cont.*

Formwork Type		Labor Cost	Material Cost	Speed of Construction	Geometries	Surface Quality	Reusability
CNC-milled styrofoam		Low	Medium	Medium	Unlimited	High (with coating)	Yes
3D-printed plastic		Low	High	Medium	Non-traditional shapes possible	Low	No
Mesh mold		Medium	Medium	High	Regular shapes	Medium	No
Sand formwork		Low	Very low	Depends on fabrication method	Unlimited	High (with release agents)	Yes
Ice formwork		Low	Very low	Depends on fabrication method	Unlimited	High	Yes

Formwork can also be categorized as a temporary or permanent structure, based on whether it is removed after the concrete has hardened [49]. Temporary forms are removed once the concrete gains sufficient strength, leaving the concrete structure exposed. They are typically used where the aesthetics of the concrete is important or when the formwork material needs to be reused [50]. Permanent formwork, on the other hand, remains in place after the concrete hardens. It provides additional structural stability and can serve as insulation or fire protection [51,52]. Permanent formwork, also known as stay-in-place (SIP) formwork, is often used in the construction of slabs and walls, and durable materials such as steel, plastic, or composites are commonly used [53].

Insulating concrete forms (ICFs) are a type of SIP formwork that not only mold the concrete but also provide thermal insulation for the finished structure [54]. ICFs are typically made from expanded polystyrene (EPS) or other insulating materials, sandwiching a core where the concrete is poured [55]. ICFs offer a high degree of thermal and noise insulation, which can significantly improve the energy efficiency and acoustic properties of buildings [56,57]. The insulating properties of walls with ICF remains throughout the lifespan of the structure, leading to long-term energy savings and improved sustainability [58]. ICFs can provide a smooth surface that requires minimal additional finishing, and they are typically resistant to moisture, reducing the risk of mold and mildew. ICF construction can be more expensive than traditional formwork methods due to the cost of the insulating forms, but the high initial costs may be regained by the long-term energy savings [59]. ICFs also require careful installation to prevent misalignment or displacement during concrete pouring. Despite the challenges, the benefits of energy efficiency, noise reduction, durability, and speed of construction have led to an increasing use of ICFs in residential and commercial buildings [60]. Other categories of formwork systems and technologies include, for example, dissolvable materials [61,62], 3D-printed forms [59], sliding forms [63], self-climbing formwork [64], and self-supporting formwork [65].

The selection of suitable formwork materials is a critical decision in construction projects, as it significantly impacts the cost, timeline, and quality of the project. Factors to consider when selecting formwork materials are summarized in Table 2. A comprehensive understanding of the properties and implications of each formwork type can help engineers and construction professionals to choose the best solution for their project, leading to safer, more efficient, and cost-effective construction [4,5,8].

Table 2. Factors to consider when choosing type and material for formwork in concrete construction.

Factor to Consider	Description
Project requirements	The size, complexity, and design of the project will determine the formwork type. For instance, for complex designs with curves, flexible formwork such as timber or plywood may be more suitable. For large projects requiring high load-bearing capacity, steel, or aluminum formwork would be more appropriate.
Cost considerations	Formwork can constitute a significant portion of the project cost. Therefore, cost considerations such as the initial investment, the number of reuses, and maintenance costs should be considered. While steel and aluminum formwork may have a higher initial cost, they offer a higher number of reuses, which could be cost effective in the long run.
Concrete surface quality	The formwork material can influence the finish of the concrete surface. For instance, steel and aluminum formwork typically leave a smooth finish, while timber may leave a rougher texture.
Labor skills and availability	Some formwork types require skilled labor for assembly and disassembly. The availability and the cost of personnel should also be considered in the selection of formwork.

3. Formwork Design

The structural design of formwork is another critical aspect of concrete construction, requiring a balance between different considerations such as safety, cost, and performance. One of the central aspects of formwork design is managing the form pressure exerted by the fresh concrete [66–70]. Form pressure is the pressure generated by fresh concrete as it is poured inside the formwork system during construction, and it is the decisive factor in formwork design, as the formwork must have the capacity to withstand the concrete's pressure without deformation or failure. The design process begins with the calculation of form pressure, which depends on several material parameters of the concrete, the rate of placement, and the ambient conditions [71], as discussed in Table 3.

Table 3. Factors to consider when calculating the form pressure generated by fresh concrete.

Factor to Consider	Description
Workability	Highly workable concrete, such as self-consolidating concrete, exerts a higher initial pressure on the formwork due to its fluid nature. This requires a stronger formwork design in comparison to traditional vibrated concrete [72].
Rate of Hardening	The rate at which concrete hardens affects the form pressure. The pressure is typically higher in the beginning when the concrete is still very fluid and reduces as the concrete gains its material strength [73]. A faster thixotropic hardening reduces the duration of maximum pressure, allowing for lighter formwork design [74]. Different types and contents of cement harden and gain strength at different rates. Rapid hardening cement and the inclusion of certain additives lead to quicker strength gain, and the formwork removal can be performed earlier than for ordinary Portland cement [75].

Table 3. *Cont.*

Factor to Consider	Description
Temperature	The temperature affects the rate of concrete hardening, and hence the form pressure. Higher temperatures accelerate the hardening process and strength development of concrete, which ultimately reduces the form pressure [76]. Rapid drying can however lead to shrinkage and cracking [77], so measures such as curing under wet burlap or plastic sheets may be necessary [78]. Lower temperatures can on the other hand delay the hardening [79], and therefore increase the form pressure.
Use of Admixtures	Certain chemical admixtures can alter the material properties of the concrete, ultimately affecting the form pressure. Superplasticizers can, for example, be implemented in the mix to increase the workability, which can also increase the form pressure [67]. Accelerating admixtures can be used to increase the rate of hydration and therefore also the form pressure [80].

The hydrostatic pressure theory has traditionally been used to calculate form pressure, especially for self-consolidating concrete, assuming that the pressure distribution is the same as that of a fluid at rest [81]. Pascal's principle states that the hydrostatic pressure (P_h) of a fluid at rest is the product of the material density (ρ), the gravity (g), and the height of the concrete (h), as calculated in Equation (1). The pressure is considered equal in all directions and can therefore represent the pressure a self-consolidating concrete exerts on the formwork before its initial setting [82].

$$P_h = \rho g h \tag{1}$$

Concrete is however not a fluid, and the pressure distribution is influenced by its thixotropic nature, meaning that the pressure reduces as the chemical reactions within the concrete proceed and generates a material that can carry more and more of its own weight [83]. At some point, the concrete will be able to carry its own weight without generating any pressure to the formwork, and further on the concrete structure will be able to carry large additional loads [84]. More accurate models have been developed over the years to better estimate the form pressure generated by self-consolidating concrete and account for the rate of concrete hardening, but many countries have not implemented design guidelines and still rely on hydrostatic models for SCC [85–91].

Once the form pressure has been estimated, the formwork components can be designed to withstand the maximum pressure. Formwork design involves selecting the appropriate material and thickness for the formwork panels, determining the size, and spacing of supporting members, and designing the connections and bracing to ensure stability [92]. Several other factors in addition to the form pressure also affect the formwork design, as discussed in Table 4, and it is important to understand their contribution to create safe and efficient form systems for concrete construction.

Table 4. Factors to consider when designing formwork for concrete construction.

Factor to Consider	Description
Loading Conditions	In addition to the form pressure from the concrete, formwork must also withstand other loads, including construction loads, wind loads, and the weight of workers and equipment [93].
Formwork Material	The material of the formwork affects its strength, stiffness, weight, and durability, all of which influence the design. For instance, steel formwork can withstand higher pressures than timber formwork, but it is also heavier and may require more support [94]. The formwork material affects the adhesion and surface properties of the concrete.

Table 4. *Cont.*

Factor to Consider	Description
Project Requirements	The size and complexity of the structure, the required surface finish, and the construction schedule all influence the design and requirements of the formwork. More complex structures may require custom-designed formwork, while simpler structures can use standard modular systems [95].
Cost Considerations	The cost of formwork can significantly impact the overall project cost. Therefore, the formwork design must balance cost and performance. This includes considering the initial cost, the cost of assembly and disassembly, the number of reuses, and maintenance costs [96].

4. Engineering Considerations in Formwork Design and Use

4.1. Form Stripping

Form stripping, or striking, is a critical step in the construction process of concrete structures. It involves removing the formwork after the concrete has gained sufficient stability and strength to carry its own weight and any additional loads during construction [97]. Stripping must be carried out very carefully to ensure the quality of the concrete structure and the safety of workers [98]. The process of form stripping typically begins with assessing the strength and stability of the concrete. This is usually assessed by testing the compressive strength on cube or cylinder samples, but there are a variety of experience-based methods that have been historically used in concrete construction. The concrete strength can also be evaluated using several other non-destructive testing methods, such as the maturity method, rebound hammer tests, penetration resistance tests, pullout tests, or ultrasonic pulse velocity tests [99]. As soon as the concrete strength is sufficient, the formwork must be removed carefully to reduce the construction costs and prevent damage to the concrete surface [61]. This often involves removing fasteners and supports, starting from the top of vertical forms or the bottom of horizontal forms, and working downwards or upwards, respectively [1].

Form stripping can have a significant impact on the surface quality of the finished concrete structure. Properly timed and executed stripping can result in a smooth, uniform surface with minimal aesthetic or structural defects. Premature form stripping can lead to surface damage, such as chipping or spalling, and structural defects, such as cracking or deformation [100]. Thermal shocking and early freezing are two additional phenomena that can occur if the form is stripped prematurely in cold weather [19,101]. A compressive strength of 5 MPa is usually recommended to avoid severe problems due to the early freezing of concrete [102]. Late stripping can cause surface damage due to adhesion of concrete to the formwork and may also hinder the curing process [103]. The ideal stripping time depends on several factors, including the concrete mix, curing conditions, and additional construction loads [104]. Another important consideration is the project time and cost, as previous studies have shown, is that formwork operations may take 50–75% of the total time spent in concrete construction [105] and account for 35–60% of the costs [4].

The process of form stripping can differ between vertical and horizontal structures. For vertical structures such as walls and columns, stripping typically starts from the top and works downwards. This allows the lower portions of the formwork to continue supporting the concrete as the upper portions are removed. The strength requirement for the form stripping of vertical members is that they should be able to carry their self-weight and only small additional loads, which typically implies a compressive strength of 2–10 MPa [97,106]. There are, however, studies demonstrating that a compressive strength of 1.5 MPa is sufficient for the form stripping of vertical columns without risking damage or deformations [76].

For horizontal structures such as beams and slabs, stripping usually starts from the bottom (the sides of the slab) and continues upwards. The supports under the slab are removed last, considering it is not a ground slab. The general strength requirement for removing the supporting formwork under horizontal members is a compressive strength of a minimum of 70% of the concrete's final (28 d) strength for members spanning up to 6 m, and 85% for spans over 6 m [107]. Shores are typically installed under horizontal forms to carry and transfer the loads from the slab downwards through the structure until sufficient strength has been achieved [108], as shown in Figure 2. For projects requiring early form stripping, reshoring may be applied to continue supporting the horizontal concrete members during construction [109].

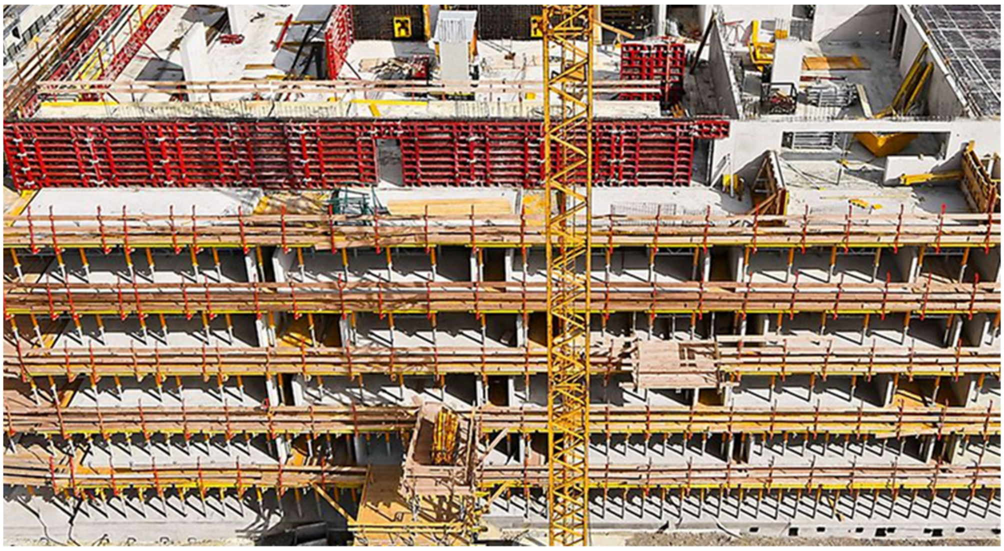


Figure 2. Cast-in-place construction of a multi-story concrete structure with horizontal and vertical formwork and supporting shores.

4.2. Alternative Binders and Their Impact

As the construction industry seeks more sustainable and efficient practices, the use of alternative binders in concrete has gained more and more interest over the last years [18,110–114]. These new types of binders can improve the environmental footprint of concrete and offer unique material properties that can ultimately influence the formwork design and requirements for form stripping [15,115]. Alternative binders, including supplementary cementitious materials (SCMs), are materials that can partially replace Portland cement in the concrete mix [116].

Common SCMs include fly ash, slag, and silica fume, but more recently, binders including geopolymers and limestone calcined clay cement (LC3) have also been introduced as alternatives to cement [117–120]. A short description of common alternative binders and their impact on the concrete properties is given in Table 5. Fly ash and slag typically slows down the setting and hardening, resulting in a prolonged need of formwork and ultimately a slower construction rate, which may be negative for projects with tight time schedules. Other alternative binders, such as silica fume, may have the impact of accelerating the setting and hardening of concrete, and can therefore be used to reduce the form stripping time.

Table 5. Alternative binders and their impact on concrete and formwork.

Alternative Binder	Description
Fly ash	Fly ash is a byproduct of coal combustion in power plants. Fly ash can improve the workability and durability of concrete, but it slows the setting and hardening process, which can affect formwork design and stripping [121].

Table 5. *Cont.*

Alternative Binder	Description
Slag	Slag cement or ground-granulated blast-furnace slag (GGBFS) is a byproduct of iron production. Slag cement enhances the durability and workability of concrete, but like fly ash, it slows the setting and hardening process [122].
Silica fume	Silica fume is a byproduct of silicon or ferrosilicon alloy production. It can replace 5–10% of the cement. Silica fume increases the strength and durability of concrete, but it can reduce workability and accelerate the setting, which can reduce the time required to initiate formwork stripping [123].
Geopolymers	Geopolymers are a type of inorganic polymer produced from aluminosilicate materials, such as fly ash or metakaolin. They offer high strength and durability, but their setting behavior is different from traditional cement, which requires adjustments in formwork design and stripping [124].
LC3	LC3 is a blend of limestone, calcined clay, and clinker. It offers similar performance to ordinary Portland cement, but with a significantly lower carbon footprint. The impact of LC3 on formwork is similar to that of ordinary cement [125].

4.3. Sustainability of Formwork

Sustainability has become a crucial concern in civil engineering and construction industries due to the increasing pressure on the world's resources and the effects of climate change [126–129]. As an important component of concrete construction, formwork affects the overall sustainability of the construction process [130]. Formwork materials vary in their environmental footprint. Traditional timber formwork, while renewable, often involves significant energy use and carbon emissions in harvesting and transportation [131]. Furthermore, the use of certain types of timber, such as tropical hardwoods, can contribute to deforestation and loss of biodiversity [132]. However, timber formwork can be sustainably sourced from managed forests, which mitigates these environmental impacts [133]. Metal formwork, such as steel or aluminium, requires high energy for extraction and production, contributing to large carbon emissions [134]. However, these materials are durable and can be reused many times, reducing their environmental impact over their lifetime. Plastic formwork, particularly that made from recycled plastics, has the potential to reduce waste and carbon emissions [135]. However, the production process of plastic can also be energy intensive, and the disposal of plastic formwork at the end of its life can contribute to plastic waste if not properly managed [136].

Construction activities are known to generate a significant amount of waste, and formwork is no exception [137]. Damaged formwork components, offcuts from formwork installation, and residue from concrete casting all contribute to construction waste. Reducing formwork waste can be achieved through careful planning and design to minimize offcuts, using adjustable formwork systems, and implementing quality control measures to prevent damage [138]. The sustainability of formwork is significantly improved by reusing and recycling formwork materials [139]. Steel and aluminium formwork can be reused many times due to their durability, and can be recycled at the end of their life [140]. Timber formwork may also be reused if properly cared for and can also be repurposed or recycled at the end of its life as shown in Figure 3 [29]. Plastic formwork can be recycled, although the feasibility of this depends on the type of plastic used and local recycling facilities [141].

(a) (b)

Figure 3. (**a**) Depot of timber formwork for reuse. (**b**) Reused formwork [29].

The application of digital technology in formwork design and management can also help to improve the overall sustainability of concrete construction. For example, Building Information Modeling (BIM) can be used to enhance formwork design by optimizing the material use and reducing waste [142]. BIM can also improve formwork planning, allowing for better coordination and reducing the risk of damage or errors that could result in waste [50,140]. The sustainability of formwork in concrete construction is a complex issue that involves the consideration of material choices, waste management, and the implementation of technology. While significant progress has been made over the last years, there is still substantial potential for further improvement in formwork practices.

4.4. Safety Considerations

Formwork construction and operations, like all construction activities, comes with certain risks and hazards [143]. Ensuring the safety of construction workers and maintaining the structural integrity of formwork systems are paramount to the successful execution of concrete construction projects [144]. This section will discuss critical safety considerations in formwork design, construction, and stripping, and outline best practices to mitigate potential risks. The formwork design phase sets the foundation for the safe execution of the construction project [145]. Design considerations include load calculations, anticipated concrete pressures, lateral stability, and the use of appropriate safety measures such as guardrails, braces, and ties [146]. Accurate load calculations account for the concrete's weight, any additional loads (e.g., equipment, workers), and potential dynamic loads caused by concrete pouring and vibrations [71]. During the construction phase, it is critical to ensure that the formwork is installed according to the design specifications. Deviations can compromise the structure's integrity and lead to catastrophic failures [1]. Workers should be trained to recognize and manage risks associated with working at heights, handling heavy materials, and working around concrete pours. Proper personal protective equipment (PPE) should be worn at all times, including helmets, safety shoes, gloves, and high-visibility clothing.

Formwork stripping poses a unique set of risks as workers may be injured by falling components, concrete residues, or sudden collapses [93,98]. To mitigate these risks, stripping should be planned and executed under the supervision of a competent person. Workers should be properly trained and use appropriate PPE. Furthermore, stripping should be performed in a sequence that maintains the stability of the structure at all times. Several best practices can enhance safety in formwork operations as discussed in Table 6.

Table 6. Practices to enhance safety in formwork operations.

Safety Practice	Description
Regular inspections	Regular inspections can help identify potential issues before they escalate into serious problems [147]. Inspections should be carried out before pouring concrete, during the pour, and before formwork stripping.
Worker training	Workers should be trained not only in the tasks they need to perform but also in recognizing and managing potential risks. This includes understanding load limits, handling materials safely, and recognizing signs of potential structural instability [148].
Emergency training	All construction sites should have emergency plans in place, including evacuation procedures and immediate action protocols in the event of a formwork failure [149].
Use of technology	Technology can aid in enhancing formwork safety. For example, Building Information Modeling (BIM) can help in planning and visualizing formwork installation and stripping, reducing the likelihood of errors [148]. Similarly, modern monitoring systems can track structural changes in real time, providing early warnings of potential issues [15].

Safety is an integral aspect of formwork operations that should be addressed at every stage of the process. By incorporating robust safety measures into formwork design, construction, and stripping, construction sites can minimize risks, protect workers, and ensure the successful execution of concrete construction projects. The development and adoption of new technologies and best practices should continue to enhance formwork safety in the future.

4.5. Cost Considerations

Formwork constitutes a significant portion (35–60%) of the total cost in concrete construction projects [4]. Hence, understanding and managing the costs associated with formwork is essential for project success. This section will reflect on various aspects of formwork cost analysis, including formwork material costs, labor costs, reuse and recycling considerations, and the impact of technology on formwork costs. The cost of formwork materials can vary widely depending on the type of formwork system used. Traditional timber formwork is generally the cheapest material option, but it has a limited lifespan and can only be reused a few times before its quality degrades [5,29]. On the other hand, metal formwork systems, such as steel or aluminium, have a higher upfront cost but offer a longer lifespan and higher reusability, leading to lower costs in the long run [31,36]. Plastic formwork can also be a cost-effective solution, especially when recycled materials are used [5,32,35]. Labor costs are a major component of formwork costs [150,151]. These include the costs of assembling and disassembling the formwork, inspecting the formwork for safety, and repairing and maintaining the formwork. Factors that can impact labor costs include the complexity of the formwork system, the skill level of the workers, and local wage rates. Labor costs can be reduced through efficient formwork design, worker training, and the use of formwork systems that are easy to assemble and disassemble [95,152].

The ability to reuse and recycle formwork materials can significantly impact the overall formwork cost [5,29,153]. Reusable formwork systems, such as modular or system formwork, may have a higher initial cost but can result in lower costs per use if reused many times [26,95]. Additionally, the salvage value of formwork materials that can be recycled, such as steel or aluminium, can help offset the overall cost [31]. Technological advancements can have a significant impact on formwork costs. Digital technology, such as Building Information Modeling (BIM), can improve formwork design efficiency, reduce material waste, and streamline the construction process, leading to cost savings [50,126,145]. Additionally, technologies like 3D printing offer the potential to create custom formwork components at lower costs [2,40,59]. However, these technologies also require investment in software, equipment, and training. Strategies for optimizing formwork costs are discussed in Table 7.

Table 7. Strategies to optimize formwork costs.

Strategy	Description
Formwork selection	Choosing the right formwork system for the project can result in substantial cost savings. This decision should consider the cost of the formwork material, its lifespan and reusability, labor costs for assembly and disassembly, and the complexity of the concrete structure [94,95].
Efficient design	Efficient formwork design can minimize material use, reduce labor needs, and prevent costly mistakes. This can be facilitated through the use of digital tools like BIM and deep learning [66,71,92,96].
Worker training	Well-trained workers can assemble and disassemble formwork more efficiently and make fewer mistakes, reducing labor costs and material waste [150,151].
Maintenance and care	Proper maintenance and care of formwork materials can extend their lifespan and reusability, lowering the overall cost [154].

Formwork cost analysis is a multifaceted issue that involves considering material costs, labor costs, the impacts of reuse and recycling, and the role of technology. By understanding these factors and applying cost-optimization strategies, it is possible to control and reduce the costs associated with formwork in concrete construction.

5. Case Studies

Case studies provide valuable insights into real-world applications and outcomes of formwork in concrete construction. This section will briefly examine eight diverse case studies, which have been previously reported, and discuss their main findings. The cases are presented in Table 8.

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

Figure 4. The KnitCandela concrete shell [156]. (**a**) Knitted textile formwork (photo: Maria Verhulst); (**b**) first layer of concrete (photo: Mariana Popescu); (**c**) finished concrete shell with textile interior (photo: Angelica Ibarra).

These first three case studies demonstrate the diverse applications and benefits of different formwork systems in concrete construction projects. They also illustrate how the selection of formwork can impact project outcomes in terms of cost, quality, and sustainability. Cases 4–6 provide further insights into the versatile applications of formwork in concrete construction and highlight the crucial role formwork plays in achieving project objectives such as energy efficiency, architectural precision, and process efficiency. The final two cases show how formwork systems can be selected and adapted to meet specific project needs and constraints. All cases demonstrate that the type of formwork chosen plays a crucial role in the project's success, from large complex shell structures to low-cost housing.

Table 8. Previously reported case studies and their main findings.

Case	Type of Formwork	Findings	Demonstration
1	System formwork	Rahim and Haron presented a case study of a 260-unit condominium project in Malaysia, where system formwork was used. The research highlighted the benefits of system formwork in such projects, including faster construction times, lower labor requirements, and high-quality concrete finishes. Despite the higher initial cost of system formwork, the study demonstrated significant cost savings over the project's lifecycle due to the repeated use of the formwork [155].	Selection of formwork
2	Knitted formwork	A study by Popescu et al. demonstrated the design and application of a custom formwork system in the construction of KnitCandela, a complex curved concrete waffle shell structure, as shown in Figure 4. The research demonstrated that the custom-knitted textile formwork allowed for precision in shaping the concrete elements of the structure, despite the high upfront cost. The ability to create advanced concrete elements and shapes, with minimal need for correction or finishing, may lead to overall cost savings in similar projects [156].	
3	Recycled plastic formwork	Lo presented a case study of how the transition from traditional timber formwork to recycled plastic formwork can improve the overall sustainability of the construction industry in Taiwan. The study showed that the use of recycled plastic formwork has the potential to reduce environmental impacts and contribute to achieving sustainability goals in different construction projects. The plastic formwork was found to be lightweight, easy to handle, and provide improved potential for reduced costs and improved recyclability [157].	
4	Insulated concrete formwork	The use of permanent insulated concrete formwork (ICF) to improve energy efficiency was examined by Oloke. They explored a project in the UK that used PIF for the construction of 30 apartments in a two-story residential building. The study discussed that ICF not only offers benefits during the construction phase, such as quick assembly and excellent concrete finishes, but also improves the energy efficiency of the building significantly, reducing heating and cooling costs for the inhabitants. They also mentioned that ICFs offer better soundproofing and reduce the need for maintenance [158].	Versatility of formwork
5	Timber formwork	The role of traditional timber formwork in restoration projects was investigated by Miranda et al. They studied the restoration project of Piscina das Marés, saltwater swimming pools and facilities in Portugal, that required the use of timber formwork to replicate the original architectural details of the concrete surfaces. The study showed that in such specialized scenarios, traditional timber formwork could offer advantages in terms of flexibility and adaptability, even though it required skilled craftsmanship and was more time consuming [159].	
6	BIM optimized formwork	Hyun et al. carried out a study on the impact of Building Information Modeling (BIM) in formwork design for a hospital project. The study demonstrated that the use of BIM technology resulted in a more efficient design process, reduced material wastage, and facilitated better coordination among different construction teams, leading to cost and time savings. They concluded that the implementation of BIM in formwork design has the potential to enable construction managers to make more cost-conscious decisions regarding formwork [96].	
7	Self-climbing formwork	A case study examining the application of self-climbing formwork in constructing the Taizhou Bridge in China was performed by Liu et al. The Taizhou Bridge, with a main span of 1080 m and a maximum tower height of 192 m, presented unique engineering challenges. The study revealed how self-climbing formwork was leveraged to address several of these concrete construction challenges. Despite the initial high cost, the advantages of speedy construction times (30 m^3/h), safety benefits, and excellent quality concrete finishes were evident. This study exemplifies how climbing formwork can be applied to large-scale infrastructure projects where typical formwork systems might not be suitable [160].	Formwork for special purposes
8	3D-printed plastic formwork	Huber et al. investigated the use of 3D-printed plastic forms in a study of automated formwork construction. The project addressed several engineering challenges as it investigated the construction of ribbed concrete slabs with complex geometries, using custom-designed plastic formwork. The research highlighted the cost effectiveness of the customized forms, as they enabled the construction of reinforced concrete slabs with a 40% reduction of concrete compared to solid slabs constructed with traditional forms. In addition, the study found that the automated production of plastic formwork significantly reduced the requirement for skilled labor, enabling structurally efficient slabs, and offering durable, quality finishes [161].	

6. Future Trends

The field of formwork design and use is evolving rapidly, driven by technological innovations, increasing environmental concerns, and the ongoing quest for efficiency and cost effectiveness in the construction industry. This section explores several emerging trends in the scope of formwork design and use, which could potentially revolutionize how concrete construction will be approached in the future.

Digital technologies are predicted to have a significant impact on formwork design and use over the upcoming years. These technologies, including Building Information Modeling (BIM) [162], Augmented Reality (AR) [163], 3D printing [164], and Artificial

Intelligence (AI) [165], offer promising solutions to enhance efficiency, accuracy, and safety in formwork processes [166]. Building Information Modeling (BIM) involves the digital representation of physical and functional characteristics of a facility and is being increasingly used in matters of formwork design and optimization. It allows for more precise planning, leading to optimized formwork solutions, reduced material use and waste, and improved coordination among different construction teams. As BIM technology continues to advance, its wide range of application in formwork design is likely to become more widespread. Augmented Reality (AR) superimposes a computer-generated image on a user's view of the real world and can therefore provide valuable assistance in terms of formwork assembly and inspection processes. By visualizing the correct assembly of formwork components and identifying potential issues before they occur, AR can contribute to enhanced safety, accuracy, and efficiency on construction sites. The fast advancements in the field of 3D-printing technologies have highlighted exciting possibilities for a wide range of specialized and complex applications in formwork design and production. 3D printing offers the potential to produce complex formwork shapes that would be difficult and time consuming to create using traditional methods. This can lead to more architectural freedom, reduced labor costs, and quicker construction times. Moreover, 3D-printed formwork can be made from a variety of novel or recycled materials, contributing to important sustainability improvements in the field of concrete construction.

Sustainability is becoming a key concern in the construction industry, which is constantly exploring the opportunities of reduced environmental impact through the development of new materials [130], technologies [167], and circular concepts [168]. This has led to the development of more sustainable formwork systems, including the use of recycled or recyclable materials, reusable formwork, and permanent formwork that becomes an integral part of the final structure. The use of recycled materials in formwork production can significantly reduce the environmental impact of construction activities. Examples include recycled plastic formwork and formwork including waste products such as fly ash or rubber. Reusable formwork systems offer the advantage of reducing material consumption and waste over a period of several construction projects. They can also be more cost effective over the lifespan of only one single project, as the formwork can be used multiple times even within the same project. Permanent formwork systems, such as Insulating Concrete Forms (ICFs) or Permanent Insulated Formworks (PIFs), can enhance the energy efficiency, as well as the acoustic properties of buildings, but it also offers the advantage of reducing waste from formwork removal and disposal.

Safety is always a key concern in the construction industry and is also important to consider during formwork design and operation. Innovations in formwork safety include the development of safer formwork systems [169] and the use of safety enhancing technologies [170]. Safer formwork systems focus on improving the stability and robustness of formwork structures, reducing the risk of failures that can affect both the safety and the quality of the concrete structure. They also aim to enhance worker safety during formwork assembly and disassembly, for instance, through safer connecting mechanisms and protection systems against falls. Technological innovations can also enhance safety in formwork operations. For example, sensors can be used to monitor formwork loads and environmental conditions, providing early warnings of potential safety issues. Advanced sensors and intelligent systems can be embedded into the formwork to continuously monitor and predict the form pressure, but they can also improve safety by detecting early signs of failure. Real-time data from sensors can provide valuable insights for adjusting the construction processes, enhancing the overall safety, productivity, and quality of concrete operations. Robotic technology is another promising trend in enhancing safety [171]. Robots can be utilized for heavy lifting, precise placement of formwork panels, and performing repetitive tasks, reducing human exposure to hazardous situations. While the initial implementation of robotic technology could be expensive, the long-term benefits in terms of safety, efficiency, and cost savings have the potential of becoming substantial. Prefabricated and modular formwork systems are gaining popularity due to their potential to reduce construction times, improve the quality of concrete structures, and decrease labor requirements [172]. These systems typically involve the production of formwork components off site, which are then transported to the construction site for assembly. The advantages include increased control over formwork quality, reduced need for skilled labor on site, and faster construction times due to the ability to assemble large formwork sections simultaneously.

The future will most likely witness the development of 'smart' formwork systems that integrate a combination of the above trends. These systems could for example include digitally designed and prefabricated formwork systems, utilizing recycled and sustainable materials, while being equipped with integrated sensors for the real-time monitoring and utilizing of Artificial Intelligence to predict the outcome. Such systems will offer unparalleled benefits in terms of cost effectiveness, quality control, safety, and sustainability. The future of formwork design and use offers many emerging possibilities as the understanding and technologies continue to develop. Emerging technologies, combined with a drive towards more sustainable and safer construction practices, offer several opportunities to transform formwork practices in the construction industry.

7. Conclusions

The engineering aspects of formwork for concrete construction include several complex but critical considerations in the construction process. This paper provided a comprehensive examination of these aspects, including the application of different formwork types, their design based on form pressure, the requirements of formwork stripping, the impact of alternative binders, and their part in improving the sustainability of concrete construction. Different types of formwork systems present unique benefits and drawbacks in terms of cost, durability, flexibility, and environmental impact. The choice of a suitable system depends on the specifics of the project in consideration, from its scope to its allocated budget. For example, the emerging use of Insulated Concrete Forms (ICFs) presents promising possibilities for energy-efficient and cost-effective houses. In terms of formwork design, accurate form pressure calculation, influenced by factors like the mix design of concrete, the rate of placement, and ambient temperature, is crucial for the overall safety and can therefore be used as a type of quality assurance. The form stripping process is another important aspect, with its timing and methodology impacting the integrity and appearance of the final structure.

The paper also discussed the significance of sustainability in formwork systems. This can be achieved by choosing sustainable materials to promote recycling and reuse, as the industry moves rapidly towards more environmentally friendly practices. Safety considerations are also important aspects of formwork use in construction, with proper design, assembly and dismantling practices, worker training, and technological systems contributing to improved safety. A comprehensive understanding of formwork costs must consider material expenses, as well as labor costs, assembly and dismantling times, and maintenance requirements. The case studies of the paper illustrated the diverse applications and versatility of formwork systems in various projects, demonstrating the need to adapt formwork solutions to specific project requirements and constraints.

Promising future trends such as digital technologies, modular formwork, and 'smart' systems provide excellent opportunities to enhance efficiency, safety, and sustainability in formwork operations. The adoption of innovative technologies and materials offers significant benefits compared to traditional options, but this also presents new challenges such as the need for training, uncertainty of new materials, and the requirement for regulatory frameworks. Future research could further investigate the real-world application and performance of the new formwork materials and technologies discussed in this paper. Further exploration in these areas will support the journey towards more effective and sustainable practices in concrete construction.

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References

1. Hurd, M.K. *Formwork for Concrete*, 7th ed.; American Concrete Institute: Farmington Hills, MI, USA, 2005.
2. Wang, L.; Yang, Y.; Yao, L.; Ma, G. Interfacial bonding properties of 3D printed permanent formwork with the post-casted concrete. *Cem. Concr. Compos.* **2022**, *128*, 104457. [CrossRef]
3. Devi, K.; Yadav, T. Cost Comparison of Different Types of Formworks. *J. Build. Mater. Sci.* **2023**, *5*, 32–38. [CrossRef]
4. Kreiger, E.L.; Kreiger, M.A.; Case, M.P. Development of the construction processes for reinforced additively constructed concrete. *Add. Manuf.* **2019**, *28*, 39–49. [CrossRef]
5. 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]
6. Duarte, G.; Brown, N.; Memari, A.; Duarte, J.P. Learning from historical structures under compression for concrete 3D printing construction. *J. Build. Eng.* **2021**, *43*, 103009. [CrossRef]
7. Vitti, P. Mortars and masonry—Structural lime and gypsum mortars in antiquity and Middle Ages. *Archae. Anthrop. Sci.* **2021**, *13*, 164. [CrossRef]
8. Das, R.; Bhattacharya, I.; Saha, R. Comparative study between different types of formwork. *Int. Res. J. Adv. Eng. Sci.* **2016**, *1*, 173–175.
9. Wang, Z.; Liang, X.; Wang, Y.; Zhai, T. Experimental and theoretical investigations on the flexural behavior of RC slabs with steel-PVA hybrid fiber reinforced cementitious composite (HFRCC) permanent formwork. *Case Stud. Constr. Mater.* **2022**, *17*, e01432. [CrossRef]
10. Liu, Y.; Zhang, J.; Chang, J.; Xie, S.; Zhao, Y. Effect of the Thermal Insulation Cover Curing on Temperature Rise and Early-Age Strength of Concrete. *Materials* **2022**, *15*, 2781. [CrossRef]
11. Mishra, M.; Lourenço, P.B.; Ramana, G.V. Structural health monitoring of civil engineering structures by using the internet of things: A review. *J. Build. Eng.* **2022**, *48*, 103954. [CrossRef]
12. Gamil, Y.; Nilimaa, J.; Emborg, M.; Cwirzen, A. Lateral Formwork Pressure for Self-Compacting Concrete—A Review of Prediction Models and Monitoring Technologies. *Materials* **2021**, *14*, 4767. [CrossRef] [PubMed]
13. Nilimaa, J. Lateral Form Pressure Induced by SCC. In Proceedings of the Nordic Concrete Research XXIV NCR Symposium 2022, Stockholm, Sweden, 17–19 August 2022.
14. Gamil, Y.; Cwirzen, A.; Nilimaa, J.; Emborg, M. The Impact of Different Parameters on the Formwork Pressure Exerted by Self-Compacting Concrete. *Materials* **2023**, *16*, 759. [CrossRef] [PubMed]
15. Gamil, Y.; Nilimaa, J.; Cwirzen, A.; Emborg, M. Experimental based assessment of formwork pressure theoretical design models for self-compacting concrete. *J. Build. Eng.* **2023**, *68*, 106085. [CrossRef]
16. Collivignarelli, M.C.; Abba, A.; Miino, M.C.; Cillari, G.; Ricciardi, P. A review on alternative binders, admixtures and water for the production of sustainable concrete. *J. Clean. Prod.* **2021**, *295*, 126408. [CrossRef]
17. Hossain, M.U.; Liu, J.C.; Xuan, D.; Ng, S.T.; Ye, H.; Abdulla, S.J. Designing sustainable concrete mixes with potentially alternative binder systems: Multicriteria decision making process. *J. Build. Eng.* **2022**, *45*, 103587. [CrossRef]
18. Nilimaa, J. Smart materials and technologies for sustainable concrete construction. *Devel. Built Env.* **2023**, *15*, 100177. [CrossRef]
19. Nilimaa, J.; Zhaka, V. An Overview of Smart Materials and Technologies for Concrete Construction in Cold Weather. *Eng* **2023**, *4*, 1550–1580. [CrossRef]
20. Busch, P.; Kendall, A.; Murphy, C.W.; Miller, S.A. Literature review on policies to mitigate GHG emissions for cement and concrete. *Reso. Conserv. Recycl.* **2022**, *182*, 106278. [CrossRef]
21. Sithole, N.T.; Tsotetsi, N.T.; Mashifana, T.; Sillanpää, M. Alternative cleaner production of sustainable concrete from waste foundry sand and slag. *J. Clean. Prod.* **2022**, *336*, 130399. [CrossRef]
22. Lehne, J.; Preston, F. Making Concrete Change: Innovation in Low-carbon Cement and Concrete, Chatham House. United Kingdom. Available online: https://policycommons.net/artifacts/1423241/making-concrete-change/2037504/ (accessed on 14 July 2023).
23. Tayeh, B.A.; Hamada, H.M.; Almeshal, I.; Bakar, B.A. Durability and mechanical properties of cement concrete comprising pozzolanic materials with alkali-activated binder: A comprehensive review. *Case Stud. Constr. Mater.* **2022**, *17*, e01429. [CrossRef]
24. Mehsas, B.; Siline, M.; Zeghichi, L. The effect of using low reactive metakaolin on performances of geopolymer binder. *Innov. Infra. Sol.* **2022**, *7*, 233. [CrossRef]
25. Gowripalan, N.; Shakor, P.; Rocker, P. Pressure exerted on formwork by self-compacting concrete at early ages: A review. *Case Stud. Constr. Mater.* **2021**, *15*, e00642. [CrossRef]

26. Fakhratov, M.A.; Akbari, M.S.; Hosaini, A.; Dayoub, N. Comparison of the tunnel formwork system and traditional formwork system. *AIP Conf. Proc.* **2022**, *2559*, 060009. [CrossRef]
27. Ling, Y.Y.; Leo, K.C. Reusing timber formwork: Importance of workmen's efficiency and attitude. *Build. Env.* **2000**, *3*, 135–143. [CrossRef]
28. Tierney, L.; Safiuddin, M. Insights into Concrete Forming, Reinforcing, and Pouring in Building Construction. *Buildings* **2022**, *12*, 1303. [CrossRef]
29. Pronk, A.; Brancart, S.; Sanders, F. Reusing Timber Formwork in Building Construction: Testing, Redesign, and Socio-Economic Reflection. *Urb. Plan.* **2022**, *7*, 81–96. [CrossRef]
30. Czarnecki, S.; Sadowski, Ł. Morphological properties of the cement skin: Understanding the effect of contact with formwork. *Case Stud. Constr. Mater.* **2022**, *16*, e01007. [CrossRef]
31. Li, S.; Wang, J.; Yu, Z.; Li, Y.; Guo, H. Study on the Bearing Capacity of Steel Formwork Concrete Columns. *Buildings* **2023**, *13*, 820. [CrossRef]
32. Luo, D.; Zou, X. Analysis of GMT Composite Material-based Building Formwork. *J. Phys. Conf. Ser.* **2023**, *2510*, 012014. [CrossRef]
33. Sun, H.; Liu, Q.; Li, Y.; Liu, M. The Factors Influencing the Saving of Energy and the Reduction of Emissions in the Construction Companies of Prefabricated Buildings. *J. Civ. Eng. Urb. Plan.* **2023**, *5*, 70–75. [CrossRef]
34. Gao, K.; Xu, J.; Zhu, Y.; Zhang, Z.; Zeng, Q. Study on the Technology and Mechanism of Cleaning Architectural Aluminum Formwork for Concrete Pouring by High Energy and High Repetition Frequency Pulsed Laser. *Photonics* **2023**, *10*, 242. [CrossRef]
35. Din, I.M.U.; Kumar, C. Impact of Plastic Formwork over Conventional Formwork. *Int. J. Sci. Eng. Rese.* **2015**, *5*, 478–483.
36. Mukhopadhyay, B.; Bose, R.; Roy, S. A Strategical Method of Proper Resizing and Reusing of Construction Formwork Materials. In Proceedings of the Smart and Sustainable Technologies: Rural and Tribal Development Using IoT and Cloud Computing: Proceedings of ICSST 2021, Odisha, India, 16–18 December 2021. [CrossRef]
37. Gericke, O.; Kovaleva, D.; Haase, W.; Sobek, W. Fabrication of Concrete Parts Using a Frozen Sand Formwork. In Proceedings of the IASS Annual Symposia, Tokyo, Japan, 26–30 September 2016.
38. Gericke, O.; Kovaleva, D.; Haase, W.; Sobek, W. Production of Curved Concrete Sandwich Panels Using a Frozen Sand Formwork. In Proceedings of the IASS Annual Symposia, Hamburg, Germany, 25–28 September 2017.
39. Aghaei Meibodi, M.; Jipa, A.; Giesecke, R.; Shammas, D.; Bernhard, M.; Leschok, M.; Graser, K.; Dillenburger, B. Smart Slab: Computational Design and Digital Fabrication of a Lightweight Concrete Slab. In Proceedings of the Acadia 2018 Recalibration: On Imprecision and Infidelity: Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture, Mexico City, Mexico, 18–20 October 2018.
40. Jipa, M.A.; Aghaei Meibodi, M.; Giesecke, R.; Shammas, D.; Leschok, M.; Bernhard, M.; Dillenburger, B. 3D-Printed Formwork for Prefabricated Concrete slabs. In Proceedings of the 1st International Conference on 3D Construction Printing (3DcP), Melbourne, Australia, 26–28 November 2018.
41. Sitnikov, V. Ice formwork for high-performance concrete: A model of lean production for prefabricated concrete industry. *Structures* **2019**, *18*, 109–116. [CrossRef]
42. Sitnikov, V. Ice Formwork for Ultra-High Performance Concrete: Simulation of Ice Melting Deformations. In Proceedings of the Design Modelling Symposium, Paris, France, 16–20 September 2017. [CrossRef]
43. Sitnikov, V. Ice Formwork for High-Performance Concrete: A Model of Lean Production for Prefabricated Concrete Industry. In Proceedings of the IASS Annual Symposia, Boston, MA, USA, 16–20 July 2018.
44. Barnett, E. The Design of an Integrated System for Rapid Prototyping with Ice. Ph.D. Thesis, McGill University, Montreal, QC, Canada, May 2012.
45. Pronk, A.; Moonen, Y.; Ao, C.; Luo, P.; Wu, Y. 3D Printing of Ice. In Proceedings of the IASS Annual Symposia, Hamburg, Germany, 25–28 September 2017.
46. Pronk, A.; Jansen, D.; Kara, K.; Laar, J.V.; Willems, H. Structural Behavior of Ice Composite for 3D Printing. In Proceedings of the IASS Annual Symposia, Barcelona, Spain, 7–10 October 2019.
47. Sitnikov, V. Ice Formwork: The Rationale and Potential of Ice-Based Moulding Systems for the Production of Complex-Geometry Precast Concrete. Ph.D. Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 3 December 2020.
48. Wei, L. An Innovative Formwork System Based on Ice and Sand for Casting Optimised Concrete Components. Ph.D. Thesis, RMIT University, Melbourne, Australia, 7 December 2022.
49. Zhang, R.; Hu, P.; Zheng, X.; Cai, L.; Guo, R.; Wei, D. Shear behavior of RC slender beams without stirrups by using precast U-shaped ECC permanent formwork. *Constr. Build. Mater.* **2020**, *260*, 120430. [CrossRef]
50. Jin, Z.; Gambatese, J. BIM for Temporary Structures: Development of a Revit API Plug-in for Concrete Formwork. In Proceedings of the CSCE Annual Conference, Laval, QC, Canada, 12–15 June 2019.
51. Jiang, X.; Zhang, S.; Gu, Z.; Wang, L.; Zhao, Y. Study on Permanent Thermal Insulation Formwork of Mass Concrete Prepared by Different Types of Nano-modified Lightweight Aggregate. *J. Phys. Conf. Ser.* **2021**, *2011*, 012070. [CrossRef]
52. Murillo, M.; Tutikian, B.F.; Ortolan, V.; Oliveira, M.L.; Sampaio, C.H.; Gómez, L. Fire resistance performance of concrete-PVC panels with polyvinyl chloride (PVC) stay in place (SIP) formwork. *J. Mater. Rese. Tech.* **2019**, *8*, 4094–4107. [CrossRef]
53. Leung, C.K.; Cao, Q. of pseudo-ductile permanent formwork for durable concrete structures. *Mater. Struct.* **2010**, *43*, 993–1007. [CrossRef]

54. Bruno, R.; Carpino, C.; Bevilacqua, P.; Settino, J.; Arcuri, N. A novel Stay–In–Place formwork for vertical walls in residential nZEB developed for the Mediterranean climate: Hygrothermal, energy, comfort and economic analyses. *J. Build. Eng.* **2022**, *45*, 103593. [CrossRef]
55. Mantesi, E.; Hopfe, C.J.; Mourkos, K.; Glass, J.; Cook, M. Empirical and computational evidence for thermal mass assessment: The example of insulating concrete formwork. *Ener. Build.* **2019**, *188*, 314–332. [CrossRef]
56. Kanagaraj, B.; Kiran, T.; Gunasekaran, J.; Nammalvar, A.; Arulraj, P.; Gurupatham, B.G.A.; Roy, K. Performance of Sustainable Insulated Wall Panels with Geopolymer Concrete. *Materials* **2022**, *15*, 8801. [CrossRef]
57. Kashan, M.E.; Fung, A.S.; Eisapour, A.H. Insulated concrete form foundation wall as solar thermal energy storage for Cold-Climate building heating system. *Ener. Conv. Mana. X* **2023**, *19*, 100391. [CrossRef]
58. Sharma, A.; Mishra, I.; Anurag. Review of Modern Techniques and Automation in the Construction Industry. *Sust. Infrastr. Dev.* **2022**, *199*, 21–30. [CrossRef]
59. Jipa, A.; Dillenburger, B. 3D printed formwork for concrete: State-of-the-art, opportunities, challenges, and applications. *3D Print. Add. Manuf.* **2022**, *9*, 84–107. [CrossRef] [PubMed]
60. Cruz, A.S.; Cunha, E.G.D. The impact of climate change on the thermal-energy performance of the SCIP and ICF wall systems for social housing in Brazil. *Indoor Built Env.* **2022**, *31*, 838–852. [CrossRef]
61. Leschok, M.; Dillenburger, B. Dissolvable 3DP Formwork. In Proceedings of the Association for Computer Aided Design in Architecture, Austin, TX, USA, 24–26 October 2019.
62. Farahbakhsh, M.; Borhani, A.; Kalantar, N.; Rybkowski, Z. PRINT in PRINT: A Nested Robotic Fabrication Strategy for 3D Printing Dissolvable Formwork of a Stackable Column. In Proceedings of the CAAD Futures, Los Angeles, CA, USA, 16–18 July 2021. [CrossRef]
63. Travush, V.; Erofeev, V.; Bulgakov, A.; Buzalo, N. Mechatronic complex based on sliding formwork for the construction of monolithic high-rise buildings and tower-type structures made of reinforced concrete. *IOP Conf. Ser. Mater. Sci. Eng.* **2022**, *913*, 022009. [CrossRef]
64. Hong, G.H.; Jung, S.W. Development of auto-climbing formwork system for composite core walls. *J. Asian Arch. Build. Eng.* **2022**, *21*, 511–520. [CrossRef]
65. Henriksen, T.; Lo, S.; Knaack, U.; Kirkegaard, P.H. Developing and testing a novel manufacturing method for complex geometry thin-walled GFRC panels by fabricating a 10 m high, self-supporting GFRC hyperbolic shell. *Arch. Eng. Des. Mana.* **2022**, *19*, 480–510. [CrossRef]
66. 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]
67. Gregori, A.; Ferron, R.P.; Sun, Z.; Shah, S.P. Experimental simulation of self-consolidating concrete formwork pressure. *ACI Mater. J.* **2008**, *105*, 97.
68. Glinicki, M.A.; Gołaszewski, J.; Cygan, G. Formwork Pressure of a Heavyweight Self-Compacting Concrete Mix. *Materials* **2021**, *14*, 1549. [CrossRef]
69. Billberg, P. Form Pressure Generated by Self-Compacting Concrete: Influence of Thixotropy and Structural Behaviour at Rest. Ph.D. Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 27 October 2006.
70. Perrot, A.; Pierre, A.; Vitaloni, S.; Picandet, V. Prediction of lateral form pressure exerted by concrete at low casting rates. *Mater. Struct.* **2015**, *48*, 2315–2322. [CrossRef]
71. Proske, T.; Khayat, K.H.; Omran, A.; Leitzbach, O. Form pressure generated by fresh concrete: A review about practice in formwork design. *Mater. Struct.* **2014**, *47*, 1099–1113. [CrossRef]
72. Kim, J.H.; Noemi, N.; Shah, S.P. Effect of powder materials on the rheology and formwork pressure of self-consolidating concrete. *Cem. Concr. Comp.* **2012**, *34*, 746–753. [CrossRef]
73. Talesnick, M.; Katz, A. Measuring lateral pressure of concrete: From casting through hardening. *Constr. Build. Mater.* **2012**, *34*, 211–217. [CrossRef]
74. Assaad, J.; Khayat, K.H.; Mesbah, H. Variation of formwork pressure with thixotropy of self-consolidating concrete. *Mater. J.* **2003**, *100*, 29–37.
75. Jiao, D.; De Schryver, R.; Shi, C.; De Schutter, G. Thixotropic structural build-up of cement-based materials: A state-of-the-art review. *Cem. Concr. Comp.* **2021**, *122*, 104152. [CrossRef]
76. Santilli, A.; Teixeira, S.; Puente, I. Influence of temperature and concrete reinforcement on vertical formwork design. *Constr. Build. Mater.* **2015**, *88*, 188–195. [CrossRef]
77. Nilimaa, J.; Hösthagen, A.; Emborg, M. Thermal Crack Risk of Concrete Structures: Evaluation of Theoretical Models for Tunnels and Bridges. *Nordic Concr. Rese.* **2017**, *56*, 55–69.
78. Nilimaa, J.; Zhaka, V. Material and Environmental Aspects of Concrete Flooring in Cold Climate. *Constr. Mater.* **2023**, *3*, 180–201. [CrossRef]
79. Surahyo, A. Hot and cold weather concreting. In *Concrete Construction: Practical Problems and Solutions*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 257–272. [CrossRef]
80. Ghoddousi, P.; Shirzadi Javid, A.A.; Ghodrati Amiri, G.; Donyadideh, K. Predicting the formwork lateral pressure of self-consolidating concrete based on experimental thixotropy values. *Int. J. Civ. Eng.* **2019**, *17*, 1131–1144. [CrossRef]

81. Cygan, G.; Golaszewski, J.; Drewniok, M.P. Influence on Type of Cement on the SCC Formwork Pressure during and after Casting. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *471*, 112025. [CrossRef]
82. De Schutter, G.; Bartos, P.J.; Domone, P.; Gibbs, J. *Self-Compacting Concrete*; Whittles Publishing: Dunbeath, Scotland, 2008.
83. Khayat, K.H.; Assaad, J.J. Use of thixotropy-enhancing agent to reduce formwork pressure exerted by self-consolidating concrete. *ACI Mater. J.* **2008**, *105*, 88–96.
84. Assaad, J.; Khayat, K.H. Kinetics of formwork pressure drop of self-consolidating concrete containing various types and contents of binder. *Cem. Concr. Rese.* **2005**, *35*, 1522–1530. [CrossRef]
85. Roby, H.G. Pressure of concrete on forms. *Civ. Eng.* **1935**, *5*, 162–166.
86. Gardner, N.J. Pressure of concrete against formwork. *J. Proc.* **1980**, *77*, 279–286. [CrossRef]
87. Billberg, P.H.; Roussel, N.; Amziane, S.; Beitzel, M.; Charitou, G.; Freund, B.; Gardner, N.J.; Grampeix, G.; Graubner, C.-A.; Keller, L.; et al. Field validation of models for predicting lateral form pressure exerted by SCC. *Cem. Concr. Comp.* **2014**, *54*, 70–79. [CrossRef]
88. Ovarlez, G.; Roussel, N. A physical model for the prediction of lateral stress exerted by self-compacting concrete on formwork. *Mater. Struct.* **2006**, *39*, 269–279. [CrossRef]
89. Henschen, J.D.; Castaneda, D.I.; Lange, D.A. Formwork pressure model for self-consolidating concrete using pressure decay signature. *ACI Mater. J.* **2018**, *115*, 339–348. [CrossRef]
90. Kwon, S.H.; Phung, Q.T.; Park, H.Y.; Kim, J.H.; Shah, S.P. Effect of wall friction on variation of formwork pressure over time in self-consolidating concrete. *Cem. Concr. Rese.* **2011**, *41*, 90–101. [CrossRef]
91. *DIN 18218:2010-01*; Pressure of Fresh Concrete on Vertical Formwork. Beuth Verlag: Berlin/Heidelberg, Germany, 2010. [CrossRef]
92. Lu, Z.; Zhang, M.; Guo, C. Dynamic performance of high supporting formwork under horizontal impact load. *Int. J. Sim. Proc. Mod.* **2019**, *14*, 407–419. [CrossRef]
93. Moon, S.; Yang, B.; Choi, E. Safety guideline for safe concrete placement utilizing the information on the structural behavior of formwork. *J. Constr. Eng. Mana.* **2018**, *144*, 04018108. [CrossRef]
94. Rajeshkumar, V.; Anandaraj, S.; Kavinkumar, V.; Elango, K.S. Analysis of factors influencing formwork material selection in construction buildings. *Mater. Today Proc.* **2021**, *37*, 880–885. [CrossRef]
95. Terzioglu, T.; Polat, G.; Turkoglu, H. Analysis of Formwork System Selection Criteria for Building Construction Projects: A Comparative Study. *Buildings* **2021**, *11*, 618. [CrossRef]
96. Hyun, C.; Jin, C.; Shen, Z.; Kim, H. Automated optimization of formwork design through spatial analysis in building information modeling. *Auto. Constr.* **2018**, *95*, 193–205. [CrossRef]
97. John, S.T.; Mohan, A.; Philip, M.S.; Sarkar, P.; Davis, R. An IoT device for striking of vertical concrete formwork. *Eng. Constr. Arch. Mana.* **2022**, *29*, 1991–2010. [CrossRef]
98. Chellappa, V.; Salve, U.R. Understanding the fall-related safety issues in concrete formwork. *E3S Web Conf.* **2021**, *263*, 02007. [CrossRef]
99. Long, A.E.; Henderson, G.D.; Montgomery, F.R. Why assess the properties of near-surface concrete? *Constr. Build. Mater.* **2001**, *15*, 65–79. [CrossRef]
100. Evans, S. Architectural concrete: Case study of a high quality off-form concrete finish. *Aus. J. Civ. Eng.* **2003**, *1*, 77–84. [CrossRef]
101. Richardson, M. Degradation of concrete in cold weather conditions. In *Durability of Concrete and Cement Composites*; Page, C.L., Page, M.M., Eds.; Woodhead Publishing Limited: Cambridge, UK, 2007; pp. 282–315.
102. Cui, J.; Duc Van, N.; Zhang, F.; Hama, Y. Evaluation of Applicability of Minimum Required Compressive Strength for Cold Weather Concreting Based on Winter Meteorological Factors. *Materials* **2022**, *15*, 8490. [CrossRef]
103. Meeks, K.W.; Carino, N.J. *Curing of High-Performance Concrete: Report of the State-of-the-Art, NSTIR 6295*; US Department of Commerce, Technology Administration, National Institute of Standards and Technology: Gaithersburg, MD, USA, 1999.
104. Muller, J.R. Monitoring concrete temperature to determine formwork stripping time. *Civ. Eng.* **1984**, *10*, 501–506. Available online: https://hdl.handle.net/10520/AJA10212019_13653 (accessed on 17 July 2023).
105. Hajibabaee, A.; Behravan, A.; O'Quinn, K.; Robertson, B.; Ley, M.T. Impact of Early Formwork Removal on Concrete Drying and Chloride Ion Diffusion. *J. Mater. Civ. Eng.* **2023**, *35*, 04023171. [CrossRef]
106. Rudeli, N.; Santilli, A.; Arrambide, F. Striking of vertical concrete elements: An analysis using the maturity method. *Eng. Struct.* **2015**, *95*, 40–48. [CrossRef]
107. Skibicki, S. Optimization of Cost of Building with Concrete Slabs Based on the Maturity Method. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *245*, 022061. [CrossRef]
108. Azkune, M.; Puente, I.; Santilli, A. Shore overloads during shoring removal. *Eng. Struct.* **2010**, *32*, 3629–3638. [CrossRef]
109. Mosallam, K.; Chen, W.F. Design considerations for formwork in multistorey concrete buildings. *Eng. Struct.* **1990**, *12*, 163–172. [CrossRef]
110. Srividya, T.; Kannan Rajkumar, P.R.; Sivasakthi, M.; Sujitha, A.; Jeyalakshmi, R. A state-of-the-art on development of geopolymer concrete and its field applications. *Case Stud. Constr. Mater.* **2022**, *16*, e00812. [CrossRef]
111. Song, Q.; Guo, M.Z.; Ling, T.C. A review of elevated-temperature properties of alternative binders: Supplementary cementitious materials and alkali-activated materials. *Constr. Build. Mater.* **2022**, *341*, 127894. [CrossRef]
112. Revilla-Cuesta, V.; Evangelista, L.; de Brito, J.; Skaf, M.; Manso, J.M. Shrinkage prediction of recycled aggregate structural concrete with alternative binders through partial correction coefficients. *Cem. Concr. Compos.* **2022**, *129*, 104506. [CrossRef]

113. Adesina, A. Recent advances in the concrete industry to reduce its carbon dioxide emissions. *Env. Chall.* **2020**, *1*, 100004. [CrossRef]
114. Bhattacherjee, S.; Basavaraj, A.S.; Rahul, A.V.; Santhanam, M.; Gettu, R.; Panda, B.; Schlangen, E.; Chen, Y.; Copuroglu, O.; Ma, G.; et al. Sustainable materials for 3D concrete printing. *Cem. Concr. Compos.* **2021**, *122*, 104156. [CrossRef]
115. Miller, S.A.; Myers, R.J. Environmental impacts of alternative cement binders. *Env. Sci. Tech.* **2019**, *54*, 677–686. [CrossRef] [PubMed]
116. Naqi, A.; Jang, J.G. Recent Progress in Green Cement Technology Utilizing Low-Carbon Emission Fuels and Raw Materials: A Review. *Sustainability* **2019**, *11*, 537. [CrossRef]
117. Singh, N.B.; Middendorf, B. Geopolymers as an alternative to Portland cement: An overview. *Constr. Build. Mater.* **2020**, *237*, 117455. [CrossRef]
118. Peng, Y.; Unluer, C. Development of alternative cementitious binders for 3D printing applications: A critical review of progress, advantages and challenges. *Compos. B Eng.* **2022**, *252*, 110492. [CrossRef]
119. Bhavani, S.; Prasad, M.L.V. Strength and durability properties of SCC developed using limestone calcined clay cement (LC3). *Mater. Today Proc.* **2023**. *In Press*. [CrossRef]
120. Redondo-Soto, C.; Morales-Cantero, A.; Cuesta, A.; Santacruz, I.; Gastaldi, D.; Canonico, F.; Aranda, M.A. Limestone calcined clay binders based on a Belite-rich cement. *Cem. Concr. Rese.* **2023**, *163*, 107018. [CrossRef]
121. Aldawsari, S.; Kampmann, R.; Harnisch, J.; Rohde, C. Setting Time, Microstructure, and Durability Properties of Low Calcium Fly Ash/Slag Geopolymer: A Review. *Materials* **2022**, *15*, 876. [CrossRef]
122. Li, L.; Xie, J.; Zhang, B.; Feng, Y.; Yang, J. A state-of-the-art review on the setting behaviours of ground granulated blast furnace slag-and metakaolin-based alkali-activated materials. *Constr. Build. Mater.* **2023**, *368*, 130389. [CrossRef]
123. Kim, B.-J.; Lee, G.-W.; Choi, Y.-C. Hydration and Mechanical Properties of High-Volume Fly Ash Concrete with Nano-Silica and Silica Fume. *Materials* **2022**, *15*, 6599. [CrossRef]
124. Zhang, P.; Sun, X.; Wang, F.; Wang, J. Mechanical Properties and Durability of Geopolymer Recycled Aggregate Concrete: A Review. *Polymers* **2023**, *15*, 615. [CrossRef]
125. Zhao, Y.; Zhang, Y. A Review on Hydration Process and Setting Time of Limestone Calcined Clay Cement (LC3). *Solids* **2023**, *4*, 24–38. [CrossRef]
126. Grebenkov, D.S. Depletion of resources by a population of diffusing species. *Phys. Rev. E* **2022**, *105*, 054402. [CrossRef] [PubMed]
127. Wada, Y.; Van Beek, L.P.; Van Kempen, C.M.; Reckman, J.W.; Vasak, S.; Bierkens, M.F. Global depletion of groundwater resources. *Geophys. Res. Lett.* **2010**, *37*, L20402. [CrossRef]
128. de Andrade Salgado, F.; de Andrade Silva, F. Recycled aggregates from construction and demolition waste towards an application on structural concrete: A review. *J. Build. Eng.* **2022**, *52*, 104452. [CrossRef]
129. Eštoková, A.; Wolfová Fabiánová, M.; Ondová, M. Concrete structures and their impacts on climate change and water and raw material resource depletion. *Int. J. Civ. Eng.* **2022**, *20*, 735–747. [CrossRef]
130. Li, W.; Lin, X.; Xie, Y.M. A sustainable formwork system based on ice pattern and sand mould for fabricating customised concrete components. *Rapid Prototyping J.* **2023**, *29*, 639–654. [CrossRef]
131. Mandala, R.S.K.; Nayaka, R.R. A state of art review on time, cost and sustainable benefits of modern construction techniques for affordable housing. *Constr. Innov.* **2023**. *In press*. [CrossRef]
132. Bamwesigye, D.; Chipfakacha, R.; Yeboah, E. Forest and Land Rights at a Time of Deforestation and Climate Change: Land and Resource Use Crisis in Uganda. *Land* **2022**, *11*, 2092. [CrossRef]
133. Sheppard, J.P.; Chamberlain, J.; Agúndez, D.; Bhattacharya, P.; Chirwa, P.W.; Gontcharov, A.; Sagona, W.C.J.; Shen, H.L.; Tadesse, W.; Mutke, S. Sustainable forest management beyond the timber-oriented status quo: Transitioning to co-production of timber and non-wood forest products—A global perspective. *Curr. Forest. Rep.* **2020**, *6*, 26–40. [CrossRef]
134. Nidheesh, P.V.; Kumar, M.S. An overview of environmental sustainability in cement and steel production. *J. Clean. Prod.* **2019**, *231*, 856–871. [CrossRef]
135. Nam, K.-Y.; Lim, M.-K. Life Cycle Environmental Impact Assessment and Applicability of Synthetic Resin Formwork. *Materials* **2023**, *16*, 696. [CrossRef] [PubMed]
136. Ferreira-Filipe, D.A.; Paço, A.; Duarte, A.C.; Rocha-Santos, T.; Patrício Silva, A.L. Are Biobased Plastics Green Alternatives?—A Critical Review. *Int. J. Environ. Res. Public Health* **2021**, *18*, 7729. [CrossRef] [PubMed]
137. Yuan, R.; Guo, F.; Qian, Y.; Cheng, B.; Li, J.; Tang, X.; Peng, X. A system dynamic model for simulating the potential of prefabrication on construction waste reduction. *Env. Sci. Pollut. Res.* **2022**, *29*, 12589–12600. [CrossRef] [PubMed]
138. Cheng, B.; Huang, J.; Lu, K.; Li, J.; Gao, G.; Wang, T.; Chen, H. BIM-enabled life cycle assessment of concrete formwork waste reduction through prefabrication. *Sust. Ener. Tech. Ass.* **2022**, *53*, 102449. [CrossRef]
139. Mei, Z.; Xu, M.; Luo, S.; Tan, Y.; Li, H. Concrete formwork reuse in a supply chain with dynamic changes using ABMS and discrete events. *J. Clean. Prod.* **2022**, *332*, 130038. [CrossRef]
140. Lee, B.; Choi, H.; Min, B.; Lee, D.-E. Applicability of Formwork Automation Design Software for Aluminum Formwork. *Appl. Sci.* **2020**, *10*, 9029. [CrossRef]
141. Kareem, W.B.; Okwori, R.O.; Abubakar, H.O.; Nuhu, A.; Dickson, E.I. Evaluation of wood and plastic formworks in building construction industry for sustainable development. *J. Phy. Conf. Ser.* **2019**, *1378*, 032007. [CrossRef]

142. Mei, Z.; Xu, M.; Wu, P.; Luo, S.; Wang, J.; Tan, Y. BIM-based framework for formwork planning considering potential reuse. *J. Mana. Eng.* **2022**, *38*, 04021090. [CrossRef]
143. López-Arquillos, A.; Rubio-Romero, J.C.; Gibb, A.G.; Gambatese, J.A. Safety risk assessment for vertical concrete formwork activities in civil engineering construction. *Work* **2014**, *49*, 183–192. [CrossRef]
144. Haduong, A.; Kim, J.J.; Balali, V. Statistical Results on Incidents for Formwork Safety in Concrete Structures. In Proceedings of the Construction Research Congress 2018, New Orleans, LA, USA, 2–4 April 2018; Available online: https://ascelibrary.org/doi/abs/10.1061/9780784481288.063 (accessed on 17 July 2023).
145. Jin, Z.; Gambatese, J. BIM-Based Timber Formwork Design and Modeling. *Pract. Per. Struct. Des. Constr.* **2023**, *28*, 04022057. [CrossRef]
146. Amede, E.A.; Hailemariam, E.K.; Hailemariam, L.M.; Nuramo, D.A. Identification of factors on the possibility of bamboo as a scaffolding and a formwork material in Ethiopia. *Cogent Eng.* **2022**, *9*, 2051692. [CrossRef]
147. Park, C.S.; Kim, H.J. A framework for construction safety management and visualization system. *Autom. Constr.* **2013**, *33*, 95–103. [CrossRef]
148. Kazar, G.; Semra, Ç.O.M.U. Developing a virtual safety training tool for scaffolding and formwork activities. *Teknik Dergi* **2023**, *33*, 11729–11748. [CrossRef]
149. Zhou, Y.C.; Yang, J.; Luo, X.; Yang, S.Y. Research upon Safety Management of steel tubular scaffold with couplers Formwork Support. *Appl. Mech. Mater.* **2012**, *174*, 3253–3257. [CrossRef]
150. Hayashi, S.; Gondo, T. Analysis of the construction of a reinforced-concrete free-form roof formwork and the development of a unit-construction method. *J. Build. Eng.* **2021**, *34*, 101924. [CrossRef]
151. Kim, J.H.; Beacraft, M.W.; Kwon, S.H.; Shah, S.P. Simple analytical model for formwork design of self-consolidating concrete. *ACI Mater. J.* **2011**, *108*, 38–45. [CrossRef]
152. Ko, C.H.; Wang, W.C.; Kuo, J.D. Improving formwork engineering using the Toyota Way. *J. Eng. Proj. Prod. Mana.* **2011**, *1*, 13–27. [CrossRef]
153. Wang, L.; Chen, S.S.; Tsang, D.C.; Poon, C.S.; Shih, K. Value-added recycling of construction waste wood into noise and thermal insulating cement-bonded particleboards. *Constr. Build. Mater.* **2016**, *125*, 316–325. [CrossRef]
154. Abreu, M.M.D.; Lordsleem, A.C., Jr. Aluminum formwork system: Loss and productivity. *Built Env. Proj. Asset Mana.* **2019**, *9*, 616–627. [CrossRef]
155. Rahim, M.S.M.; Haron, N.A. Construction cost comparison between conventional and formwork system for condominium project. *Int. J. Adv. Stud. Comp. Sci. Eng.* **2013**, *2*, 19–25.
156. Popescu, M.; Rippmann, M.; Liew, A.; Reiter, L.; Flatt, R.J.; Van Mele, T.; Block, P. Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell. *Structures* **2021**, *31*, 1287–1299. [CrossRef]
157. Lo, C.L. Environmental benefits of renewable building materials: A case study in Taiwan. *Ener. Build.* **2017**, *140*, 236–244. [CrossRef]
158. Oloke, D. A conceptual framework for integrated Designers Risk Assessments—A case study of an Insulated Concrete Formwork framed project. *IOP Conf. Ser. Earth Env. Sci.* **2022**, *1101*, 032021. [CrossRef]
159. Miranda, J.; Valenca, J.; Costa, H.; Julio, E. Methodology for the restoration of heritage built in exposed concrete. The case study of 'Piscina das Marés', Portugal. *Constr. Build. Mater.* **2022**, *328*, 127040. [CrossRef]
160. Liu, X.; Hu, Y.; Chen, D.; Wang, L. Safety control of hydraulic self-climbing formwork in south tower construction of Taizhou Bridge. *Proc. Eng.* **2012**, *45*, 248–252. [CrossRef]
161. Huber, T.; Burger, J.; Mata-Falcón, J.; Kaufmann, W. Structural design and testing of material optimized ribbed RC slabs with 3D printed formwork. *Struct. Concr.* **2023**, *24*, 1932–1955. [CrossRef]
162. Arenas, N.F.; Shafique, M. Recent progress on BIM-based sustainable buildings: State of the art review. *Dev. Built Env.* **2023**, *15*, 100176. [CrossRef]
163. El Kassis, R.; Ayer, S.K.; El Asmar, M. Augmented Reality Applications for Synchronized Communication in Construction: A Review of Challenges and Opportunities. *Appl. Sci.* **2023**, *13*, 7614. [CrossRef]
164. Jindal, B.B.; Jangra, P. 3D Printed Concrete: A comprehensive review of raw material's properties, synthesis, performance, and potential field applications. *Constr. Build. Mater.* **2023**, *387*, 131614. [CrossRef]
165. Zandifaez, P.; Shamsabadi, E.A.; Nezhad, A.A.; Zhou, H.; Dias-da-Costa, D. AI-Assisted optimisation of green concrete mixes incorporating recycled concrete aggregates. *Constr. Build. Mater.* **2023**, *391*, 131851. [CrossRef]
166. Kim, I.; Kim, Y.; Chin, S. Deep-Learning-Based Sound Classification Model for Concrete Pouring Work Monitoring at a Construction Site. *Appl. Sci.* **2023**, *13*, 4789. [CrossRef]
167. Singh, N.; Colangelo, F.; Farina, I. Sustainable Non-Conventional Concrete 3D Printing—A Review. *Sustainability* **2023**, *15*, 10121. [CrossRef]
168. Venkatesan, S.; Afroz, M.; Navaratnam, S.; Gravina, R. Circular-Economy-Based Approach to Utilizing Cardboard in Sustainable Building Construction. *Buildings* **2023**, *13*, 181. [CrossRef]
169. Rane, N.L.; Achari, A.; Kadam, D. Evaluating the Selection Criteria of Formwork System (FS) for RCC Building Construction. *Int. J. Eng. Trends Tech.* **2023**, *71*, 197–205. [CrossRef]
170. Wang, Y. Construction of intelligent multi-construction management platform for bridges based on BIM technology. *Intell. Build. Int.* **2023**, *In press*, 1–14. [CrossRef]

171. Gappmaier, P.; Reichenbach, S.; Kromoser, B. Automated Production Process for Structure-Optimised Concrete Elements. In Proceedings of the Fib Symposium 2023, Istanbul, Turkey, 5–7 June 2023. [CrossRef]
172. Yang, Y.; Chen, B.; Chen, Y.; Zhou, H.; Liu, F.; Xie, X.; Chen, J.; Guo, W.; Wang, H. Performances of Concrete Columns with Modular UHPC Permanent Formworks Under Axial Load. *Int. J. Concr. Struct. Mater.* **2023**, *17*, 38. [CrossRef]