International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Research Article)

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Evaluating the benefits of Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) for Rehabilitation of Dams: Insights for Potential Integration into the KDRP in Zambia

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International Journal of Science and Research Archive, 2025, 14(02), 391-400

Publication history: Received on 25 December 2024; revised on 02 February 2025; accepted on 05 February 2025

Article DOI: https://doi.org/10.30574/ijsra.2025.14.2.0360

Abstract

Ultra-high-performance fiber-reinforced concrete (UHPFRC) is a cutting-edge material in the field of cement-based engineering, offering significant advancements over traditional concrete. Its superior compressive strength along with its enhanced durability, has garnered growing interest across the globe. UHPFRC's ability to withstand aggressive conditions and its high resistance to abrasion and corrosion make it particularly suitable for applications demanding long-term performance. Experiments carried out on UHPFRC has revealed a compressive strength greater than 150MPa. The choice of fibers, their quantity, alignment, and length are crucial factors that shape the mechanical characteristics of UHPFRC. UHPFRC has gained notable notoriety as a versatile material that can be tailored to suit specific project needs as its mechanical properties can be modified to match the requirements of the intended application. Developing sustainable structures is essential for advancing Zambia's energy sector, particularly in the construction and rehabilitation of dams, with a specific focus on large-scale hydroelectric power facilities like the Kariba Dam. Because of the damage in its significant parts, such as the plunge pool and sluice gates, the Kariba Dam is now in a dangerous state that needs urgent rehabilitation. The continued operation of the Kariba Dam depends heavily on timely rehabilitation efforts to address aging infrastructure and environmental wear. Traditional concrete often exhibits limitations that require frequent repairs and high costs. UHPFRC has emerged as a promising alternative to conventional concrete due to its superior mechanical properties, durability, and reduced environmental footprint. The study compares UHPFRC with conventional concrete, highlighting the benefits and limitations of each material in dam rehabilitation. By analyzing the Kariba Dam Rehabilitation Project (KDRP), the paper explores how Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) could offer a superior alternative to conventional concrete. It discusses the material's characteristics, its advantages in terms of structural performance and longevity, and the economic and environmental implications. The study argues that while conventional concrete has been the material of choice for decades due to its availability, cost-effectiveness, and proven performance, UHPFRC offers superior durability, strength, and longevity, which could extend the lifespan of Zambia's existing dams.

Keywords: UHPFRC; Concrete; Kariba Dam Rehabilitation Project; Hydraulic Structures

1. Introduction

Concrete stands as one of the most widely used building material in civil and hydraulic engineering. In most structures, localized areas of concrete can form cracks under excessive loads if the stress exceeds its compressive or tensile strength. A standard approach to strengthening structures is either to increase their dimensions to boost overall structural integrity or to add supplementary reinforcement to areas that are particularly prone to stress. The first approach would increase design complexity and cost, while the second cannot entirely prevent cracks, but it may limit their extent. Ultra-high-performance fiber-reinforced concrete has emerged as an innovative substitute to overcome

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these problems. Ultra-high-performance fiber-reinforced Concrete (UHPFRC) marks a notable leap forward in the field of structural engineering, it integrates the remarkable mechanical attributes of Ultra-High-Performance Concrete (UHPC), the added benefits of fiber reinforcement. These fibers (steel or synthetic fibers) are usually incorporated at volumes of 1–3% and, in turn, provide unparalleled crack-bridging capabilities and a strain-hardening response under tension, making UHPFRC a versatile material for structural applications requiring both strength and durability. in comparison with concrete, UHPFRC exhibits significantly higher compressive strength that often exceeds 150 MPa and exhibits far more superior durability [1-3]. Therefore, the utilization of UHPFRC in critical or high-stress areas of structures can improve the structure's overall strength and mechanical properties. These properties have made UHPFRC a material option for consideration in rehabilitating dams and hydraulic structures in Zambia.

Dams are vital in Zambia's infrastructure, supporting hydroelectric power generation and water resource management. Kariba Dam, one of the largest dams in Africa, has played a central role in these efforts since its completion in the 1950s and is a critical infrastructure for both Zambia and Zimbabwe. However, like many large infrastructure projects, Kariba Dam faces significant challenges related to aging and maintenance, leading to the launch of the Kariba Dam Rehabilitation Project (KDRP) [4]. The Kariba Dam Rehabilitation Project (KDRP) 's overall goal is to improve the energy supply's reliability and promote clean energy in Zambia and Zimbabwe while reducing the risk of dam failure. To achieve this, specific objectives are to support the Zambezi River Authority (ZRA) in rehabilitating Kariba Dam, stabilizing its plunge pool, and repairing the spillway in accordance with international safety standards to ensure the long-term safety and operational efficiency of the dam [5]. Zambia relies heavily on hydroelectric power as a primary source of energy, with the Kariba Dam being one of the most significant projects in the country. As the demand for electricity increases, existing dams need to be upgraded to enhance capacity and efficiency. Traditional construction materials, particularly conventional concrete, have been the go-to choice for constructing/rehabilitating these structures due to their availability, cost, and ease of use. However, there are limitations associated with conventional concrete, such as susceptibility to cracking, lower tensile strength, and the need for frequent maintenance. Reducing the frequency of maintenance in dam construction is essential as it leads to significant cost savings by minimizing the expenses associated with materials, labor, and the specialized equipment needed for repairs. Ultra-High-Performance Concrete (UHPFRC) presents a novel solution that addresses these limitations. UHPFRC is a type of concrete characterized by its high compressive strength, enhanced durability, and improved resistance to environmental degradation [6]. This paper examines the use of Ultra-High-Performance Concrete (UHPFRC) as an alternative material for the rehabilitation of dams in Zambia, with a focus on how its unique properties could benefit the Kariba Dam in terms of reducing maintenance, increasing structural resilience, and extending its operational life.

Figure 1 Elevated view of Kariba Dam and rehabilitation works

2. Properties of UHPFRC

UHPFRC possesses numerous key mechanical properties that make it an ideal material for dam/rehabilitation construction. Its exceptionally high compressive strength allows it to withstand extreme loads and pressures [7], making it suitable for critical structural elements in dams. The fiber type, orientation and volume determine the mechanical properties that will be exhibited by UHPFRC. For example, steel achieves an increase of 6% in compressive strength, while polypropylene increases it by 2.5% [8]. UHPFRC also has remarkable tensile strength and ductility (generally between 7-15 MPa), significantly reducing the risk of cracking and enhancing the overall structural integrity of structures such as dams and bridges [9]. The mechanical properties of UHPFRC can enhance the structural integrity and longevity of hydroelectric power stations. Its exceptional compressive strength, often exceeding 150 MPa, allows for the construction of more resilient and thinner structural elements, which can withstand higher loads and stress without compromising safety. This enhanced structural performance is crucial in resisting the high pressures and environmental stresses that dams face, such as water flow, temperature fluctuations, and potential seismic activity.

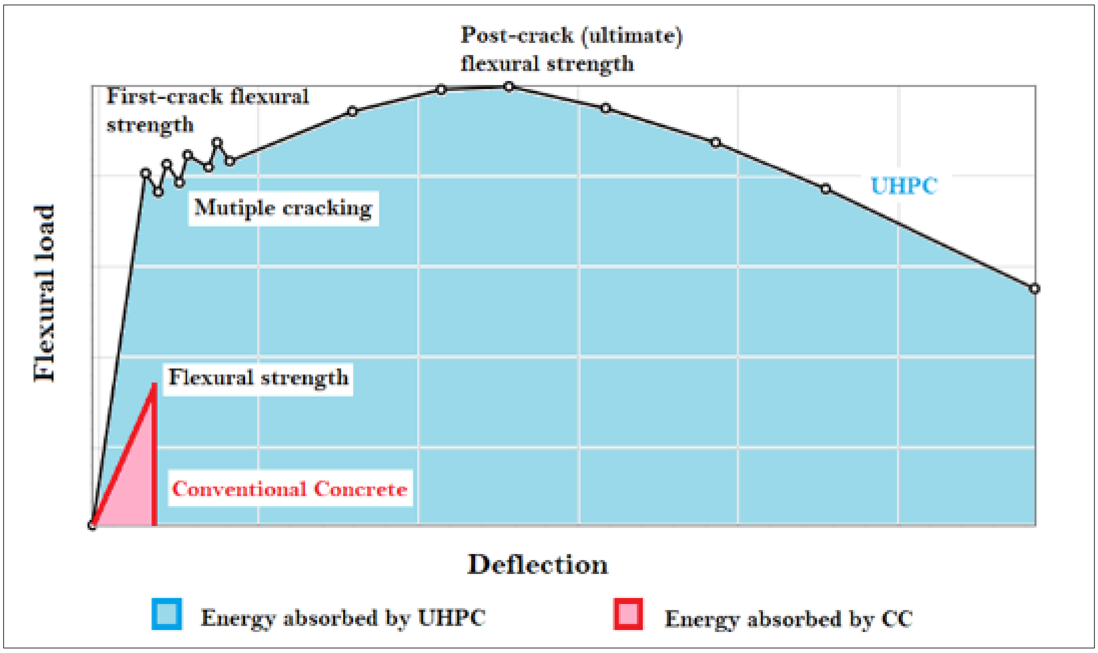

Figure 2 Comparison analysis according to ASTM C1609 Standard Test

The ASTM C1609 is the standard test method for the flexural performance of Fiber-Reinforced Concrete [10]. Experiments carried out, as depicted in figure 2, concluded that UHPFRC exhibited superior tensile strength at first cracking and exhibited peak tensile strength with significant deflection (ductility) beyond cracking when compared to conventional concrete. This high tensile strength allows for much higher shear resistance and its ability absorb significantly more energy before failure makes it better suited for applications requiring high durability, resistance to cracking, and the ability to withstand dynamic or impact loads.

Additionally, UHPFRC's low permeability and superior durability make it highly resistant to water infiltration, chemical attacks, and environmental degradation [11], which are common issues with conventional concrete. As a result, dams constructed with UHPFRC are less prone to cracking, erosion, and other forms of deterioration, significantly extending their operational lifespan and reducing the need for frequent maintenance. This leads to more significant long-term cost savings and ensures the dam remains a reliable source of hydroelectric power and water management for decades, making UHPFRC a highly advantageous material for dam construction in Zambia. UHPFRC offers substantial advantages, particularly regarding reduced material usage and cost efficiency. The superior mechanical properties of UHPFRC allow for the design of thinner and lighter structural elements without compromising strength or safety. Due to its exceptional strength and durability, UHPFRC allows for the design of thinner and lighter structural elements without sacrificing safety or performance. This reduction in material volume would not only lower the overall weight of the structure but would also minimize the quantity of raw materials (e.g., concrete) required, leading to cost savings in material procurement and transportation. Additionally, the longer lifespan and lower maintenance requirements of UHPFRC further enhance cost efficiency, as the need for repairs and reinforcements is significantly reduced over the dam's operational life [12]. Although UHPFRC may have a higher initial cost compared to conventional concrete, these savings in material usage, transportation, and maintenance can offset the initial investment, making UHPFRC a cost-effective option for dam construction in Zambia. This reduction in material usage can lead to cost savings in terms of both construction and transportation. While UHPFRC is more expensive per unit volume than conventional concrete, the overall cost of a project can be reduced due to decreased material requirements and lower maintenance needs over the lifespan of the structure. Ongoing research in UHPFRC is focused on developing a more sustainable version of the material, aiming to reduce the amount of steel fiber used while still maintaining its mechanical properties. The high density and reduced porosity of UHPFRC contribute to its superior durability compared to conventional concrete and even standard High-Performance Concrete (HPC). This research is crucial for enhancing the material's eco-efficiency without compromising its structural integrity and longevity.

Table 1 Properties of Concrete and UHPFRC according to ACI 239R

Material characteristics	Concrete	Ultra-High-Performance Concrete
Compressive strength (MPa)	20 - 40	150 - 250
Tensile strength (MPa)	1 - 3	7 - 15
Elastic modulus (GPa)	25 - 30	40 - 50

3. Kariba Dam Rehabilitation Project (KDRP)

The Kariba Dam Rehabilitation Project (KDRP) is a significant initiative aimed at ensuring the longevity and efficient operation of the Kariba Dam, which has been serving the people of Zambia and Zimbabwe for over 60 years. The project was identified as necessary after routine monitoring revealed the need for rehabilitation works to maintain the dam's contribution to energy security and economic prosperity in the regions. The project involves the reshaping of the plunge pool (a deep erosion-formed basin downstream of the dam where water falls from the spillway) and the overall maintenance of the spillway gates to ensure perpetual operation of the dam in accordance to international safety standards [4]. The project is expected to restore the dam to internationally acceptable operational standards, facilitating the sustained generation of electricity. When completed, the rehabilitation project will increase the dam's lifespan from 50 to 100 years and benefit three million people through risk reduction and mitigation while assisting in sustaining power generation estimated at 10 gigawatts annually.

The first phase of the project is the reshaping of the plunge pool and the second phase is the rehabilitation of the spill gates. The KDRP is expected to take approximately 10 years. The first phase of the project began in February 2017 and if on schedule it is expected to be completed by the end of 2025 or early 2026. which is when the second phase is expected to be completed. The project is co-financed by the EU, World Bank (WB), African Development Bank (AfDB), Swedish International Development Cooperation Agency (SIDA), and Zambezi River Authority (ZRA). The total cost of the project is approximately $294 million.

3.1. Reshaping the Plunge Pool

The reshaping of the plunge pool is the first phase of the KDRP it involved the meticulous process of modifying the basin’s dimensions and forms. The objective was to mitigate the erosion caused by the force of water ejected from the dam's spillway gates. This erosion had the potential to compromise the dam's structural integrity over time. The Zambezi River Authority (ZRA) has been monitoring the performance of the dam since its construction in 1958. In recent years during their routine monitoring of the dam infrastructure the ZRA and independent contractors had recommended that rehabilitation works be carried out on the plunge pool to enhance stability and prevent further damage to the dam foundation. This initial phase entailed excavating approximately 300,100 m^3 of rock through careful drilling and controlled blasting, coupled with the stabilization of 20,000 m^2 of slopes using anchors and shotcrete. The reshaped pool was designed to increase its size, which in turn would reduce the pressure exerted by the water on its base, thereby slowing down the erosion of the natural rock floor.

In addition to improving safety and extending the dam's lifespan, the project also included the construction of a reinforced concrete slab to cover the weak-rock zone downstream of the dam, protecting it from possible future erosion. This was a critical step towards ensuring the dam's continued functionality and safety. The successful completion of these works underscored the commitment to supporting Zimbabwe and Zambia in finalizing this project, securing the dam’s stability, and maintaining its clean power generation capacity. At present, The Kariba Dam Rehabilitation Project has reached a significant milestone with the completion of the plunge pool reshaping.

Figure 3 Reshaping of Plunge pool

3.2. Refurbishing the Spillway

The second phase is the refurbishment of the spillway, it is extremely crucial for maintaining the dam's functionality and safety. The spillway, which consists of six gates in the upper part of the concrete dam wall, is responsible for releasing water into the plunge pool to manage reservoir water levels. Over time, the concrete structure has naturally expanded due to exposure to water, which can affect the smooth operation of the gates and potentially cause them to jam. The refurbishment process aims to address these issues by refurbishing the spillway gates to ensure their continued full operability in the long term. Independent external consultants who undertake five-yearly inspections of the dam's infrastructure have also recommended that a movable back-up gate be installed on the upstream side of the dam wall as an additional safeguard. The project will involve the refurbishment of the upstream stop-beam guides, replacement of secondary concrete, and the design, fabrication, and installation of an emergency gate and a new gantry as an additional safety precaution.

The Zambezi River Authority (ZRA) awarded the tender for the rehabilitation of the Kariba Dam spillway to a consortium comprising GE Hydro France and Freyssinet International. The spillway refurbishment contract, valued at $53,684,000, is primarily funded by the World Bank and the African Development Bank. The project is expected to be completed by the first quarter of 2025, ensuring the long-term safe operation of the Kariba Dam and its continued contribution to Zambia and Zimbabwe's energy security and economic prosperity.

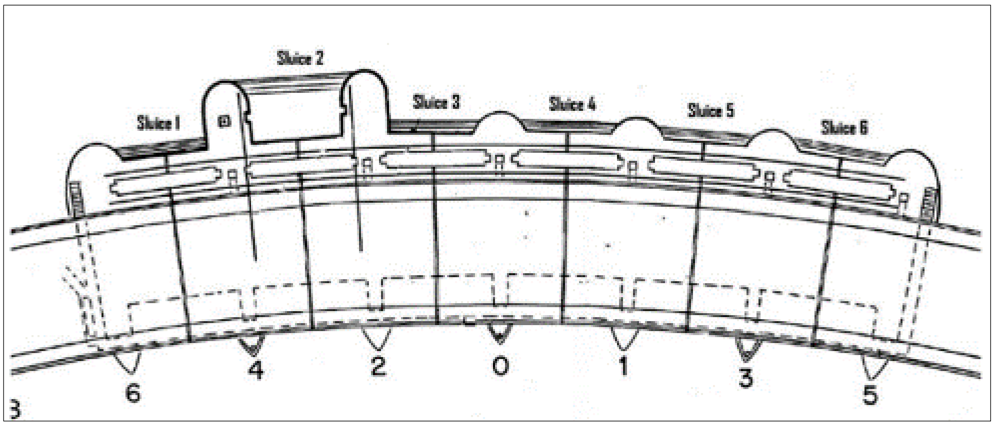

Figure 4 Section plan of the spillway and sluice gates

4. Economic and Environmental Implications of the use of UHPFRC

The initial cost of UHPFRC is higher than that of conventional concrete due to the required specialized materials and production processes. However, the long-term economic benefits, including reduced maintenance costs, extended service life, and decreased material usage, make UHPFRC a cost-effective option for hydroelectric power station construction in the long run. The potential for using locally available materials and incorporating industrial by-products as SCMs can further offset the initial costs. By reducing the frequency of maintenance and the need for replacement materials, UHPFRC contributes to a lower environmental impact over the lifespan of a structure. The ability to incorporate SCMs reduces the overall carbon footprint of the concrete mix, aligning with global sustainability goals. Additionally, the reduced weight of UHPFRC structures can lower transportation emissions, further contributing to environmental sustainability.

The environmental impact of construction materials has been a growing concern in civil engineering. The use of UHPFRC can contribute to more sustainable construction practices as it can be formulated using eco-friendly materials, such as recycled aggregates and industrial by-products, such as fly ash or silica fume, which not only enhance the material properties but also reduce the carbon footprint associated with concrete production [13], contributing to more sustainable infrastructure. Its high strength allows for the use of less material as this property allows for the creation of reinforcements with smaller dimensions and limited weight, which in turn reduces the extraction and consumption of natural resources like cement and aggregates. This decrease in material usage also lowers the environmental impact directly associated with the production and transportation of construction materials, leading to a smaller carbon footprint. Additionally, UHPFRC's superior durability and resistance to environmental degradation means that structures such as dams and bridges rehabilitated with this material have longer lifespans and require less frequent maintenance and repairs. This reduces the need for disruptive construction activities over time, minimizing environmental disturbances to surrounding ecosystems [14]. Furthermore, the longevity of UHPFRC structures contributes to sustainable water management and energy production, ensuring that these resources are utilized efficiently with minimal environmental impact over the dam's operational life. Table 2 compares the environmental and economic impacts of UHPFRC and Conventional concrete (CC) from studies carried by Wang et al (2024) and Sameer et al (2019), highlighting differences in strength, embodied energy, CO_2 emissions, durability, maintenance, and costs [15,16].

Table 2 Summary of the environmental and economic impacts of UHPFRC and Conventional concrete (CC)

Impact Factor	CC	UHPFRC	Observations
Compressive Strength (MPa)	30 - 50	150 - 200	UHPFRC exhibits significantly higher compressive strength, allowing for reduced material usage in structural applications.
Embodied Energy (MJ/m^3)	2000 - 3000	4000 - 5000	UHPFRC has higher embodied energy due to increased cement content and specialized materials.
CO_2 Emissions (kg CO_2/m^3)	300 - 400	600 - 800	The production of UHPFRC results in higher CO_2 emissions, primarily due to its higher cement content.
	50 - 75	100+	UHPFRC's superior durability can lead to extended service life, reducing the frequency of repairs and replacements.
Maintenance Frequency	Higher	Lower	Due to its enhanced properties, UHPFRC structures require less frequent maintenance.
Initial Material Cost ($\$/m^3$)	100-150	300-500	UHPFRC is more expensive upfront due to specialized materials and production processes.

5. Application of UHPFRC in Rehabilitation Projects

Recent progress in enhancing its properties and deepening our understanding of its behavior has broadened its application across numerous sectors. Its exceptional tensile and shear strength positions UHPFRC as an optimal material for bolstering structural elements like bridge columns, beams, and critical parts of large water retention structures, such as dams, which require extended service life. As previously discussed, UHPFRC's capacity to absorb substantial energy and undergo significant deformation beyond its initial cracking point renders it highly suitable for use in hydraulic, marine, and offshore settings. This material's ability to withstand harsh environments and resist damage makes it a valuable asset in prolonging the lifespan of critical infrastructure.

In 2013, Louis Guingot, Djamel Dekhil, and Pierre Soulier presented their findings on the use of UHPFRC in the rehabilitation of various structures in France [17]. These structures included dams, bridge channels, and hydroelectric plants, which required protection from the impacts of water, abrasion, and harsh environmental conditions. The research highlighted several projects where UHPFRC was successfully applied to enhance the durability and performance of these structures. The use of UHPFRC in these applications demonstrated its innovative potential for hydraulic structures that are regularly exposed to severe environmental conditions. Some of dams rehabilitated include The Caderousse and Beaucaire Dams which faced significant challenges with their hydraulic vertical screens due to exposure to harsh environmental conditions. The Caderousse and Beaucaire Dams have been operational for nearly four decades. Over this period, the upper sections of their concrete walls have experienced degradation. This deterioration is primarily attributed to the corrosion of steel reinforcement bar and carbonation of the concrete. These screens endure high water pressure, wear from debris and sediment, freeze-thaw cycles, and chemical attacks from substances like sulfates and chlorides. The Compagnie Nationale du Rhône (CNR) sought a material with very low permeability to shield existing steel reinforcement bars, coupled with high early compressive strength and high resistance to abrasion and. Consequently, UHPFRC with a porosity of 4 to 6% was selected, boasting an abrasive strength of 0.8 and achieving 100 MPa in compressive strength within just three days. It ensured a long-lasting repair that could withstand tensile and compressive stresses, making the structures more resilient. Additionally, UHPFRC's rapid strength gain minimized downtime, allowing the dams to quickly resume their critical roles in flood management and irrigation. This repair method not only restored the structural integrity of the dams but also enhanced their performance, demonstrating the value of UHPFRC in rehabilitating aging infrastructure effectively and efficiently.

Figure 5 Caderousse Dam's screen rakes after completion of UHPFRC repairs, August 2011 [17]

Figure 6 In-situ UHPFRC casting Beaucaire Dam, September 2012 [17]

Bridge deck slabs are highly suitable for rehabilitation and strengthening using Ultra-High Performance Fiber Reinforced Concrete (UHPFRC). The process generally involves removing the top 20-40 mm of reinforced concrete (RC) by high-pressure water or sandblasting, followed by pouring a layer of R-UHPFRC ranging from 20 to 70 mm in width, tailored to the specific project requirements. This additional layer not only reinforces the structure but can also serve as a waterproof membrane. Research has been conducted to study the behavior of UHPFRC under punching effects in the connection zone between the deck and piers, which is vital for understanding its performance in bridge rehabilitation [18,19]. One such project is The Log Čezsoški bridge in Slovenia, its use was evaluated in the context of global warming's impact on different materials, including standard concrete, ECO concrete, standard UHPFRC, or ECO UHPFRC. The study revealed the benefits of ECO UHPFRC when considered over the structure's life-cycle [20]. A financial comparison of the work done on a bridge over the Morge river in Switzerland was also conducted, which included not only the deck but also UHPFRC kerbs [21]. A comprehensive report of rehabilitation projects carried out by Brühwiler and Denarié in Switzerland from 2004 to 2015 was compiled, highlighting the extensive use of UHPFRC in various structural applications [22]. One of the latest applications in Switzerland involved a viaduct suffering from Alkali-Silica Reaction (ASR) problems [23]. The UHPFRC layer applied served dual purposes: controlling ASR expansion due to the material's low porosity and enhancing the deck slab's strength by 40%. In France, an innovative procedure for I girder bridges was developed, where two continuous side cheeks were cast in situ on the bottom heels on either side of the beam webs [24]. This method allowed for more cost-effective and faster construction compared to conventional methods. In North America, while UHPFRC is often used for new structures, its application in existing bridges is limited to precast slabs to replace concrete decks and filling dilation joints.

5.1. Challenges and Considerations

While Ultra-High-Performance Concrete (UHPFRC) offers significant advantages for dam construction, its implementation also presents a number challenges and considerations that must be addressed. One of the major challenges is the higher initial cost of UHPFRC compared to conventional concrete, which may be a concern for budget-constrained projects in Zambia. The specialized materials and manufacturing processes required for UHPFRC, including the use of fine powders, steel fibers, and high-quality cement, contribute to these costs. Additionally, the production and placement of UHPFRC require advanced technical expertise and equipment, which may not be readily available in the region, potentially leading to increased training and logistical expenses. Another consideration is the potential difficulty in sourcing the specific raw materials needed for UHPFRC locally, which could necessitate importing these materials, further raising costs and complicating supply chains. Finally, regulatory and standardization issues may arise, as existing building codes and standards in Zambia might not accommodate the use of UHPFRC in structural applications. Updating these regulations to include UHPFRC would be essential to ensure its safe and effective use in infrastructure projects [25]. These challenges highlight the need for careful planning, investment in technical capacity, and a comprehensive evaluation of the long-term cost-benefit analysis when considering using UHPFRC in dam construction projects like those in Zambia

6. Conclusion

The exceptional mechanical characteristics of Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) have made it suitable for a variety of applications across different structural types, demonstrating its reliability in diverse conditions. While it is predominantly used in bridge construction, other structures like hydroelectric facilities could also significantly benefit from its enhanced characteristics. UHPFRC's versatility in being either cast on-site or as a precast element contributes to prolonging the lifespan of structures. Its capability to be effectively cast on steep inclines is particularly advantageous, achieving positive outcomes. This feature enables the restoration of areas that are typically hard to reach with conventional methods. Implementing UHPFRC in Zambia's hydroelectric power stations could be a beneficial strategy to boost the structural integrity, longevity, and eco-friendliness of these vital installations. Despite the potentially higher upfront costs, the enduring advantages such as decreased maintenance needs, a longer operational lifespan, and a reduced ecological footprint justify the expenditure. Nevertheless, it is essential to tackle issues concerning the availability of materials, the level of technical know-how, and regulatory standards to ensure the successful integration of UHPFRC into Zambia's hydroelectric sector. Additional research and trial projects are advised to assess the practical viability and to refine the application of UHPFRC in this specific context.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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