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Multi-Criteria Risk Analysis of Ultra-High Performance Concrete Application in Structures

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Abstract: In developing countries, ultra-high-performance concrete (UHPC) has not garnered sufficient attention, and its potential industrial applications remain largely unexplored and underdeveloped. The purpose of this paper is to assess the risk associated with integrating UHPC technology into the construction industry, focusing on economic, technical, and environmental facets, as highlighted by global research endeavors in this domain. In this study, a risk model is validated by analyzing diverse UHPC mix proportions from various studies and assessing the associated risk indices concerning constituent materials. The findings demonstrate that incorporating UHPC as a more robust alternative to earlier generations is plausible when considering multiple perspectives within the concrete industry. The preeminence of compressive strength and the significance of service life as a pivotal cost factor during the maintenance period, coupled with comprehensive risk indices, underscore the excellence of UHPC. Comparing UHPC with high-performance concrete (HPC) and normal concrete (NC), it becomes evident that UHPC exerts a notably lower adverse impact on the ecosystem. Additionally, UHPC proves to be a more economically viable option, warranting the replacement of existing technologies.

Keywords: ultra-high-performance concrete; risk assessment; fault tree analysis; semi-quantitative risk evaluation; durability

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1. Introduction

In a world characterized by rapid technological advancements and the constant emergence of integrated techniques aimed at enhancing and optimizing quality, it is undeniable that newly emerging methods, due to their swift introduction into the industry and the high demand for cost-effective, efficient, and expedited construction processes, might occasionally evade the scrutiny of supervisors, designers, and even seasoned professionals in the field [1–12]. Hence, effective management of the risks associated with the introduction of such techniques and innovations, particularly in the realm of materials, becomes imperative [13,14].

Numerous research endeavors have focused on construction risk management, some of which are specifically concentrated on the concrete industry. Al-Bahar et al. [15], pioneers of systematic risk analysis for construction projects, introduced a risk model named the Construction Risk Management System (CRMS) in 1990 to provide a methodical approach for risk analysis in construction projects. Research studies have also honed in on specific risk management aspects extending beyond national boundaries. For instance, Wang et al. [16] devised a hierarchical level framework to classify project risks, considering factors such as country of origin, verified market, and risk types, especially relevant for developing countries adopting technologies from industrialized nations. Such complexities earn construction projects the label of "high risk business", as noted by Zhi [17], largely attributed to the lack of site information that amplifies risk factors and compromises accurate project prediction. Akintoye et al. [18] outlined three fundamental tools for risk assessment: intuition, judgment, and experience, underscoring that insufficient knowledge and lingering doubts can render risk analyses inadequate and uncertain.

In recent times, mathematically based computer-aided techniques such as fuzzy logic have been employed for a more systematic analysis of construction risks [19,20]. These methods aid project managers in categorizing and estimating the risks associated with complex projects, thereby guiding corrective actions. Furthermore, significant efforts have been directed toward establishing a framework for life cycle assessment (LCA) of concrete production and its environmental impact on ecosystems [14,21,22].

Undoubtedly, ultra-high-performance concrete (UHPC), pioneered by Larrard and Sedran [23] and practically optimized in the 1990s, represents a cornerstone of modern construction and a catalyst for fundamental shifts in conventional structural design. While extensive research has been undertaken in this realm [23–25], the prominence of UHPC's role has become more apparent. Although its use, which is renowned for its exceptional mechanical strength, is still evolving, experimental tests have substantiated its capabilities, leading to the construction of real structures using UHPC [26,27]. This study pertains to a specific facet of UHPC research: examining its ductility. Given its high strength and inherent brittleness, investigating UHPC's ductility stands as a crucial research domain in modern concrete technologies [28,29]. Technically, UHPC is defined as concrete possessing compressive strengths exceeding 110 MPa, exceptional resistance to impact and dynamic loads, and the requisite ductility to avert sudden rupture.

In response to the surging demand for high-strength concrete and its applications in contemporary structures, the lack of comprehensive research on UHPC is evident. As a modern material offering remarkable advantages, UHPC has the potential to instigate profound changes in the concrete industry of any developing nation. However, UHPC is not without its drawbacks, notably its high brittleness. Several studies have explored methods, including the use of steel fibers, to enhance the plasticity and ductility of UHPC, yet a comprehensive investigation into the effects of employing UHPC in concrete-related structures remains an open question [30]. Moreover, the potential negative environmental impacts and practical risks of UHPC have yet to be definitively clarified. Thus, this paper aims to evaluate the risks associated with introducing UHPC into related industries after providing a brief historical overview and a comparative assessment of its properties in relation to high-performance concrete (HPC) and normal concrete (NC).

The versatile applications of UHPC, ranging from structural mainframes to building facades, position it as a viable option, particularly in scenarios where durability is a key consideration [31]. Given the prevalent exposure to corrosive environments in certain regions, structures in such areas necessitate durable materials that resist corrosion. High-strength concrete (HSC) stands as a promising candidate, not only due to the robust resistance of its reinforcement against corrosion but also its cost-effectiveness and relatively lower maintenance costs throughout the building's service life [32].

Various design and analysis programs can be employed to optimize a structure's service life based on mixture, mechanical properties, and durability [33–36]. Nevertheless, UHPC still requires a more solid industrial foundation to compete effectively. It is clear that a significant level of compressive strength is essential to effectively withstand rebar corrosion. Furthermore, when the concrete strength decreases, there arises a necessity to increase the cover thickness. This adjustment guarantees the attainment of a specified service life but also results in the consumption of more materials, consequently driving up construction costs.

This cover thickness is limited by instructions such as ACI 440 [37]. However, in the case of UHPC, thickness can be decreased substantially due to fine-grained sand as aggregate in this concrete, so the crack widths which in case of tensile stresses originating from sources such as shrinkage will occur with high possibility, may appear on the surface up to 2 mm, and the corrosion will initiate in a much shorter time period leading to a substantial decrease in the service life of the structure [38]. Based on the origin of the cracks, structural cracks due to loading of the structure are almost inevitable and can be protected by measures such as coatings and active filler agents [39]. On similar challenges such as shrinkage, the behavior and preventive measures could be applied for all strength classes of concretes including UHPCs [40]. Recent advancements in the cement composite industry have led to the development of UHPC, enabling the creation of highly durable structures with minimal cover thickness and element dimensions (within design limitations) [41].

2. Ultra-High-Performance Concrete

2.1. Background

Over the past two decades, significant endeavors have been dedicated to addressing the brittleness and fragile nature of cement composites, leading to the emergence of a specialized field known as high-performance fiber-reinforced concrete, with Japanese researchers often hailed as pioneers in this domain [41–43]. Several noteworthy studies have delved into this type of composite, including the work of Kunieda et al. in 2006 [44].

The origins of the terms “high-performance” and “ultra-high-performance concrete” trace back to the 1960s when steel fiber was first employed to manage cracking. Early researchers, such as Romaldi and Batson in 1963 [45], delved into the fracture mechanics of steel fiber-reinforced concrete. The 1990s witnessed a shift toward the production of high ductile fiber-reinforced concrete. In 1992 [46] and 1993 [47], Li et al. conducted a comprehensive study on the behavior of strain-hardening fiber-reinforced composites and initiated investigations into the effects of fibers on materials post-cracking. Notably, Habel et al. [48] conducted comparative impact and static loading tests on UHPC, evaluating quasi-static and dynamic loading on UHPC plates. Yeng et al. [28] explored the influence of aggregate types and curing regimes on UHPC properties, examining three aggregate varieties and two curing temperatures (20 °C and 90 °C). While the study of creep and shrinkage in UHPC is still in its infancy, Garas et al.’s article [49] serves as a primary reference in this area. Their findings indicated that incorporating 2% short steel fibers can reduce creep by up to 40%, while thermal curing at 90 °C for two days leads to a 70% reduction in creep. Another significant avenue of UHPC research is the exploration of flexural behavior in specimens subjected to varying loading rates. Pyo et al. [50] investigated the flexural behavior of UHPC containing different amounts and shapes of fibers under various loading rates.

In a review study, Yang et al. [51] discussed the effects of different fibers on the mechanical properties of UHPC. They reported that fibers play an important role in improving tensile strength, compressive strength, and MOE. The combined use of steel fibers leads to a decrease in the flowability of UHPC, which can result in a non-uniform distribution of fibers and an increase in porosity, and as a result, the service life of UHPC decreases. They emphasized that polymer fibers used in UHPC increase permeability and decrease pore pressure at high temperatures. In addition, hybrid fibers can significantly bring reinforcement effects to UHPC. Sherzer et al. [52] presented a multiscale analysis method to model concrete structures. They emphasized that the modeling of concrete behavior is considered a serious challenge due to the need to bridge between the cement scale and the concrete scale. In another study, Sherzer et al. [53] investigated fracturing through aggregates by the Lattice Discrete Particle Model (LDPM) for high-strength concrete (HSC). They compared the results of their method with real crack scans and succeeded in obtaining matching fracturing patterns. Additionally, a good match was obtained between the modeling results and the experimental results of the three-point bending strength of HSC.

2.2. Definition and Properties

Drawing from the research conducted by the Portland Cement Society, ultra-high-performance concrete (UHPC), also known as reactive powder concrete, is a material renowned for its impressive combination of high strength and ductility. Typically composed of Portland cement, silica fume, quartz powder, fine silica sand, superplasticizer, water, and steel or organic fibers, UHPC has achieved remarkable compressive strength of approximately 200 MPa and flexural strength of around 48 MPa.

The constituents are typically grouped into three pre-mixed categories: powder (including cement, silica fume, quartz powder, and sand), superplasticizer, and fibers. Ductile behavior takes precedence in the formulation of ultra-high performance concrete (UHPC), empowering the material to endure deformations, flexural stresses, and tensile loads even in the presence of initial crack formation. The elimination of traditional bar reinforcement has greatly simplified the construction process, allowing for diverse shaping possibilities [54–56].

Various international organizations and societies are actively engaged in the development of codes and standards for UHPC. In Asia, the Japan Society of Civil Engineers (JSCE) has undertaken substantial investigations and presented recommendations for the design and construction of high-performance fiber-reinforced cement composites (HPFRCC), categorizing UHPC (or UHPFRC as a fiber-reinforced class) within this enhanced mechanical material framework [57]. The French Association of Civil Engineering (AFGC) has similarly formulated recommendations for structural design using UHPFRC [58]. In the United States, the American Concrete Institute (ACI) has released its inaugural code for the structural application of UHPC [59]. Furthermore, the first ASTM standard for UHPC was introduced in 2017 [60].

2.3. Introduction to Industry

Owing to its unique mechanical and physical attributes, ultra-high-performance concrete (UHPC) holds tremendous potential for widespread utilization in contemporary structures. Nevertheless, the realization of this potential on a large scale has been somewhat limited, with only a handful of structures worldwide having been constructed at true scales. Notably, substantial efforts have been undertaken in the United States across academic and industrial spheres to harness the capabilities of UHPC in both industrial and civil projects.

An instrumental initiative in this realm is the formation of a group known as "Working UHPC". This group is focused on the development of comprehensive instructions that encompass every stage of UHPC production, from casting to testing and terminology. To visually represent the initial connection between the conceptual and practical aspects of UHPC, a flowchart could be devised, illustrating scientific methods for enhancing quality and implementing systematic enhancements (Figure 1).

The incorporation of UHPC as a sophisticated material, often in conjunction with steel casings such as steel tubes, whether additionally reinforced or confined by external steel walls, has the potential to revolutionize the design of next-generation skyscrapers [61–63]. Notably, endeavors have already been initiated to explore structural possibilities for high-rise buildings [64,65]. However, certain challenges persist, many of which have been investigated across diverse research fields. Among these, a particularly significant challenge lies in comprehending the seismic behavior of UHPC elements, whether used individually, as strengthening components, or in conjunction with other materials. This challenge stems from the inherently brittle nature of UHPC [66–68].

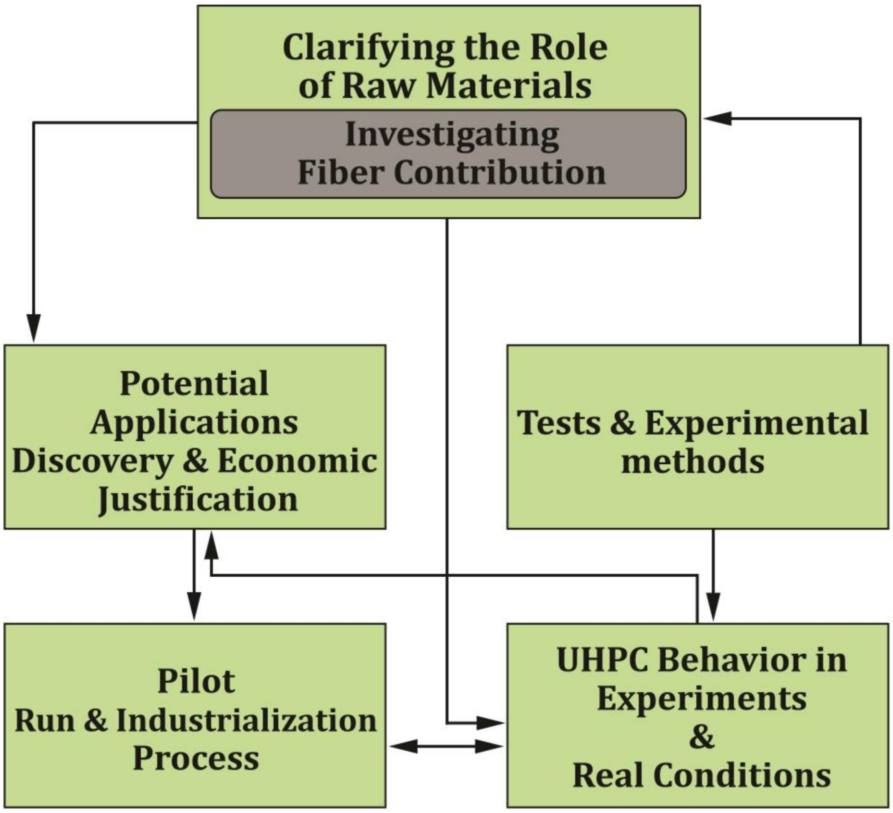


Figure 1. Common areas of research on UHPC.

2.4. Technical Problems

1. High Cost and Economic Justification Gap: The production cost of UHPC is notably higher, amounting to a minimum of 6.6 times that of ordinary concrete [69,70] Moreover, limited manufacturers, such as Lafarge, offer comprehensive industrial support for the requisite raw materials [70–73]. Nonetheless, intricate applications such as concrete-filled steel tubes (CFST) for columns and steel–concrete–steel sandwich composites are garnering attention [72,73].
2. Compatibility of Indigenous Materials: UHPC necessitates specific materials in its mixture, which may not always be locally available. The intricate task of gauging and optimizing material quantities further complicates the attainment of the desired concrete formulation at every project site.
3. Sensitivity to In Situ Casting Conditions: The imperative for exceptionally high strength (exceeding 120 MPa) renders UHPC exceedingly susceptible to environmental and placement conditions. Mixing, curing, relative humidity, thermal conditions, and setting time collectively impact the mechanical attributes of UHPC.
4. Technical Complexities in Connections: The realm of connections and bonds involving UHPC layers/elements and other structural materials remains largely uncharted. The bond between UHPC and the hardened layer of structural concrete, whether in early stages or from existing structures, has been a subject of research for an extended period [74,75].
5. Absence of Standard Specifications: While numerous tests devised for conventional concrete by ASTM are applied to UHPC, a consensus is yet to be reached regarding grading and mix proportions. Moreover, in dynamic loading scenarios, this type of concrete exhibits behavior that is relatively unexplored.
6. Demand for UHPC Production Facilities and Skilled Workforce: Given the substantial cost of UHPC and the limited operational capacity, establishing production facilities

lacks economic viability. Additionally, a trained workforce is essential for the proper casting and placement of UHPC components.

3. Multi-Criteria Risk Assessment

There exist heavily structured and mathematically modeled tools to assess the sustainability of structures based on statistical data. However, a deficiency remains in anticipating the future uncertainties associated with complex projects and emerging concrete technologies, particularly in the swiftly evolving landscape of civil engineering [74,76]. Establishing a suitable framework is essential to prevent unilateral decision-making that could yield erroneous or misleading outcomes [77]. To attain the study's objectives and enable the practical application of results within the industry, the consideration of environmental performance as a paramount evaluation factor should be undertaken in a holistic manner [78].

Leveraging risk management techniques, considering a multitude of diverse parameters, serves as a familiar research strategy within the industry [79]. Evaluating the mechanical and durability attributes of distinct concrete generations can pave the way for the prudent and assured integration of emerging technologies, such as UHPC, into the realm of construction. Constructing a hypothetical framework to assess genuine risk measures can yield a systematic and robust evaluation of both technical and economic facets of projects, while also illuminating the potential risks associated with the structures' service life [80–82].

Among the methods of risk evaluation, the semi-quantitative approach stands out, providing a categorization for both the probability of occurrence and the impact of risks. When the practical application of a quantitative method is hampered by operational complexities and a scarcity of trained labor resources, the semi-quantitative method emerges as a promising alternative for evaluating risks in civil projects. This approach involves five steps to classify the likelihood of occurrence and to examine the effects of risks, as presented in Table 1. The table features qualitative indices in conjunction with corresponding numerical values. The incidence probability and risk impact are determined and interpreted using Equation (1):

$$R.I = P + C - (P \times C), \tag{1}$$

Here, $R.I$ represents the risk index, while P and C denote the incidence probability and the risk effects, respectively [80]. Employing a fault tree analysis (FTA) (Figure 2) can aid in categorizing and addressing primary issues, fostering a better comprehension of problems. These problems are classified into three primary categories and nine subcategories, which may vary based on the evaluation's type and sensitivity, and the results of local resource experiments.

Table 1. Probabilities, effects, and qualitative risk index.

			Effects				
			Negligible	**Low**	**Moderate**	**High**	**Critical**
			0.1	**0.3**	**0.5**	**0.7**	**0.9**
Incidence probability	Certain	0.9	Moderate	Moderate	High	High	High
	Probable	0.7	Low	Moderate	Moderate	High	High
	Possible	0.5	Low	Moderate	Moderate	Moderate	High
	Improbable	0.3	Low	Low	Moderate	Moderate	High
	Rare	0.1	Low	Low	Low	Moderate	Moderate

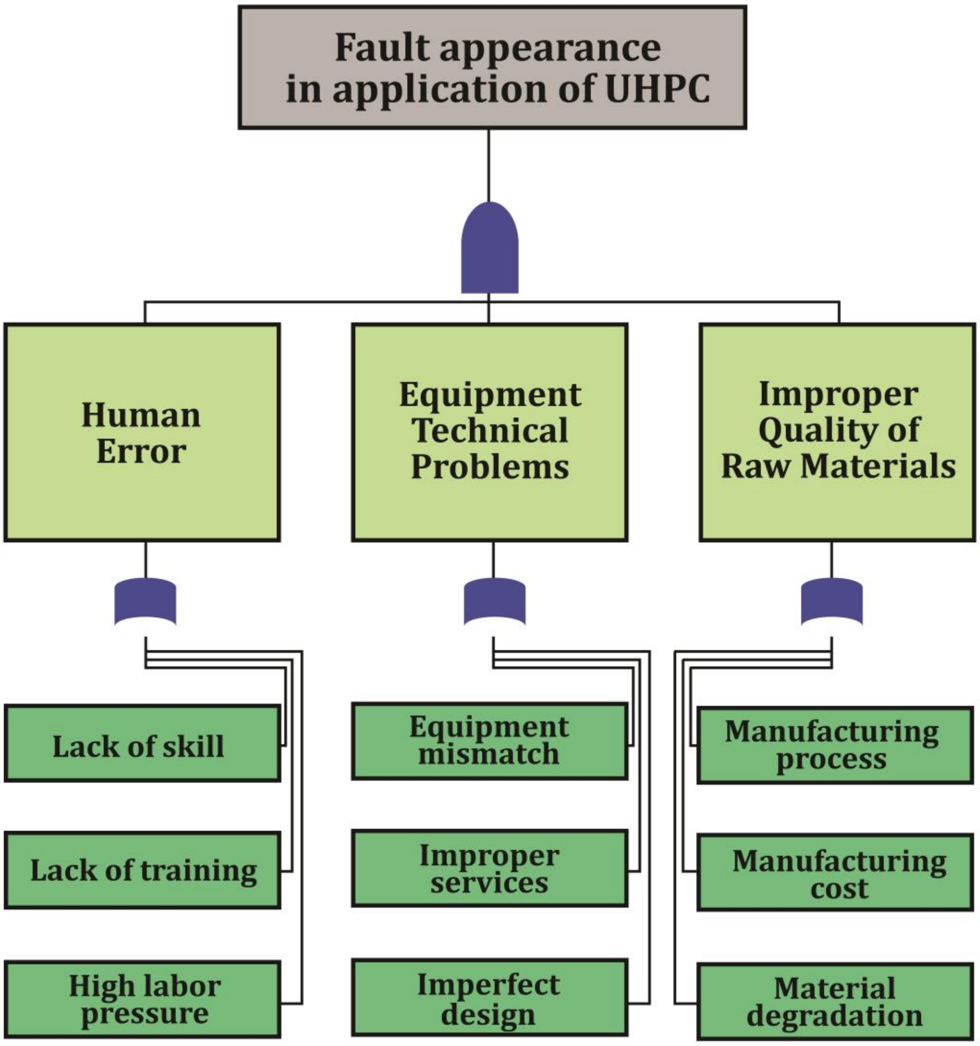


Figure 2. Fault Tree of UHPC application in civil projects.

Assigning numerical values to the effects and incidence probabilities and then interlinking them through a relationship matrix can establish a sophisticated rating system that serves as a quantifying tool (Table 1). By leveraging statistical data derived from questionnaires completed by experts, a weighting procedure is formulated, transforming the fault tree analysis (FTA) into meaningful numerical representations (Table 2).

3.1. Risk Evaluation Based on Mix Proportions

In this section, an informed assessment of UHPC mix proportions and the interrelationships among materials has been conducted to evaluate risks. To achieve this, the risk evaluation of these mix proportions incorporates the economic implications of using specific materials, taking into account their costs and complexities. The following types of risks have been considered for these proportions:

1. Economic Risk: This pertains to the potential undesirable escalation of costs and the risk associated with selecting a more economically efficient option that may compromise technical quality.
2. Technical Risk: This encompasses complexities and factors beyond control, such as unknown chemical parameters in superplasticizers, where an increase in these parameters can raise the risk level.

3. Environmental Risk: This is determined based on the constituents and the environmental impact emitted by the manufacturing industry, which can either be negative or positive (e.g., pollution reduction).

Table 2. Evaluation of risks involved in using UHPC.

Risk	Incidence Probability		Effects		Risk Evaluation	
	Qualitative Index	Probability	Qualitative Index	Effect	Qualitative Index	Risk Index
Improper quality of raw materials						
Manufacturing process	Improbable	0.35	Low	0.4	Low	0.61
Manufacturing cost	Rare	0.15	Negligible	0.2	Low	0.32
Material degradation	Improbable	0.35	Moderate	0.6	Moderate	0.74
Equipment technical problems						
Equipment mismatch	Certain	0.85	Moderate	0.45	High	0.92
Improper services	Rare	0.2	Moderate	0.45	Low	0.56
Imperfect design	Improbable	0.35	High	0.75	Moderate	0.84
Human error						
Lack of skill	Rare	0.2	High	0.65	Moderate	0.72
Lack of training	Probable	0.8	High	0.65	High	0.93
High labor pressure	Rare	0.15	Moderate	0.45	Low	0.53

3.2. Weighing and Synchronizing

Based on the significant risk parameters, it becomes necessary to establish a criterion for comparing various types of risks associated with each constituent material. Utilizing available information from manufacturers and employing a valuation scale facilitates these comparisons. To achieve this, fundamental valuation and risk parameters were assigned to each constituent material. Subsequently, by applying the designated measure for each material, the overall risk index (ORI) for each mix proportion was computed. There are many studies evaluating the embodied CO_2 (eCO_2) in the scale of kg CO_2 per kg of the material and cement is one of the most polluting materials which as a product made of clinker in cement factories requires a lot of fuel to be made and releases CO_2 as a byproduct [83]. Considering this greenhouse gas alone as an environmental factor which is mentioned separately in the last column of Table 3 has some flaws and omits so many influential parameters which make it unreliable as an environmental pollution factor [84,85]. The data presented in Table 3 were compiled based on definitions of different risk types and through collaboration with 42 experts specializing in concrete technology. The average evaluations for each material within these three categories carry a similar weighting, akin to the dominance analysis employed for formulating UHPC mixtures in a broader life cycle assessment (LCA) perspective [86]. Experts were chosen based on their expertise spanning three key domains: academia specializing in concrete technology, adeptness in construction management for projects centered around concrete, and proficiency as concrete technicians in ready-mixed concrete facilities. All selected experts boasted an extensive professional track record exceeding 15 years. Their assessments, based on the qualitative indices from Tables 1 and 2, underwent analysis using fundamental statistical techniques such as mean calculations, and the resultant averages were consolidated in Table 3. The approach considered in this table provides better insight of the risk parameters especially in the environmental section. At the first glance, cement as a main environmental risk has a close relationship with eCO_2 which shows the impact of the greenhouse gas on the opinion of experts. Otherwise, some materials such as aggregate, water, and silica fume are so underrated partly because of neglecting some purification, packaging, and transport operations which may vary a lot between countries and projects. On the other hand, materials such as superplasticizer and steel fiber are overrated potentially because their pivotal role in the overall performance and optimization of UHPC mix is not considered thoroughly. Some studies considered the role of blended cements as environmentally positive materials and their eCO_2 is reported to be lower than cements [87]. There is a solid debate on this matter; however, in the opinion of the authors of this paper, when silica fume alone can cut the CO_2 footprint of the cement consumption in concrete mix designs up to 20% (based on Tables 3 and 4), blended cements are so underrated.

Table 3. Risk information of UHPC constituent materials.

N.O.	Material	Economic Risk	Technical Risk	Environmental Risk	eCO_2/Ref.
1	Cement	0.2	0.3	0.85	0.83 [88]
2	Aggregate	0.1	0.1	0.15	0.01 [78]
3	Water	0.05	0.05	0.05	0.001 [89]
4	Silica Fume	0.5	0.2	0.05	0.016 [90]
5	Superplasticizer	0.85	0.9	0.45	0.72 [91]
6	Steel Fiber	0.75	0.25	0.65	1.497 [92]

For a more accurate investigation on the effects of constituent materials on the risk of making different strength classes of concretes, 12 mix proportion designs were selected from different studies. These proportions are given in Table 4, and the details of these studies are in Table A1. Three different types of concrete, three different compressive strength levels, various silica fume replacements for cement in different percentages, and distinct ratios for water/cementitious and superplasticizer/cementitious materials were chosen. Thus, a wide range of technical and economic options inspected. Obtaining a mix design with technical or economic optimization is a complicated task to fulfill which leads to encountering a wide variety of choices. By the addition of risk parameters to the process of choosing optimum mix design, other effective parameters such as environmental pollution and operational complexities can be expressed in the language of mathematics. There are multiple mechanical properties for evaluation of concretes and their behavior based on loading parameters, geometries of specimens, and reinforcement and data extraction techniques which change significantly based on the class of concrete and its constituent materials [93]. Despite the existence of some case studies on the mechanical behavior of eco-efficient UHPCs, expanding studies such as those on the post-crack of these materials is challenging [94]. Therefore, investigation of all effective parameters in a risk assessment study such as the present paper is not feasible. So, a universal mechanical characteristic such as compressive strength is considered for risk assessment. Drawing from the research background, when engaging in higher-level risk assessment techniques involving a greater number of parameters, two specific formulas have been identified and can be employed as follows:

$$O.R.I. = 1 - ((1 - P) \times (1 - Q) \times (1 - R)), \tag{2}$$

$$O.R.I. = P \times Q \times R, \tag{3}$$

With reference to Table 3, P, Q, and R are Economic Risk, Technical Risk, and Environmental Risk, respectively.

Table 4. Mix designs for three strength classes of concretes.

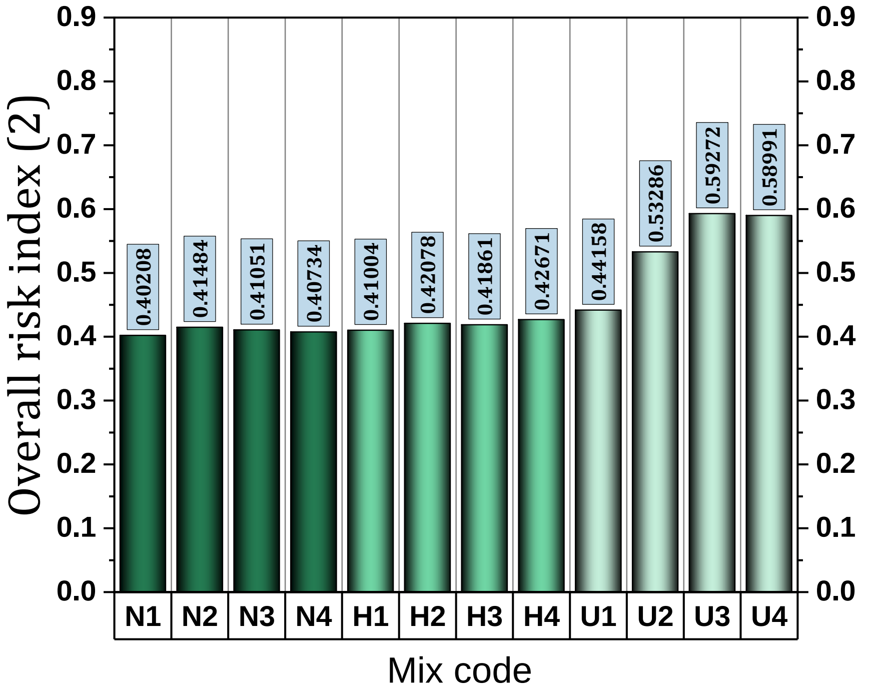
Mix	Cementitious Materials (CM) (Kg/m^3)	Ratios (/CM)			Fiber Content (Kg/m^3)	f′c (MPa)	Ref.
		Silica Fume	Water	Superplasticizer			
N1	413	0	0.46	0	0	35.9	[95]
N2	413	0	0.46	0	59	46.9	[96]
N3	440	0	0.45	0.0125	0	39	[97]
N4	440	0.1	0.45	0.021	0	41.8	[56]
H1	413	0.1	0.35	0.04	29.5	75.2	[96]
H2	500	0.15	0.35	0.0267	0	70	[98]
H3	500	0.1	0.3	0.0018	0	107.9	[99]
H4	520	0.15	0.26	0.035	0	95.7	[100]
U1	600	0.2	0.25	0.025	0	130	[101]
U2	853	0.15	0.2	0.0352	155	166.1	[102]
U3	1187	0.2	0.15	0.014	146	198.5	[103]
U4	1125	0.2	0.16	0.032	157	140	[104]

4. Discussion

A comparison of the results obtained from the aforementioned formulas leads to the same conclusion as depicted in Table 5. As shown in Figure 3, the patterns in both charts exhibit similarities, but the sensitivity in ORI3 is notably heightened. In both charts, U4 exhibits the highest level of risk, attributed to its higher cement content. However, basing judgments solely on this parameter is premature. Therefore, it becomes essential to comparatively assess two deterministic properties of concrete: the 28-day compressive strength, representative of mechanical properties, and the service life, indicative of durability, in relation to both types of ORI.

Table 5. Risk index calculations for different mixture proportions.

Mix	Weight Ratios of Constituent Materials						Overall Risk Index (2)	Overall Risk Index (3)
	Cement	Silica Fume	Water	S.P	Aggregate	Steel Fiber		
N1	0.172	0.000	0.079	0.000	0.749	0.000	0.402	0.0091
N2	0.168	0.000	0.077	0.000	0.731	0.024	0.415	0.0118
N3	0.185	0.000	0.083	0.002	0.730	0.000	0.411	0.0105
N4	0.169	0.017	0.084	0.004	0.727	0.000	0.407	0.0103
H1	0.152	0.015	0.059	0.006	0.756	0.012	0.410	0.0118
H2	0.181	0.027	0.073	0.005	0.713	0.000	0.421	0.0116
H3	0.184	0.018	0.061	0.000	0.736	0.000	0.419	0.0100
H4	0.184	0.028	0.055	0.007	0.726	0.000	0.427	0.0123
U1	0.205	0.041	0.061	0.006	0.687	0.000	0.442	0.0130
U2	0.288	0.043	0.066	0.011	0.531	0.060	0.533	0.0263
U3	0.381	0.076	0.069	0.006	0.412	0.056	0.593	0.0289
U4	0.365	0.073	0.070	0.013	0.418	0.061	0.590	0.0312



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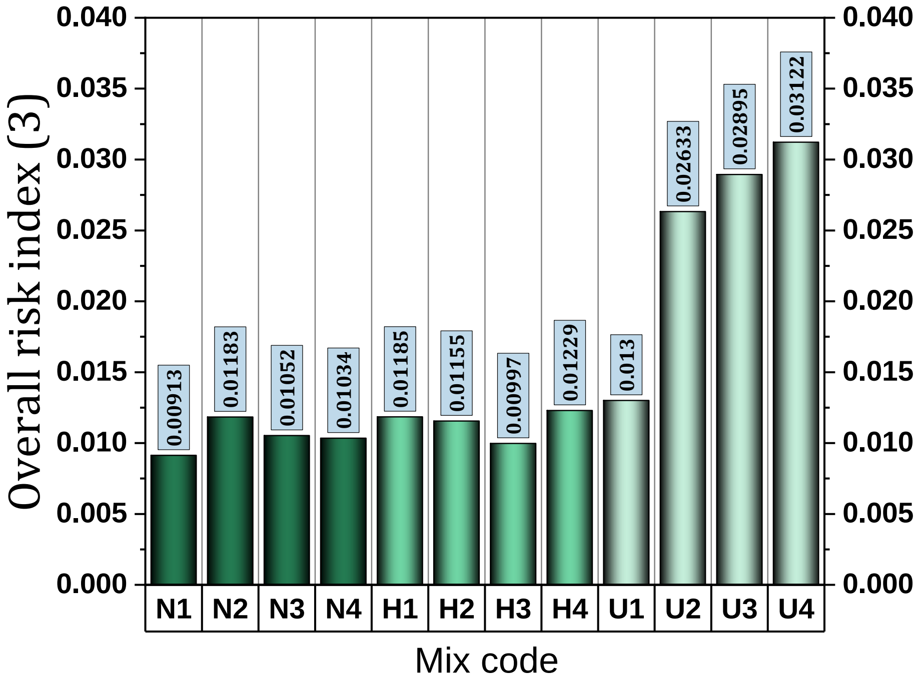
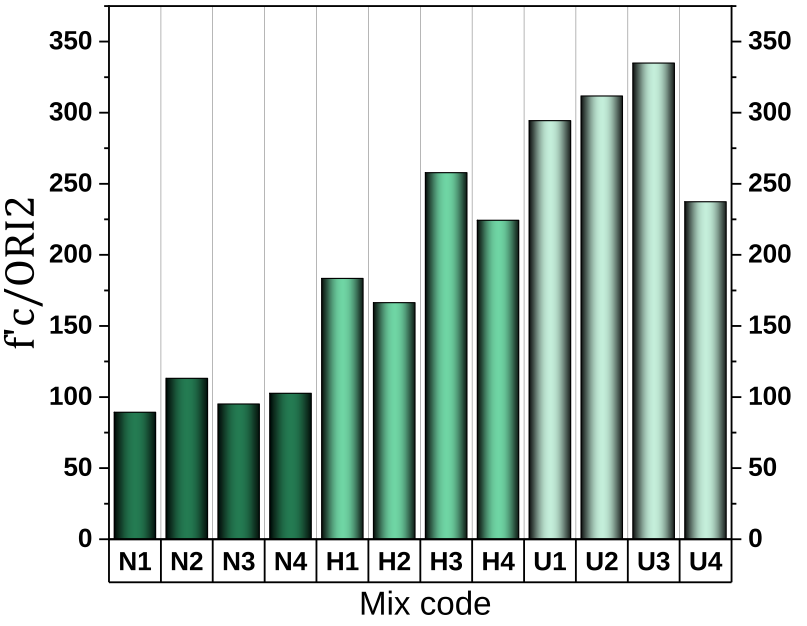


(**b**)

Figure 3. Overall risk index measures for different mix designs (**a**) index 2 and (**b**) index 3.

As illustrated in Figure 4, two variations of compressive strength values per unit risk ($f'c$/ORIX) establish the concept of technical value in light of the risk associated with a specific material. This definition aligns with the concept of compressive strength per unit cost, encompassing a broad spectrum of risks, among which economic risk constitutes an integral facet of the comprehensive risk framework [105].



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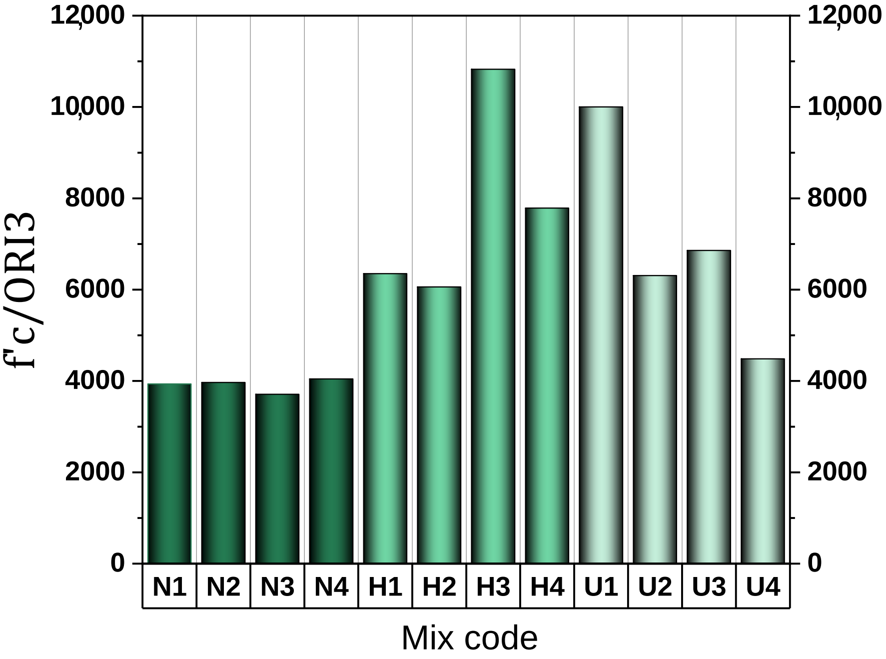


(**b**)

Figure 4. Compressive strength value of a unit risk for (**a**) ORI2 and (**b**) ORI3.

Through two distinct analyses, divergent outcomes can be discerned. Remarkably, in correlation with ORI2, U3 exhibits the highest value—a finding that contradicts the results of risk assessment. This suggests that the inherent characteristics of the concrete can mitigate the impact of risk parameters by altering the design, reducing costs, and minimizing material consumption, ultimately resulting in diminished environmental risk across the project. However, ORI3 displays a propensity towards the HPC category, signifying the pivotal role of cement content, as evidenced by the lower content in U2.

In terms of the cost/return ratio, considering the various aspects discussed for defining risk parameters, a potential reduction of at least 57.5% is achievable when upgrading from conventional concrete technology to UHPC, and a reduction of 16.7% can be attained when transitioning to HPC technology with enhanced strength. This signifies that, particularly for medium to large projects, adopting UHPC technology can indeed rationalize the higher material costs associated with it [106].

In this study, the Life-365 software provided by the National Ready Mixed Concrete Association (NRMCA) served as the foundation for predicting the service life of both normal and high-performance concretes. However, to estimate the initial corrosion of reinforcing steel in UHPC, extrapolation of the data was carried out, resulting in the calculation of four UHPC mix designs for service life. It is worth noting that this estimation is theoretical, and the actual values, considering the extremely high measures obtained from durability experiments, may be adjusted from a more comprehensive standpoint [107,108]. For the sake of methodological simplicity, this study utilized a straightforward structural element—a 1D slab—as shown in Figure 5. However, the assumed cover thickness for UHPC is over-designed and lower amounts may be acceptable [91] but in order to control this parameter and avoid the consequent deep impacts of this parameter, the same measure is applied for UHPC as well [38,40].

Figure 5. A typical cross-section of a 1D slab by life-365.

As a noteworthy outcome evident from Figure 6, the UHPC Series exhibit an exponentially extended service life, positioning them as ideal contenders for obviating repair expenses for a span exceeding two centuries. The difference between normal and high-performance concretes is not exponential compared to the UHPC group and the maximum difference reaches up to 57 years which mainly depends on the pozzolan used in the formula of HPCs. Reaching extremely high service lives in structures made of UHPC owing to their exquisitely low penetration rate is quite different between UHPC mix designs and compared to HPCs varies from 32 to 263 years. This simulated assessment aligns with experimental findings derived from a range of studies focused on UHPC [109]. A number of studies are focused on the matter of cracks in UHPC and similar modern cement composites [110,111]. Cracks can severely impact the service life of reinforced concrete structures due to open pathways in the cover directly toward reinforcement [112]. However, considering the implications due to the roots of crack formations, and the impact of cracks based on the class of concrete, numerous parameters may be involved in the estimations for risk assessment analysis. Therefore, all concrete elements simulated in the software are considered intact. Various tests and experiments are employed to ascertain the durability of concretes such as UHPC. Among these, some of the most crucial ones include assessments of electrical resistivity, chemical resistance, freeze-thaw durability, and abrasion resistance [109,113]. A simplistic approach to avoid the complex challenges of making a risk assessment framework which is implied in Figure 6 may be the use of software which considers a simple and universal test such as chloride infusion data bases that covers the durability estimation and consequent service life of reinforced concrete elements. Using these assumptions and omitting the effect of multiple characteristics also helps the analysis to predict the service life with minimum complexities with acceptable error margins.

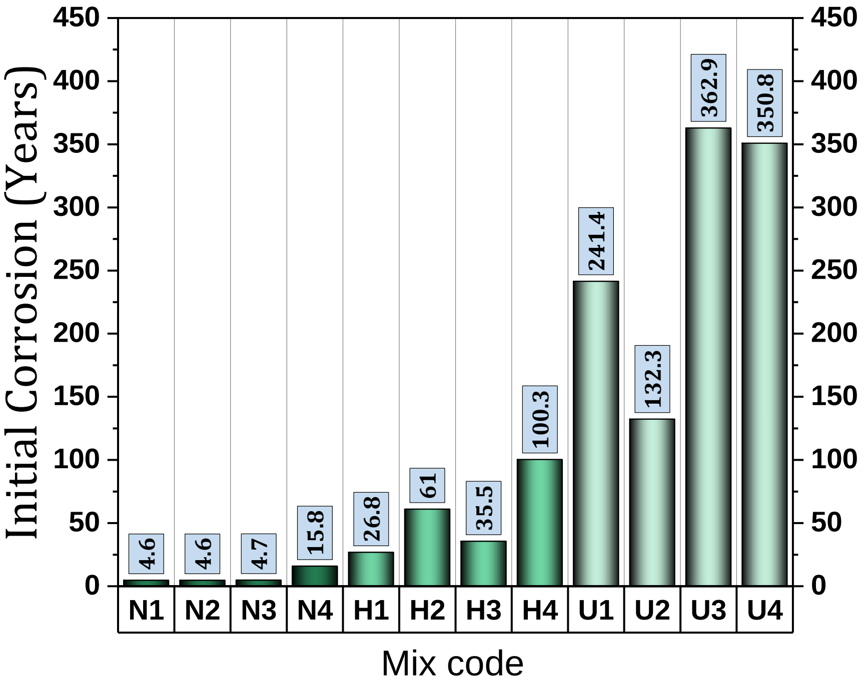
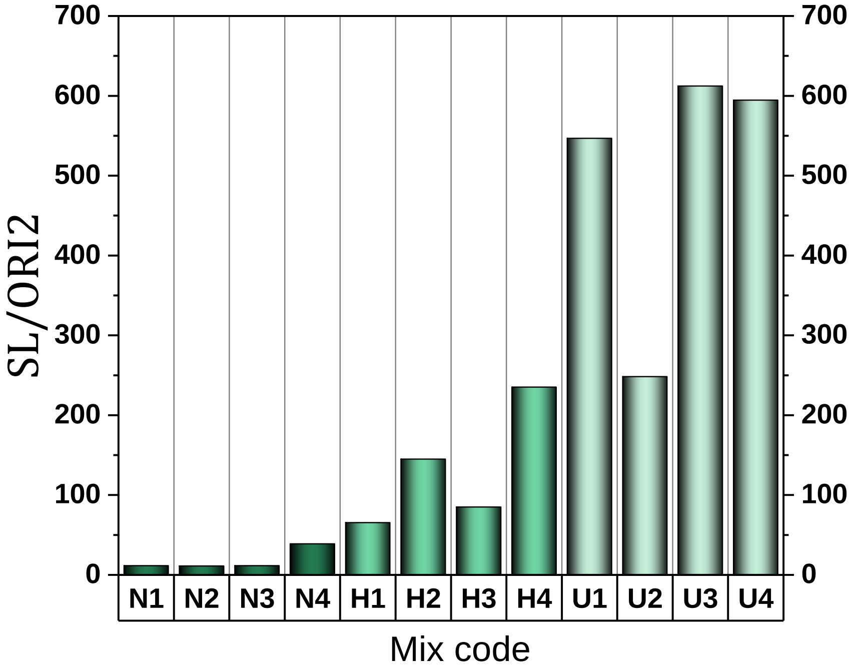


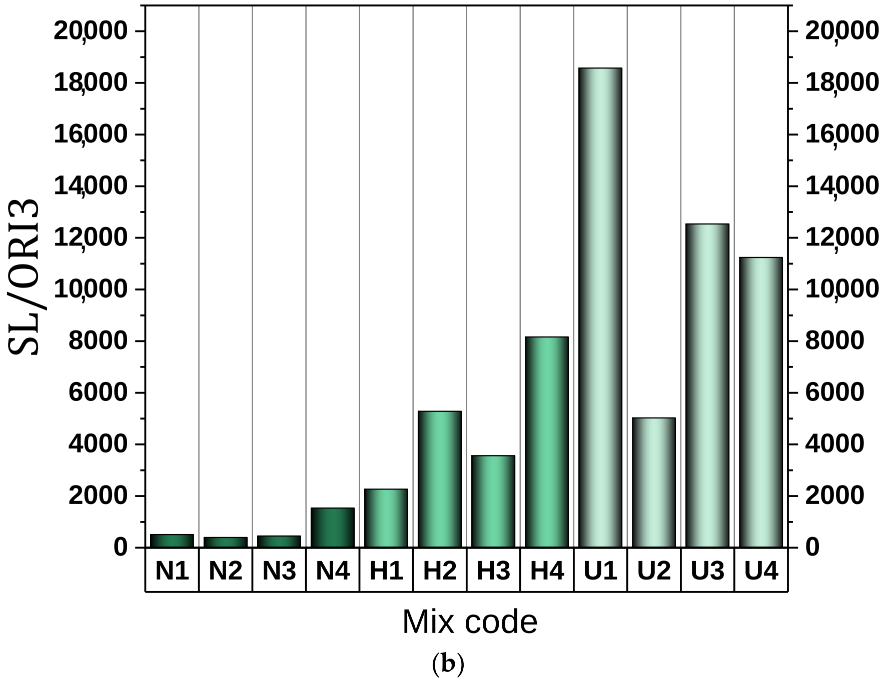
Figure 6. Comparison between NC, HPC, and UHPC service life in the chosen element model.

Reiterating the validation of the findings in Figure 6, Figure 7 further accentuates that the primary contenders are situated within the U Series. Notably, U1 emerges as the consistent preference in both ORI evaluations. Meanwhile, U2 experiences a significant decline, which can be attributed directly to its comparatively lower Service Life (SL) when compared to the other UHPC mixtures. In the case of U1 due to the difference of constituent materials, risk parameters are more influential, so these models can be crucial decision-making tools for civil engineering projects.



(**a**)

Figure 7. *Cont.*



(**b**)

Figure 7. Service life value of a unit risk for different concrete generations for (**a**) ORI2 and (**b**) ORI3.

5. Conclusions

Ultra-high-performance concrete (UHPC) stands as a sophisticated and contemporary alternative within the realm of today's concrete industry. Assessing the risks associated with adopting this technology and its integration into major industries becomes a crucial prerequisite for civil projects. Given its innovative nature and the uncharted industrial dimensions it presents, conducting a comprehensive technical and economic evaluation of UHPC poses considerable challenges. Nonetheless, risk management surfaces as a pragmatic and powerful tool that empowers project managers to assess feasibility and compare UHPC with conventional concretes. This is achieved by drawing on national studies and utilizing indigenous technological insights.

The array of literature surveyed within this article underscores that the assignment of numerical risk parameters to constituent materials, coupled with the exploration of a diverse spectrum of indigenous mix designs, lays the groundwork for selecting proportions with diminished risk values. Furthermore, optimizing mix designs predicated on risk parameters and accounting for factors such as environmental impact extends a panoramic perspective on UHPC, significantly facilitating the optimization of expansive civil projects.

The findings of this study underscore that factoring in the core concrete characteristics essential for structural design, to evaluate comprehensive risk factors, rationalizes the normalization of disparate parameters into a unified formula. A comparative analysis of the Compressive Strength per unit risk index across three distinct concrete generations illustrates that UHPC stands as a formidable competitor to high-performance concrete (HPC), exhibiting a superiority of 42% according to ORI2 and a marginal inferiority of 11% as per ORI3. Furthermore, UHPC outperforms normal concrete by a noteworthy margin of at least 77% (ORI3), gauged against the averaged outcomes of the four mixes for each class. In terms of the Service Life per unit risk index, the comparative investigation unveils UHPC's resounding dominance, showcasing an impressive minimum advantage of 146% (ORI3) over HPC and a staggering 1552% (ORI3) superiority when contrasted with normal concrete. Evidently, the UHPC series boasts discernible advantages, positioning them as formidable contenders poised to supersede preceding generations.

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Appendix A

Table A1. Appendix for Table 4.

No. Samples	Diameter of Samples	Age (Days)	Additives (Substitute Part of Cement)	Fiber Length (mm)	Curing Method	References
18	100 × 200 mm	28	Silica fume	50, 30 and 60	-	[95]
10	100 × 200 mm	28–91	Silica fume	-	Dry air curing Water curing	[97]
5	76 × 152 mm	1–5–7–14–28–90–160–180	Silica fume	30, 20 and 13	Moist	[56]
24	100 × 100 × 100 mm	7–14–28–42–90–365–400	Silica fume	-	Moist Dry	[98]
48	100 × 100 × 100 mm 100 × 200 mm	3, 7, 28, 90	Metakaolin Silica fume	-	Moist	[99]
32	150 × 150 × 150 mm	28	Silica fume	-	Moist	[100]
3	100 × 100 × 100 mm	28	Quartz powder Silica fume	6	Air curing	[101]
4	100 × 100 × 100 mm	28	Slag Fly ash	15	7 days of storage under water in a curing tank, after which it was processed in the air under laboratory conditions until day 28.	[102]
3	90 × 180 mm 70 × 140 mm	28	Crushed quartz Silica fume	13, and 3	The concrete was cured for 7 days in water at 20 °C followed by heat treatment for 4 days in water at 90 °C and 2 days in dry air at 90 °C.	[103]
16	50 × 50 × 50 mm	7–28–56	Quartz powder Silica fume	-	Moist	[104]

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