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A REVIEW OF COMPARING CORE PROPERTIES OF ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC) AND ULTRA-HIGH-PERFORMANCE FIBER-REINFORCED CONCRETE (UHPFRC)

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ABSTRACT
Ultra-High-Performance Concrete (UHPC) marks a significant advancement in concrete technology, offering superior strength and durability over traditional materials. UHPC's exceptional properties arise from its dense microstructure, enhanced with specialized binders and additives. A further innovation in this field is the development of Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC), which integrates steel fibres into UHPC. This addition enhances the material's toughness, ductility, and flexural strength, making it more versatile and resilient. This paper presents a comparative analysis of UHPC and UHPFRC, focusing on crucial properties such as compressive strength, flexural performance, impact resistance, and ductility. By examining these properties, the paper aims to highlight the advantages of UHPFRC over UHPC, particularly in structural applications. The inclusion of steel fibres in UHPFRC not only improves its mechanical performance but also extends its applicability to a wider range of engineering projects. The findings underscore UHPFRC's potential to advance sustainable and resilient construction practices, contributing significantly to the future of structural engineering. This analysis provides valuable insights into the benefits of UHPFRC, paving the way for its broader adoption in demanding construction environments

Keywords:
Ultra-High-Performance Concrete (UHPC), Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC), steel fibers, Compressive strength, Flexural performance, Impact resistance

I. Introduction

Ultra-High-Performance Concrete (UHPC) represents a significant leap forward in concrete technology, distinguished by its exceptional strength and durability. The development of Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC), which incorporates steel fibers, further enhances the material's performance by significantly improving its toughness and flexural properties. This advancement effectively addresses some of the inherent limitations found in traditional UHPC formulations. This study presents a comparative analysis of UHPC and UHPFRC, emphasizing critical performance metrics such as compressive strength, flexural resilience, impact resistance, and ductility. The objective is to underscore the advantages of UHPFRC over conventional UHPC and to explore its potential applications in modern structural engineering. The findings aim to provide valuable insights for optimizing the deployment of these advanced materials in various construction scenarios, thus contributing to the progress of structural design and material science. The study highlights the crucial role of mixed design parameters in influencing the performance of UHPC and UHPFRC, with a particular focus on the use of recycled sand. Comparative analysis reveals that the incorporation of steel fibers into the concrete mix significantly enhances both toughness and flexural performance, addressing limitations of traditional UHPC.The evaluated mix designs, encompassing both conventional UHPC and UHPFRC formulations, exhibit notable differences in their compositions and performance characteristics. Specifically, the UHPC mixes, such as NS-U-20 and NS-U-16 are characterized by water-to-binder (W/B) ratios of 0.2 and 0.16, respectively, with varying amounts of Ordinary Portland Cement (OPC), Steel Fiber (SF), and Natural Sand (NS).In contrast, the UHPFRC mixes, represented by RS-U-20 through RS-F-16-2.0, incorporate recycled sand and demonstrate enhanced performance metrics, including superior impact resistance and ductility, due to varying steel fiber volumes and water-to-binder ratios. Incorporating recycled sand into UHPFRC mixes supports sustainable construction while achieving performance levels that are equal to or even exceed those of conventional materials. These findings suggest that UHPFRC with recycled sand offers a viable and environmentally friendly alternative for high-performance concrete applications. This study encourages further research and improvement of these advanced materials, leading to new and sustainable engineering solutions in various construction areas.A comparison between UHPC and UHPFRC is essential to understand the influence of fiber reinforcement on the mechanical properties, particularly tensile strength and durability. While UHPC offers high compressive strength, UHPFRC enhances tensile performance and crack resistance, making it crucial to analyze their differences for optimized structural applications.

II. Literature

The mechanical performance of Ultra-High-Performance Concrete (UHPC) and Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) has been the focus of extensive research. Studies such as those by Nguyen et al. (2019) and Wu et al. (2016) have highlighted the impact of steel fibers on UHPC's flexural behavior and overall mechanical properties. Their findings showed that fiber inclusion significantly enhances flexural strength and toughness, offering improved durability for structural applications Fehling et al. (2014) and Habel et al. (2006) further explored the benefits of UHPFRC, demonstrating how the incorporation of fibers optimizes both compressive strength and flexural performance. Several studies have examined the behavior of UHPFRC under extreme conditions. Yang and Chen (2015) assessed its performance after exposure to elevated temperatures, showing that it retains high compressive strength and durability. Bruhwiler and Denarié (2008) investigated its use in rehabilitating concrete structures, emphasizing its crack resistance and longevity in infrastructure. Additionally, Yoo and Kang (2015) demonstrated that fiber content directly improves UHPFRC's tensile and fracture properties, solidifying its applicability in dynamic structural environments. Research on sustainability has expanded the potential uses of UHPFRC, particularly in eco-friendly construction. Tafraoui et al. (2009) introduced metakaolin into UHPC formulations to improve durability, while Mohammed et al. (2019) focused on UHPC's role in enhancing sustainability in construction. Most recently, Choi et al. (2023) showcased how recycled sand in UHPFRC formulations maintains its mechanical integrity, suggesting its viability in sustainable high-performance construction.

This study conducted a comparative analysis of UHPC and UHPFRC by evaluating their compressive strength, tensile strength, flexural strength, durability, permeability, impact resistance, and fire resistance. Standardized testing methods were employed to assess the effects of fiber reinforcement and mix design variations, highlighting the enhanced performance characteristics of UHPFRC compared to traditional UHPC.

2.1 Concrete Grade

When comparing Ultra-High-Performance Concrete (UHPC) with Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC) across various performance grades, distinct differences emerge in their characteristics. UHPC, with compressive strengths ranging from 150 MPa (M150) to 250 MPa (M250), is renowned for its exceptional strength and durability. However, the incorporation of fibers in UHPFRC not only preserves this high compressive strength but also significantly enhances other critical properties.

2.2 Design mix

The mix proportions are defined by variations in water to-binder (W/B) ratios, ranging from moderate to low values, and by differing volumes of steel fiber (SSF) to enhance structural performance. These adjustments aim to optimize mechanical properties such as compressive and tensile strength, as well as flexural resilience and durability, by balancing workability, fiber content, and binder efficiency in both recycled and natural sand-based concrete formulations. The table employs the following notations: RS/NS-U/Fxx-y.y, where 'RS' and 'NS' denote the use of recycled sand or natural sand, respectively. The 'U/F' notation distinguishes between UHPC and UHPFRC, while 'xx' represents the water-to-binder(W/B) percentage, and 'y.y' indicates the steel fiber volume percentage relative to the concrete volume. The Superplasticizer (SP) dosage is standardized at 4.0% of the binder by weight for all UHPC mixes and 4.5% for all UHPFRC mixes.

Index	Mix design (kg/m3)									W/B
	OPC	FA	SF	QP	RS	NS	W	SP	SSF	
NS-U-20 (W-NS-1)	891	–	39.3	141	–	1150	214	42.9	–	0.2
NS-U-16	931	–	41	147	–	1201	179	44.8	–	0.16
RS-U-20 (W-RS-3)	818	72.1	80.1	95.6	1084	–	199	42.6	–	0.2
RS-U-18	823	72.6	80.6	96.2	1092	–	193	42.9	–	0.18
RS-U-17	832	73.4	81.5	97.2	1104	–	184	43.4	–	0.17
RS-U-16	842	74.2	82.4	98.3	1116	–	175	43.9	–	0.16
RS-F-17-1.0	832	73.4	81.5	97.2	1104	–	184	48.8	78	0.17
RS-F-17-2.0	832	73.4	81.5	97.2	1104	–	184	48.8	156	0.17
RS-F-17-3.0	832	73.4	81.5	97.2	1104	–	184	48.8	234	0.17
RS-F-16-2.0	842	74.2	82.4	98.3	1116	–	175	49.3	156	0.16

Table 1: UHPC / UHPFRC mix proportions

2.3 Compressive Strength

The compressive strength comparison between UHPC and UHPFRC demonstrates the impact of fiber inclusion on early and long-term strength development. Below are the data from 7-day and 28-day compressive strength tests for the mix designs.

2.3.1 UHPC

The compressive strength data provided below, extracted from the test reports, are utilized to evaluate and contrast the performance of UHPC as illustrated in the accompanying graph.

Index	Compressive strength		
	7d	28d	Elastic modulus
NS-U-20	60.2	90.1	43773
RS-U-20	64.4	86.3	37355
RS-U-18	65	87.4	35544
RS-U-17	65.5	102	40153
RS-U-16	60.7	97.4	41231

Table 1: UHPC / UHPFRC mix proportions

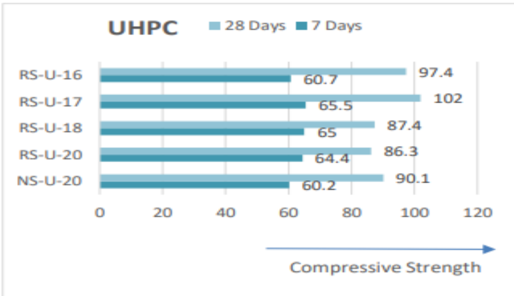

Figure 1: Compressive Strength of UHPC Graph

2.1.2 UHPFRC

The compressive strength data for Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC), as shown in Table 3, highlights its superior performance compared to traditional Ultra-High-Performance Concrete (UHPC). The inclusion of steel fibres significantly enhances the material's ability to withstand compressive loads, contributing to higher early and long-term strength development. As illustrated in Figure 2, UHPFRC consistently outperforms UHPC in terms of compressive strength over both 7-day and 28-day periods.

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Index	Compressive strength		
	7d	28d	Elastic modulus
NS-U-16	64	112	48043
RS-F-17-1.0	76	100	43506
RS-F-17-2.0	85	128	46867
RS-F-17-3.0	85	113	46645
RS-F-16-2.0	90	108	47502

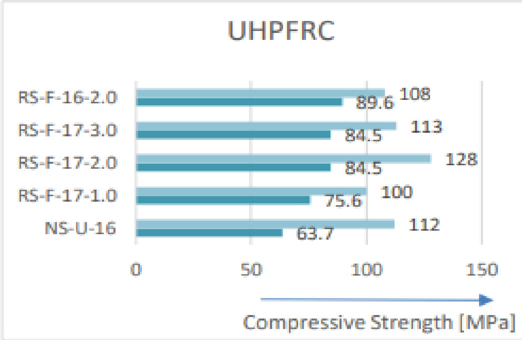

Table 3: Compressive Strength of UHPFRC Figure 2: Compressive Strength of UHPFRC Graph

2.4 Flexural Strength

The flexural strength data presented in the table highlight a comparative analysis between Ultrahigh-Performance Concrete (UHPC) and Ultra-High-performance Fiber-Reinforced Concrete (UHPFRC). As depicted, the UHPC samples (ranging from NS-U-20 to NS-U-16) exhibit varying flexural strengths, with values between 8.12 MPa and 13.5 MPa. In contrast, the UHPFRC samples (ranging from RS-F-17-1.0 to RS-F16-2.0) show enhanced flexural strengths due to the incorporation of steel fibers, with values reaching up to 18.1 MPa. This comparison underscores the significant improvements in flexural performance that can be achieved with UHPFRC, making it a superior choice for applications requiring higher flexural resilience.

Flexural strength			
Index	UHPC	Index	UHPFRC
NS-U-20	11.1	RS-F-17-1.0	9.41
RS-U-20	8.38	RS-F-17-2.0	11.9
RS-U-18	10.6	RS-F-17-3.0	18.1
RS-U-17	11	RS-F-16-2.0	14
RS-U-16	8.12		

Table: 4 Flexural Strength of UHPC & UHPFRC

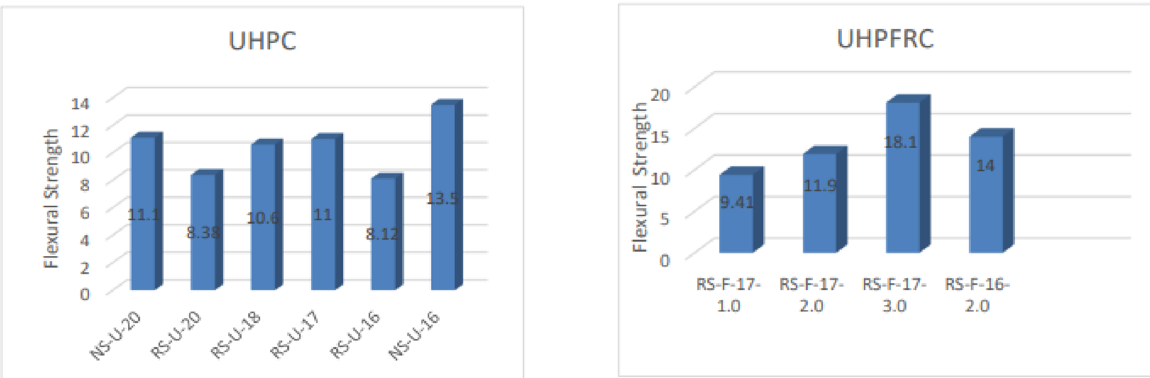

Figure : 3 Flexural Strength of UHPC & UHPFRC Graph

2.5 Tensile Strength

To convert load values (kN) into tensile strength values (MPa), the relationship is based on the cross-sectional area over which the load is applied. The tensile strength (σ) in MPa is calculated using the formula: Tensile strength (MPa) = Load(kN) / Crosssectional Area(mm2) Given a cube with a side length of 70.71 mm, the crosssectional area would be approximately 5,000 mm².

Material	Tensile Strength	Estimated Load
UHPC	8	40
UHPC	9	45
UHPC	10	50
UHPFRC	10	60
UHPFRC	12	72
UHPFRC	14	84
UHPFRC	16	96
UHPFRC	18	108
UHPFRC	20	120

Table 5 : Tensile Strength

2.6 Impact Resistance

Ultra-High-Performance Concrete (UHPC) and UltraHigh-Performance Fiber-Reinforced Concrete (UHPFRC) exhibit distinct differences in impact resistance, as indicated by their respective coefficients. UHPC, while known for its high strength, generally has lower impact resistance coefficients across various grades. Specifically, UHPC's impact resistance ranges from 0.4 to 1.5, depending on the grade, with the lowest grade (I1) having a coefficient of 0.4 to 0.6 and the highest grade (I5) ranging from 1.2 to 1.5.

In contrast, UHPFRC, enhanced with fiber reinforcement, demonstrates superior impact resistance across all grades. The coefficients for UHPFRC range from 0.6 to 2.0, with the lowest grade (I1) starting at 0.6 to 0.8 and the highest grade (I5) reaching 1.5 to 2.0. The presence of fibers in UHPFRC significantly increases its ability to absorb and dissipate energy under impact, thereby reducing the likelihood of failure or damage. This makes UHPFRC more suitable for applications where enhanced impact resistance is critical.

2.7 Toughness

Fracture toughness is a crucial measure of a material's resistance to crack propagation, reflecting its ability to endure stress concentrations and inhibit crack growth. UHPC (Ultra-High-Performance Concrete) has a fracture toughness of 1.5 MPa√m, which indicates a robust resistance to crack propagation. However, this level of toughness may be somewhat limited under highstress conditions or in structures that demand exceptional load-bearing performance.

In contrast, UHPFRC (Ultra-High-Performance FiberReinforced Concrete) exhibits a fracture toughness of 3.0 MPa√m. This higher toughness value demonstrates the superior performance of UHPFRC, largely due to its fiber reinforcement. The fibres enhance the material's capacity to absorb and dissipate energy, thereby improving its effectiveness in preventing crack growth. As a result, UHPFRC offers increased overall durability and is better suited for applications requiring high performance and resilience.

2.8 Ductility

Ductility refers to a material's ability to undergo significant plastic deformation before failure, which is often expressed as the strain at failure. UHPC (UltraHigh-Performance Concrete) has a ductility of 0.1% strain at failure. This relatively low ductility indicates that UHPC can withstand only limited deformation before failure occurs. In structural applications, this limited ductility can be a drawback, particularly in scenarios where flexibility and deformation capacity are crucial for safety and performance. On the other hand, UHPFRC (Ultra-High-Performance Fiber-Reinforced Concrete) shows a much higher ductility of 0.5% strain at failure. This increased ductility means that UHPFRC can endure greater deformation before reaching failure, which significantly enhances its ability to absorb and dissipate energy.The superior ductility of UHPFRC makes it particularly valuable in applications where flexibility, impact resistance, and the ability to accommodate deformation without sudden failure are critical. This characteristic improves the overall resilience and safety of structures, especially in seismic or dynamic loading conditions.

3 Conclusion

Based on the results obtained from numerical analysis, the following conclusions are made. The test results clearly show that UHPFRC outperforms UHPC in several key areas. UHPFRC demonstrated significantly higher 28-day compressive strengths, reaching up to 128 MPa, compared to UHPC's 102 MPa. In terms of flexural strength, UHPFRC achieved values as high as 18.1 MPa, far surpassing UHPC's maximum of 11.1 MPa. Tensile strength was also notably higher in UHPFRC, with values up to 20 MPa compared to UHPC's 10 MPa. Additionally, UHPFRC exhibited superior impact resistance, with coefficients ranging from 0.6 to 2.0, while UHPC ranged only from 0.4 to 1.5. The fracture toughness of UHPFRC was double that of UHPC, at 3.0 MPa√m versus 1.5 MPa√m, indicating better resistance to crack growth. UHPFRC's ductility, measured as strain at failure, was also significantly higher at 0.5% compared to UHPC's 0.1%, making UHPFRC a more resilient choice for structures subject to dynamic loading.

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