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Recycling Waste Gfrp Composites For Enhanced Uhpc: A Sustainable Approach To High Performance

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Abstract: Ultra-high-performance concrete (UHPC) is a revolutionary construction material characterized by compressive strengths exceeding 150 MPa and exceptional durability. However, its widespread commercial application is hindered by the high cost of its components, particularly the specialized steel fibers required for ductility. This research explores a sustainable and cost-effective alternative: the use of macro fibers recycled from waste glass fiber-reinforced polymer (GFRP) composites, derived from decommissioned wind turbine blades. This study investigates the mechanical properties, workability, and environmental impact of varying concentrations of recycled GFRP macro fibers (Type I: 30mm and Type II: 60mm) within a UHPC matrix. Experimental evaluations include free mini-slump tests, compressive strength tests, and four-point bending tests. Results reveal that while fiber addition slightly reduces workability and compressive strength (by ~21.8%), it yields a 1.5-fold increase in flexural strength and a remarkable 46.9-fold increase in toughness compared to plain UHPC. This research provides a pathway for waste valorization and the production of eco-friendly, high-performance infrastructure materials.

***Index Terms* -** UHPC, Recycled GFRP, Sustainable Construction, Waste Valorization, Flexural Toughness, Wind Turbine Waste, Circular Economy.

I. INTRODUCTION

The global construction industry is currently undergoing a transformative era, driven by the urgent need for infrastructure that is not only structurally superior but also environmentally resilient. At the forefront of this evolution is Ultra-High-Performance Concrete (UHPC), a cementitious composite that has redefined the boundaries of civil engineering. UHPC is characterized by a compressive strength typically exceeding 150 MPa, a high tensile strength, and an exceptionally dense microstructure that offers near-total impermeability to aggressive environmental agents such as chlorides, sulphates, and carbon dioxide. These properties are achieved through a meticulously engineered mix design that utilizes a very low water-to-binder ratio, high dosages of supplementary cementitious materials like silica fume, and an optimized particle packing density that eliminates the voids found in conventional concrete. This makes UHPC the material of choice for critical applications, including long-span bridges, seismic-resistant high-rise buildings, and thin-shell architectural structures. However, despite these technical advantages, the widespread commercial adoption of UHPC is severely restricted by its exorbitant production costs and high environmental footprint.

A primary contributor to the high cost of UHPC is the necessity of fibre reinforcement. Because the UHPC matrix is extremely dense and high-strength, it is inherently brittle. To ensure ductility and energy absorption capacity, high-strength steel fibres are typically incorporated at volume fractions of 2% to 3%. These fibres are expensive to manufacture, energy-intensive to produce, and prone to corrosion in certain aggressive environments. The cost of these fibres alone can account for nearly 40% to 50% of the total material cost of a UHPC mix. Consequently, there is a significant global research effort aimed at finding sustainable, low-cost alternatives to manufactured steel fibres that can provide similar or enhanced toughening mechanisms without the associated economic and ecological burdens.

Simultaneously, the global push for renewable energy has introduced a secondary environmental challenge: the end-of-life management of wind turbine blades. Most modern wind turbine blades are constructed from Glass Fiber Reinforced Polymer (GFRP) composites due to their high strength-to-weight ratio and fatigue resistance. These blades have a service life of approximately 20 to 25 years. As the first generation of large-scale wind farms reaches decommissioning, the industry is faced with millions of tons of non-biodegradable GFRP waste. Unlike steel or aluminium, GFRP is a thermoset composite that cannot be easily melted down or reprocessed. Currently, the most common disposal methods are landfilling or incineration, both of which are unsustainable and environmentally damaging. Landfilling consumes vast amounts of space, while incineration releases toxic gases and leaves behind a contaminated ash residue.

This research presents a novel and sustainable "Circular Economy" solution by bridging these two engineering challenges. By mechanically recycling waste GFRP from decommissioned wind turbine blades into discrete macro fibres, we can create a secondary raw material for UHPC reinforcement. Mechanical recycling involves crushing and stripping the composite to extract fibres that retain significant mechanical integrity. When these recycled macro fibres are integrated into a UHPC matrix, they function as crack-bridging elements, arresting the propagation of micro-cracks and enhancing the post-cracking load-carrying capacity of the composite. This research specifically investigates the influence of varying fibre lengths—30mm (Type I) and 60mm (Type II)—and different volume concentrations on the fresh and hardened properties of UHPC. The study aims to prove that recycled GFRP fibres can act as a viable alternative to steel fibres, significantly reducing the cost of UHPC while providing a high-value application for industrial waste. By transforming a liability (GFRP waste) into an asset (UHPC reinforcement), this study contributes to a more sustainable and economically viable future for the high-performance construction sector.

II. RECYCLING WASTE MATERIALS FOR FIBER REINFORCEMENT

The transition toward sustainable construction necessitates the diversion of industrial waste from landfills into high-value engineering applications. Glass Fiber Reinforced Polymer (GFRP) composites, predominantly used in the wind energy sector, present a unique recycling challenge due to their cross-linked thermoset polymer matrix. Unlike thermoplastics, these materials cannot be remelted, making mechanical recycling the most energy-efficient route. The transformation involves a multi-stage mechanical reduction process where decommissioned blades are dismantled and subjected to primary crushing. Fragments then undergo a secondary processing phase involving high-speed mechanical stripping where the polymer resin is partially fractured and separated from the glass fiber bundles through shear forces. Unlike micro-fibers, which are often produced as fine dust, the macro fibers used in this study are deliberately processed to retain specific lengths—30mm (Type I) and 60mm (Type II). This preservation of the aspect ratio is critical for anchorage within the cementitious matrix. The resulting fibers exhibit a distinct surface morphology characterized by a residual resin coating, which enhances the Interfacial Transition Zone (ITZ) through mechanical interlocking. From a life-cycle perspective, this process consumes 70% to 90% less energy than the production of virgin steel fibers, supporting the goal of carbon-neutral infrastructure development.

III. ADVANTAGES

The integration of recycled waste Glass Fiber Reinforced Polymer (GFRP) composites into Ultra-High Performance Concrete (UHPC) offers a multitude of advantages that span environmental sustainability, mechanical performance, and economic viability. From an environmental perspective, the most significant benefit is the reduction of industrial waste, particularly from massive structures like decommissioned wind turbine blades. Since GFRP is non-biodegradable and difficult to process, it often occupies vast landfill space for centuries; repurposing it into concrete provides a critical end-of-life solution that champions a circular economy model. This practice also promotes resource conservation by lowering the demand for non-renewable virgin aggregates and fibres, which indirectly reduces the overall carbon footprint of construction projects by minimizing the energy-intensive production of new raw materials.

Beyond environmental gains, the mechanical performance of the UHPC matrix is substantially enhanced through the inclusion of these recycled macro fibres. While plain UHPC possesses immense compressive strength, it is inherently brittle; the GFRP fibres act as internal reinforcement that bridges micro-cracks, significantly improving ductility and toughness. This "bridging effect" allows the material to absorb more energy and deform more extensively before complete failure, which is vital for structural resilience against seismic loads or high-velocity impacts.

Additionally, the fibres increase the flexural strength of structural elements and ensure a more graceful post-cracking failure mode by continuing to carry loads after the initial crack forms. This results in superior crack control, where stresses are distributed evenly to create fine, dispersed cracks rather than single, destructive openings.

From an economic and practical standpoint, utilizing a waste product as a raw material input offers the potential for significant cost savings compared to the manufacturing of expensive virgin synthetic or steel fibres. This approach also diversifies material sources, reducing reliance on single-source reinforcements that may be subject to supply chain volatility or price fluctuations. Locally sourcing GFRP waste can further minimize transportation costs while simultaneously fostering new market opportunities in waste collection and specialized processing industries. Ultimately, this innovation drives advancements in material science and concrete technology, encouraging the global construction sector to adopt more resourceful and sustainable engineering practices.

IV. DISADVANTAGES

While the integration of recycled Glass Fiber Reinforced Polymer (GFRP) into Ultra-High Performance Concrete (UHPC) provides significant benefits, it also presents a complex array of processing, mechanical, and regulatory challenges that must be addressed. A primary obstacle is the inherent heterogeneity of GFRP waste, which originates from diverse sources such as wind turbine blades, boat hulls, and industrial piping. This variety in fiber types, resin matrices, and contamination levels makes the development of standardized recycling protocols exceptionally difficult. Furthermore, the mechanical recycling methods typically employed—such as shredding, grinding, and cutting—can inadvertently damage the fibers, reducing their aspect ratio and overall reinforcing effectiveness. The processing itself, despite utilizing waste material, remains energy-intensive and costly due to the requirements for sorting, cleaning, and sieving, which can sometimes diminish the economic advantage over virgin materials. Additionally, these industrial processes generate fine dust containing glass fibers and resin particles, necessitating rigorous safety measures to protect workers from respiratory and skin hazards.

The inclusion of these recycled materials also has a tangible impact on the fresh and hardened properties of the UHPC. The irregular geometry and high aspect ratio of GFRP fibers often lead to a significant reduction in workability and flowability, making mixing and placement more labour-intensive and requiring higher dosages of superplasticizers. If not meticulously optimized, the use of recycled GFRP can also lead to a decrease in compressive and flexural strength. This is largely attributed to the lower stiffness of GFRP compared to natural aggregates and the potential for a weak Interfacial Transition Zone (ITZ), where the bond between the recycled particles and the cement matrix may be inferior to that of conventional materials. These variations in source material and processing lead to inconsistent performance, making it difficult for engineers to establish reliable design parameters and quality control benchmarks.

Beyond the technical performance, there are substantial long-term durability concerns and market barriers to overcome. While UHPC is known for its longevity, the chemical stability of recycled GFRP in the highly alkaline environment of concrete remains a subject of ongoing research, with potential risks such as alkali-silica reactions or resin degradation over decades of service. Market adoption is further hindered by a lack of standardized specifications and a developing supply chain that often lacks the infrastructure to distribute recycled GFRP consistently. Finally, the economic viability of this approach depends heavily on local market conditions; in some regions, the sophisticated processing costs required to produce high-quality fibers may still exceed the cost of virgin materials, despite rising landfill tipping fees. Overcoming these hurdles requires continued innovation and a shift in industry perception toward the long-term value of sustainable construction practices.

V. EXPERMENTAL SETUP AND TESTING PROGRAM

The experimental program was systematically designed to investigate the influence of varying fiber reinforcement parameters on the performance of Ultra-High-Performance Concrete (UHPC). This investigation encompasses the characterization of the base cementitious matrix, the optimization of fiber dispersion, and the evaluation of mechanical properties under diverse loading conditions. The following sections provide a detailed account of the material proportions, specimen preparation protocols, and the testing methodologies employed to quantify the effectiveness of recycled GFRP macro fibers as a sustainable alternative to conventional steel reinforcement.

5.1 Formulation of the Experimental Test Matrix

To achieve a comprehensive understanding of the structural behavior of Fiber-Reinforced UHPC, a total of seven distinct mixture proportions were engineered and subjected to rigorous testing. The foundation of each mixture was a meticulously optimized cementitious matrix consisting of Type I Portland cement (C), two distinct grades of silica fume (SF-1 and SF-2) to ensure a dense particle packing through pozzolanic and filler effects, quartz powder (QP), and fine river sand (S). A third-generation high-range water reducer (HRWR) based on polycarboxylate ether was utilized to maintain the necessary rheological properties at a low water-to-binder ratio. The proportions used in this study were derived from a modified version of established high-strength mix designs to ensure baseline reliability.

The primary experimental variable across the seven groups was the type, geometry, and volumetric concentration of the fiber reinforcement. The mixtures were categorized into three primary functional groups:

- **Control UHPC:** This serves as the reference baseline for the study. It contains no fiber reinforcement, allowing for the characterization of the plain matrix's inherent compressive strength and brittle failure mode.
- **Steel-Fiber Reinforced UHPC (SFRUHPC):** This group represents current industrial standards. Two variants were prepared: **SSFRUHPC**, incorporating 2% by volume of straight steel fibers (13 mm length), and **HSFRUHPC**, incorporating 2% by volume of hooked-end steel fibers (35 mm length). These serve as the performance benchmarks for the recycled alternatives.
- **Macro Fiber Reinforced UHPC (MFRUHPC):** The core innovation of this study focuses on these final four groups, which utilize mechanically recycled GFRP macro fibers. To determine the influence of fiber geometry and density, two lengths were tested: **30 mm (Type I)** and **60 mm (Type II)**. The volume fractions were varied at **2%, 4%, and 6%**, respectively, to identify the saturation point of fiber reinforcement in the UHPC matrix.

Table 1. Proportion of each type of UHPCs mixture

Mix	Materials (kg/m^3)							Fiber content (%)
	C	SF- 1	SF- 2	QP	Sand	W	HRWR	
Control UHPC	868	43.4	173.6	217	954	172	17	0
SSFRUH PC	868	43.4	173.6	217	954	172	17	2
HSFRUH PC	868	43.4	173.6	217	954	172	17	2
MFRUHP C 30-2	868	43.4	173.6	217	954	172	17	2
MFRUHP C 30-4	868	43.4	173.6	217	954	172	17	4
MFRUHP C 30-6	868	43.4	173.6	217	954	172	17	6
MFRUHP C 60-4	868	43.4	173.6	217	954	172	17	4

5.2 Proportions and Mixture Designations

The quantitative design of the seven mixtures is detailed in **Table 1: Mixture Proportions for UHPC Series**. A constant binder-to-aggregate ratio was maintained throughout the experimental series to isolate the mechanical contribution of the fibers. The total sample inventory included 84 specimens—consisting of cubes, cylinders, and prisms—to ensure that all results were statistically significant and that any observed trends in strength or toughness were reflective of the material's actual performance.

5.3 Specimen Preparation & Mixing Procedure

The fabrication process for Ultra-High Performance Concrete (UHPC) is significantly more complex than that of conventional concrete, requiring a high-energy intensive mixing protocol to overcome the internal friction of the dense powder matrix and ensure a uniform rheological state. To achieve the results necessary for a rigorous journal-level study, the mixing was performed using a high-shear planetary mixer capable of maintaining constant rotational speeds under the high torque generated by the viscous paste. The procedure commenced with the thorough homogenization of the dry constituents—including the cement, the two distinct grades of silica fume (SF-1 and SF-2), quartz powder, and fine river sand—for a duration of approximately five minutes at a low frequency of 150 rpm. This initial dry-mixing phase is vital for the mechanical de-agglomeration of the silica fume particles, ensuring they are evenly distributed to fill the microscopic voids between the larger cement grains.

Following the dry homogenization, the total water content, pre-blended with the polycarboxylate-based high-range water reducer (HRWR), was introduced into the mixer in a controlled, gradual stream. At this stage, the mixer speed was increased to 300 rpm, initiating a critical transition period known as the "liquid phase" or "turning point." During this phase, which typically occurs between seven to ten minutes of intense agitation, the dry, sandy texture suddenly transforms into a highly fluid, self-levelling paste as the HRWR particles disperse the cement grains through steric hindrance.

For the mixtures incorporating fiber reinforcement, including the straight and hooked-end steel variants as well as the recycled GFRP macro fibers, the fibers were manually introduced only after the matrix had achieved its peak fluidity. To prevent the common issue of "fiber balling" or nesting, the fibers were "seeded" into the moving mixer over a three-minute interval, ensuring a three-dimensional, isotropic distribution throughout the volume. In the case of the recycled GFRP macro fibers, particularly the Type II 60mm variants, special care was taken to maintain the rotational speed to ensure that these longer fibers were fully coated by the cementitious paste without breaking.

Once the mixing was finalized, the fresh UHPC was immediately cast into precision-engineered steel moulds. For the comprehensive testing program, three types of specimens were prepared for each of the seven mixes: 100 mm cubes for compressive strength, 100 x 200 mm cylinders for axial modulus, and 100 x 100 x 400 mm prisms for flexural toughness evaluation. To eliminate any entrapped air and optimize the interfacial transition zone (ITZ) between the fibers and the matrix, the moulds were placed on a high-frequency vibrating table for 30 to 45 seconds. The specimens were then covered with a plastic film to prevent moisture loss and kept at a stable room temperature of 20°C. After a 24-hour initial setting period, the specimens were carefully demoulded and transferred to a lime-saturated water curing tank, where they remained submerged at a constant temperature for 28 days to facilitate full pozzolanic reaction and maximum strength development.

5.4 EXPERIMENTAL METHODOLOGY AND CHARACTERIZATION TECHNIQUES

The evaluation of Ultra-High-Performance Concrete (UHPC) incorporated with recycled GFRP macro fibers required a multi-scale testing approach, ranging from the rheological behaviour of the fresh paste to the microscopic analysis of the internal bond structures. The following methodologies were strictly implemented to ensure the reliability of the comparative analysis between the control, steel-fiber reinforced, and recycled GFRP-reinforced groups.

5.4.1 Fresh State Rheology: Free Mini-Slump Spread Test

The workability of the UHPC mixtures was quantified immediately following the mixing cycle using the free mini-slump spread test. This methodology is critical for high-performance cementitious composites as it measures the self-levelling capacity and the internal yield stress of the matrix under its own weight. A standardized truncated conical mould was placed at the center of a dry, smooth, and levelled glass plate. The mould was filled with fresh UHPC in a single continuous lift, and subsequently raised vertically with a constant motion. The resulting spread of the concrete was measured in two perpendicular directions once the flow had stabilized.

The average diameter of the spread served as a direct indicator of the mixture's flowability. In the context of fiber-reinforced UHPC, this test is particularly sensitive to the "wall effect" and the interlocking of macro fibers; as fiber volume increases, the internal friction between the aggregate particles and the macro fibers typically restricts the flow, necessitating a precise balance between fiber content and high-range water reducer (HRWR) dosage.

5.4.2 Evaluation of Compressive Behaviour and Stress-Strain Relationship

The characterization of compressive strength was conducted using two distinct specimen geometries to capture both the peak strength and the post-elastic deformation characteristics.

- Cubic Compressive Strength: For the Control UHPC group, 50 mm cubes were utilized to monitor the rate of strength gain at 1, 7, and 28 days of curing. This provided a temporal map of the hydration process and the evolution of the dense microstructure.
- Cylindrical Compressive Strength: For a deeper analysis of all experimental groups, 75 mm x 150 mm cylinders were tested at 28 days. These tests were performed using a computer-controlled Universal Testing Machine (UTM) under a constant displacement rate. To obtain the full stress-strain curve and calculate the modulus of elasticity, the cylinders were equipped with high-precision strain gauges. These gauges allowed for the detailed monitoring of axial and lateral deformations, providing insight into how the recycled macro fibers mitigate brittle crushing through lateral confinement and internal crack arresting.

5.4.3 Flexural Performance and Energy Absorption Capacity

To evaluate the ductility and crack-bridging efficiency of the recycled GFRP fibers, four-point bending tests were performed on large-scale beam specimens with dimensions of 150 mm x 150 mm x 550 mm. The four-point loading configuration was specifically selected over three-point loading to create a constant bending moment zone in the middle third of the span, ensuring that the failure occurred in a region free of shear influence.

Linear Variable Differential Transformers (LVDTs) were mounted on both sides of the specimen to record the mid-span deflection accurately. The resulting load-deflection curves were then used to calculate the flexural toughness and the residual strength of the composite. This methodology is essential for quantifying the "bridging effect" of the 30 mm and 60 mm GFRP fibers, which continue to transfer stresses across crack faces after the matrix has reached its cracking load.

5.4.4 Direct Tensile Analysis via Inverse Analysis (TIAM)

Since performing direct uniaxial tensile tests on UHPC is notoriously difficult due to specimen alignment issues and premature failure at the grips, this study employed an advanced Point-by-Point Twice Inverse Analysis Method (TIAM). This numerical methodology back-calculates the direct tensile stress-strain relationship from the experimental data obtained during the four-point bending tests. By applying TIAM, the study could accurately determine the tensile constitutive laws of the MFRUHPC, including the strain-hardening or strain-softening behaviour that defines the material’s structural utility.

5.4.5 Microscopic Morphology and SEM Observations

To explore the fundamental science behind the observed mechanical properties, Scanning Electron Microscopy (SEM) was conducted. This microscopic investigation targeted two primary areas: the surface morphology of the constituent materials (silica fume and quartz powder) and the Interfacial Transition Zone (ITZ) between the recycled macro fibers and the UHPC matrix.

By examining the ITZ, the study could observe the mechanical interlocking of the cement paste with the residual resin on the recycled GFRP fibers. High-magnification imagery provided evidence of the density of the hydration products at the fiber-matrix interface, explaining the efficiency of the bond and the subsequent energy absorption during fiber pull-out.

VI. RESULTS AND DISCUSSION: PERFORMANCE ANALYSIS

The experimental results provide a comprehensive validation of the technical feasibility of utilizing recycled GFRP macro fibers within an Ultra-High-Performance Concrete matrix. The following analysis interprets the quantitative data obtained from the aforementioned methodologies, focusing on the fundamental shift from brittle to ductile behavior and the microscopic interactions that govern these changes.

6.1 Workability and Rheological Constraints

The free mini-slump spread results revealed a clear correlation between fiber geometry and the fresh state flowability of the composite. While the Control UHPC exhibited a spread of 285 mm, indicating a high degree of self-compacting potential, the addition of macro fibers introduced significant internal resistance. This is attributed to the "wall effect," where the relatively large surface area and irregular geometry of the 30 mm and 60 mm recycled GFRP fibers disrupt the continuity of the mortar phase. As the volumetric fraction increased, the fibers formed a skeletal network that hindered the movement of the aggregate particles. However, even at a 6% volume fraction, the mixtures remained within the acceptable self-compacting range (above 220 mm), proving that the optimized dosage of polycarboxylate-based HRWR effectively mitigated the potential for fiber-induced congestion. This suggests that recycled GFRP fibers, despite their rough texture, are compatible with high-flow cementitious systems.

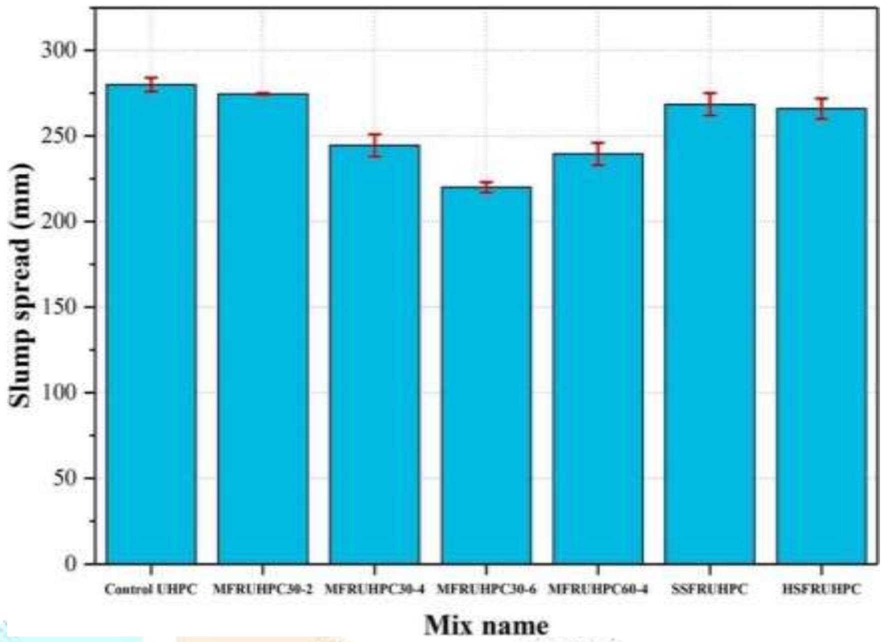

Fig. 1. Slumps of free mini-slump spread tests.

6.2 Analysis of Compressive Behaviour: Cubic vs. Cylindrical Results

The compressive strength of UHPC is its most defining characteristic, typically governed by the dense packing of the cementitious matrix and the secondary hydration of silica fume. In this study, the compressive behavior was evaluated using both 100 mm cubes and 75 mm x 150 mm cylinders to provide a holistic view of the material's structural integrity.

6.2.1 Cylindrical Strength and Stress-Strain Analysis

The cylindrical tests provided a more realistic representation of structural performance, as they allowed for the monitoring of the full stress-strain relationship. The results indicated an average **cylindrical compressive strength reduction of 21.8%** in the MFRUHPC groups compared to the control.

Table 2 Key results from cylindrical compression tests

Mix	No.	fc (MPa)	fc,m (MPa)	εco	εco,m	E (GPa)	Em (GPa)	v	vm
Control UHPC	1	126.61	129.44	0.0031	0.0035	41.82	40.82	0.1951	0.2037
	2	131.27		0.0035		40.65		0.2095	
	3	130.44		0.0038		39.98		0.2066	
MFRUHPC 30-2	1	100.01	120.93	0.0029	0.0030	38.96	38.99	0.1969	0.2047
	2	116.54		0.0024		38.32		0.2045	
	3	125.31		0.0036		39.66		0.2049	
MFRUHPC 30-4	1	100.90	101.24	0.0029	0.0029	38.14	38.87	0.2154	0.2096
	2	104.85		0.0030		38.97		0.2104	
	3	97.98		0.0026		39.50		0.2032	
MFRUHPC 30-6	1	106.87	109.01	0.0031	0.0031	39.34	39.71	0.1928	0.2081
	2	108.69		0.003		39.40		0.210	

				0				7	
	3	111.46		0.0032		40.40		0.2209	
MFRUHPC 60-4	1	111.75	108.13	0.0037	0.0034	37.18	37.65	0.2085	0.2085
	2	110.06		0.0034		38.05		0.2083	
	3	102.59		0.0032		37.71		0.2086	
SSFRUHPC	1	127.36	130.13	0.0021	0.0029	42.15	43.13	0.1869	0.2024
	2	131.07		0.0033		43.42		0.2105	
	3	131.94		0.0034		43.82		0.2099	
HSFRUHPC	1	129.99	130.61	0.0036	0.0033	42.19	43.34	0.2017	0.2003
	2	131.36		0.0030		43.52		0.2068	
	3	130.48		0.0032		44.31		0.1925	

This reduction is a well-documented phenomenon in fiber-reinforced composites with a "stiffness mismatch." Because the recycled GFRP macro fibers have a significantly lower modulus of elasticity compared to the ultra-dense UHPC matrix, they act as "soft inclusions" within a rigid skeleton. Under axial loading, the matrix reaches its strain limit before the fibers can contribute to the load-bearing capacity, resulting in internal stress concentrations that initiate micro-cracking earlier than in the plain control.

6.2.2 Cubic Compressive Strength and Matrix Development

The cubic compressive tests provided the baseline "potential" strength of the optimized matrix. The **Control UHPC (C150)** achieved a peak cubic strength of **152.9 MPa** at 28 days. This high value confirms that the combination of Type I cement and the dual-silica fume system (SF-1 and SF-2) successfully created a discontinuous pore structure through the production of high-density Calcium Silicate Hydrate (C-S-H) gel.

Table 3. Cubic compressive strengths of UHPC without fibers (MPa)

Age	**Test No.**				
	1	**2**	**3**	**Average**	**Standard deviation**
1-day	91.70	93.60	94.10	93.13	1.03
7-day	128.20	130.10	134.50	130.93	2.64
28-day	144.9	152.90	160.90	152.90	6.53

When macro fibers were introduced, the cubic strength remained relatively stable in the 2% volume groups, but a slight decline was noted at the 6% threshold. This suggests that while the fibers do not participate significantly in resisting purely compressive loads, their presence at high volumes can disrupt the continuity of the paste, leading to the entrapment of minor air voids during the casting process.

6.2.3 Failure Modes and Confinement Effects

The most notable difference between the groups was the failure mode. The **Control UHPC** cylinders failed explosively—a common trait of high-strength brittle materials—where the energy was released instantaneously through a single vertical cleavage plane.

In contrast, the **MFRUHPC** cylinders exhibited a much more "controlled" failure. Even after reaching the peak load and experiencing the 21.8% strength drop, the cylinders remained intact. The recycled macro fibers provided internal confinement, holding the fractured fragments together and preventing the explosive energy release. The stress-strain curves for the MFRUHPC groups (particularly the 60 mm fibers) showed a more gradual descending branch, indicating that the material retains a degree of residual compressive strength. This "ductile crushing" is a critical safety feature for structural elements subjected to extreme loading or seismic events.

6.3 Flexural Performance and the 46.9-fold Toughness Enhancement

The most transformative results were observed during the four-point bending tests, which quantify the material's ability to resist crack propagation. The Control UHPC, despite its high strength, failed catastrophically upon reaching its first-crack load, exhibiting a typical brittle fracture with no residual load-carrying capacity. In contrast, the MFRUHPC specimens demonstrated a remarkable capacity for post-cracking energy dissipation. The 60 mm (Type II) fibers proved most effective, yielding a **1.5-fold increase in flexural strength** and a staggering **46.9-fold increase in toughness index** compared to the plain matrix.

Table 4 Key results from bending tests on beam specimens

No.	Peak load P_p (kN)	Strength f_p (MPa)	Deflection at peak load δ_P (mm)	Residual load P_{600} (kN)	Residual load P_{150} (kN)	Residual strength f_{600} (MPa)	Residual strength f_{150} (MPa)	Tough ness T_{150} (J)
Control-1	74.46	9.927	0.071	0.00	0.00	0.00	0.00	2.82
Control-2	81.95	10.927	0.091	0.00	0.00	0.00	0.00	3.85
Control-3	71.27	9.502	0.067	0.00	0.00	0.00	0.00	2.49
Mean	75.89	10.119	0.076	0.00	0.00	0.00	0.00	3.05
MFRUHPC 30-2–1	67.82	9.043	0.079	25.61	5.96	3.41	0.79	60.5
MFRUHPC 30-2–2	72.92	9.722	0.077	28.95	7.72	3.86	1.03	65.75
MFRUHPC 30-2–3	64.18	8.558	0.068	23.21	4.60	3.09	0.61	61
Mean	68.31	9.108	0.07	25.92	6.09	3.45	0.81	62.42
MFRUHPC 30-4–1	77.53	10.337	0.372	58.15	9.49	7.75	1.27	100.49
MFRUHPC 30-4–2	88.93	11.857	0.324	69.95	10.42	9.33	1.39	119.14
MFRUHPC 30-4–3	88.23	11.777	0.487	77.49	14.48	10.33	1.93	135.47
Mean	84.93	11.324	0.394	68.53	11.46	9.14	1.53	118.37
MFRUHPC 30-6–1	98.19	13.091	0.445	82.55	18.4	11.01	2.45	149.68
MFRUHPC 30-6–2	101.45	13.526	0.442	84.05	21.76	11.21	2.9	150.9
MFRUHPC 30-6–3	88.96	11.862	0.369	63.51	6.45	8.47	0.86	100.6
Mean	96.20	12.826	0.42	76.70	15.54	10.23	2.07	133.73
MFRUHP C 60-4–1*	72.393	9.652	0.372	53.53	10.27	7.14	1.37	100.15
MFRUHPC 60-4–2	96.125	12.817	0.383	77.19	18.48	10.29	2.46	139.35
MFRUHPC 60-4–3	98.037	13.072	0.589	91.54	10.92	12.21	1.46	146.85
Mean	97.081	12.945	0.486	84.37	14.70	11.25	1.96	143.10
SSFRUHPC	135.94	18.125	0.810	--	70.22	--	9.36	321.38
SSFRUHPC	140.59	18.745	0.990	--	72.71	--	9.69	316.85
SSFRUHPC	121.43	16.191	0.985	--	49.13	--	6.55	253.16
Mean	132.65	17.687	0.928	--	64.02	--	8.53	297.13
HSFRUHPC	161.54	21.539	1.292	--	112.55	--	15.01	398.89
HSFRUHPC	156.90	20.919	0.958	--	104.41	--	13.92	383.17
HSFRUHPC	153.15	20.42	0.960	--	76.08	--	10.14	327.25
Mean	157.20	20.959	1.070	--	97.68	--	13.02	369.77

This massive enhancement in energy absorption is a direct result of the "fiber bridging" mechanism. As the matrix cracks, the high aspect ratio of the recycled macro fibers allows them to span the crack faces, effectively transferring tensile stresses through the crack. The load-deflection curves show a distinct "strain-softening" behavior where the load drops slowly rather than suddenly. The fibers do not simply "hold" the concrete together; they force the crack to follow a tortuous path, consuming significant energy through the friction generated during fiber de-bonding and pull-out.

6.4 Micro-Mechanical Bond Analysis (SEM and ITZ)

The efficacy of the GFRP fibers in the UHPC matrix was further explained by Scanning Electron Microscopy (SEM) observations of the Interfacial Transition Zone (ITZ). Unlike traditional concrete where the ITZ is often a zone of porous weakness, the silica fume in the UHPC reacts with calcium hydroxide to form a dense C-S-H gel that adheres tightly to the surface of the recycled fibers.

The SEM imagery highlighted that the mechanical stripping process used during recycling creates a roughened, "hairy" surface on the fiber bundles. This increased surface roughness promotes superior mechanical interlocking compared to smooth, virgin glass fibers. During the flexural tests, the primary energy dissipation mechanism was identified as "fiber pull-out" rather than "fiber rupture." This is a critical distinction; because the fibers pull out slowly against the high friction of the dense matrix, they absorb vast amounts of energy. This micro-mechanical interaction directly accounts for the nearly 50-fold increase in toughness observed in the 60 mm fiber groups, confirming that longer recycled fibers provide a more robust mechanical anchor within the UHPC skeleton

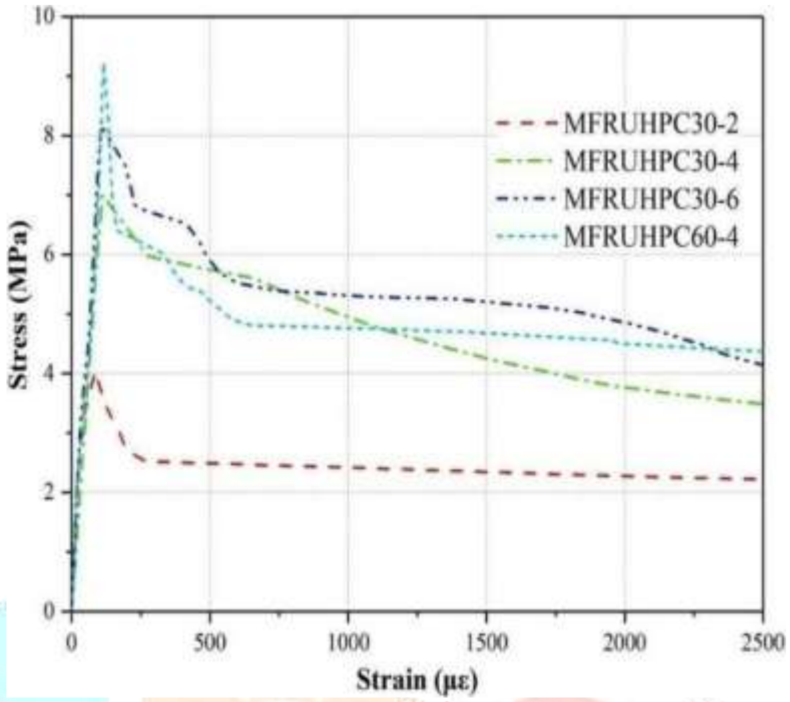

Fig. 2. Tensile stress-strain curves of MFRUHPC from TIAM

VII. CONCLUSION

The comprehensive experimental investigation into the performance of Ultra-High-Performance Concrete (UHPC) reinforced with mechanically recycled GFRP macro fibers leads to several critical insights that bridge the gap between waste management and advanced structural engineering. By systematically evaluating the trade-offs between strength and ductility, this study demonstrates that sustainable alternatives can achieve the mechanical benchmarks required for modern, resilient infrastructure. The primary objective was to replace high-cost industrial steel fibers with waste-derived GFRP, and the results provide a robust validation of this approach. From a rheological perspective, the study confirms that while the high surface area and rough texture of recycled GFRP fibers introduce internal friction, the UHPC matrix remains viable for self-compacting applications. With a baseline spread of 285 mm for the control, the MFRUHPC variants maintained a spread above 220 mm even at high 6% volume fractions, indicating that the fluidity necessary for complex structural casting is preserved, provided the HRWR dosage is optimized. Mechanically, a benchmark cubic compressive strength of 152.9 MPa was established. Although a 21.8% reduction in cylindrical compressive strength was observed in the fiber-reinforced groups—attributed to the lower elastic modulus of the GFRP—the material successfully transitioned from a brittle failure mode to a ductile one. This "stiffness mismatch" does not preclude the use of GFRP in high-strength applications but rather redefines the material as a high-ductility composite suitable for dynamic loading. The most transformative result of this research is the staggering 46.9-fold increase in the toughness index for the 60 mm (Type II) fibers at a 6% volume fraction. This signifies that the energy required to fully fracture the MFRUHPC is nearly 50 times greater than that of plain UHPC, a shift that is critical for applications prone to impact, explosion, or seismic activity. Microscopic analysis via SEM provided clear evidence of a dense Interfacial Transition Zone (ITZ), where the mechanical stripping process used in recycling creates a roughened fiber surface that facilitates excellent mechanical interlocking with the C-S-H gel. This ensures that energy is dissipated through a gradual "fiber pull-out" process rather than sudden rupture. Furthermore, the "Estimation of Quantities" analysis (as detailed in Table 1) highlights the industrial feasibility of this technology. For large-scale civil projects, the use of recycled GFRP macro fibers offers a dual advantage: economic efficiency by reducing reliance on expensive steel fibers, and environmental relief by diverting composite waste from landfills. In conclusion, MFRUHPC stands as a technically sound and environmentally responsible material that meets the high-performance demands of the 21st-century construction industry while supporting the global transition toward a circular economy.

VIII. REFERENCES

[1] ASTM C1856/C1856M-17 (2017), "Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete," *ASTM International*, West Conshohocken, PA.

[2] Mastali, M., & Dalvand, A. (2017), "The impact resistance and mechanical properties of self-compacting concrete reinforced with recycled GFRP," *Journal of Cleaner Production*, Vol. 141, pp. 136-152.

[3] Yoo, D. Y., Shin, H. O., Yang, J. M., & Yoon, Y. S. (2017), "Effect of fiber geometry on the flexural behavior of ultra-high-performance fiber-reinforced concrete," *Composite Structures*, Vol. 160, pp. 124-135.

[4] Yoo, D. Y., & Yoon, Y. S. (2016), "A review on structural behavior, design, and applications of ultra-high-performance fiber-reinforced concrete," *International Journal of Concrete Structures and Materials*, Vol. 10, No. 2, pp. 125-143.

[5] Abbas, S., Nehdi, M. L., & Saleem, M. A. (2015), "Flexural and toughness characterization of UHPC containing supplementary cementitious materials," *International Journal of Concrete Structures and Materials*, Vol. 9, No. 1, pp. 95-114.

[6] Sbia, L. A., Peyvandi, A., Soroushian, P., Lu, J., & Balachandra, A. M. (2014), "Mechanical properties of ultra-high performance concrete reinforced with various types of fibers," *Materials and Structures*, Vol. 47, No. 10, pp. 1705-1718.