Assessment of Recycled Low-Carbon Ultra-High Performance Concrete based on Recycled UHPC

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Abstract

Ultra-high-performance concrete (UHPC) is widely used in construction for its outstanding strength and durability. However, its high cement and steel fiber content leads to increased carbon emissions and environmental concerns. This study explores the use of sustainable materials in UHPC to reduce its overall environmental impact. The objective of the research is to develop a low-carbon Ultra High Performance Concrete (UHPC) and to assess the performance of recycled low-carbon ultra-high performance concrete (R-UHPC), produced from different fractions of recycled aggregate crushed from low-carbon UHPC. Low carbon UHPC based on a cement with low environmental impact (CEM IV) was first produced and optimised to ensure an improved performance in terms of fresh properties and mechanical properties including strength and durability. In the development process, UHPC with different types of fibres were assessed, including amorphous alloy and steel fibres. The Low Carbon UHPC developed, was then used as source material for the production of the Recycled Low-Carbon UHPC, based on recycled UHPC aggregate, as a substitute of the natural aggregates as is typical of recycled aggregate concrete. Different recycled UHPC mixes were designed and produced with a reference mix based on natural aggregate and three mixes with the natural aggregate replaced using recycled UHPC according to different percentage replacement values (50 and 100%). This supports the cradle-to-cradle approach in life cycle engineering applications. The research confirmed the effective regeneration of new UHPC based on the recycled UHPC, attaining the required rheological characteristics, mechanical properties, durability performance. This work supports the sustainability assessment of the end of life of Low Carbon UHPC materials and structures and the potential of recycled UHPC for new structures and retrofit structural applications.

Keywords: *Low-Carbon Ultra-High Performance Concrete, Recycled UHPC, Aggregate replacement, Mechanical Properties, UHPC Durability.*

1. Introduction

Ultra-high-performance concrete (UHPC) represents one of the most advanced cement-based materials in modern construction due to its exceptional mechanical properties and long-term durability. Despite these advantages, traditional UHPC formulations rely heavily on large quantities of cement and steel fibers, which contribute substantially to carbon dioxide emissions and raise environmental concerns. As a result, there is a growing need to develop more sustainable UHPC alternatives (Farahzadi et al, 2024). This study evaluates the extent to which environmental impacts can be reduced by integrating eco-friendly materials into UHPC mixes. Specifically, the research investigates the substitution of conventional UHPC components, in particular with low carbon cement, alternative fibres and crushed rock aggregate.

This research aims to develop a low-carbon ultra-high-performance concrete (UHPC) and to evaluate the performance of recycled low-carbon UHPC (R-UHPC) produced using aggregates derived from crushed low-carbon UHPC.

An environmentally optimized UHPC mixture was first designed using low-impact cement (CEM IV) and optimized to achieve enhanced fresh behavior, mechanical strength, and durability. The study

examined the influence of different fiber types, including steel and amorphous alloy fibers, on UHPC performance. The optimized low-carbon UHPC was subsequently reused as the parent material for producing recycled UHPC, where recycled UHPC aggregates partially or fully replaced natural aggregates. A reference mixture with natural aggregates was compared against three recycled UHPC mixes incorporating 50% and 100% recycled aggregate content. This approach aligns with cradle-to-cradle principles in life-cycle engineering. The research explores the potential of recycled UHPC in achieving satisfactory workability, mechanical performance, and durability.

The activity was conducted in the framework of the SINCERE Horizon Europe Research Project, Grant Agreement № 101123293 (SINCERE, 2026). The UHPC is developed as a low-carbon material, to be exploited in the retrofit of modern heritage structures, with structural and environment performance considerations. In this regard the UHPC is developed with consideration of environmental impact including: low clinker cement (CEM IV with natural pozzolan), alternative fibres (amorphous alloy and steel fibres) and crushed rock aggregate; and environmental performance with the incorporation of Phase Change Material.

Ultra High-Performance Concrete enables long-term durability in strategic structures with minimal maintenance; however, at end of life, recycling UHPC can significantly reduce environmental impacts associated with its high binder content and embodied energy. The feasibility of recycling previously developed UHPC mixes as partial or total replacements for natural aggregates in new UHPC has been assessed and results demonstrate that recycled aggregates derived from crushed UHDC can successfully produce new UHDC with satisfactory rheological behavior, mechanical performance, and durability characteristics (Borg et al, 2021; Roig-Flores et al, 2022; Cuenca et al, 2022). Various researchers further demonstrated the potential of Recycled UHPC aggregate for the development of UHPC, produced with varying fractions of aggregates and fines from crushed UHPC as substitutes for natural aggregates and also cement (Ferrara et al, 2023; Davolio et al, 2025). The self-healing performance of UHPC based on recycled UHPC has was assessed and improved self-healing properties of RUHPC specimen was determined with respect to specimen based on natural aggregates (Kannikachalam et al, 2023a; Kannikachalam et al, 2023b; Davolio et al, 2025). Further the potential of recycled concrete powder as a supplementary cementitious material has been determined effectively contributing to the drive towards low-carbon construction (Davolio et al, 2025; Aquino Rocha et al, 2023).

2. Methodology

Experimental programs were initiated to develop UHPC mixes incorporating recycled aggregates. Several trial mix designs were prepared using sustainable binders (including CEM IV, CEM II and LC3) and natural aggregates (siliceous river sand and dolomite sand). Workability tests (mini-cone slump tests) and hardened state mechanical tests (compressive and flexural strength tests) were performed. Based on the results obtained, optimal UHPC mix compositions were selected. The UHPC mix was developed and two types of fibres were considered: amorphous metallic fibres and steel fibres.

For recycling, aged UHPC specimens previously subjected to mechanical testing, were crushed using a laboratory jaw crusher through repeated cycles and particles were sieved to obtain aggregates smaller than 2mm. Magnetic separation was employed to remove fibers from the recycled UHPC aggregates. Density and sieve analysis of the recycled aggregates were determined. Fresh state and hardened state mechanical properties of UHPC mixes incorporating recycled aggregates were partially evaluated and mix designs with varying replacement percentages of natural aggregates by recycled UHPC aggregates were prepared.

2.1. Development of Low Carbon UHPC

2.1.1 Materials

UHPC was developed with both amorphous metallic fibres and steel fibres, in order to assess the performance of UHPC with alternative fibres, given the higher environmental impact of steel fibres. The amorphous metallic fibres consist of FibraFlex FF15E0 Fibres by Saint Gobain, (Length 15mm, Width 1mm, Thickness 24um, equivalent diameter 0.18mm, Length / Diameter Ratio 83, Number of fibres /kg 385000, specific surface 10 and density 7.2). The fibres are composed of a predominantly iron-

chromium alloy that undergoes hyper-quenching during manufacture. The steel fibres consist of Brass-plated steel micro-fibres, Readymesh MR200 by Azichem (Length 20mm, Diameter 0.22mm, Fibre density 7.85g/cm3, breaking load >2400MPa and static elastic modulus 200GPa).

Low carbon cement CEM IV was used in this phase of the research: CEM IV/B 32,5 by Titan Cement, Compressive strength at 28 days 32.5 MPa, 45 to 64 % clinker by mass with 36-55% Pozzolan. The aggregate consisted of crushed dolomite with particle size 0/2 and saturated surface dry density of 2.76 Mg/m^3 and water absorption of 0.3%.

Phase Change Material used consisted of PCM25-slurry by MikroCaps, Phase Change Materials Microcapsule dispersion (Type of membrane: Melamine-formaldehyde; Type of PCM: Paraffin wax, PCM content in dispersion 25-30%, PCM melting area 22-26 °C, Heat storage capacity (of dry microcapsules) 150-170 J/g, Density 900-970 g/L, Viscosity (at 25 °C) 10-1000 cPs, Average particles size 1-20 μm).

Three superplasticizers were used in the first phase of the research in the development of the UHPC: Master Glenium Sky 698, Master Ease 7007, Master Glenium Ace 442. The Master Glenium Ace 442 presented improved workability and was selected for the subsequent phases of the research.

2.1.2 UHPC Development

The first phase of the research included the development of UHPC through trial mixes in order to define the Ultra-High Performance Concrete with self-compacting properties and high performance in the hardened state.

Paste was first developed was assessed with respect to fresh properties (mini-slump flow) and the hardened properties (compressive strength). The mini-slump flow test was applied for cement pastes (W/C=0.30) with different superplasticizers (Master Glenium Sky 698, Master Ease 7007, Master Glenium Ace 442) across cements (CEM II, CEM IV, LC3). The spread diameter of the mini cone was determined. Glenium Ace 442 produced the highest flows (~200–220 mm) across the cements at equal SP dosage (3%), indicating superior dispersion at this W/C. Mix-to-mix variability suggests cement–admixture compatibility effects.

Ultra High performance mortar was then developed and the formulations varied primarily in cement type and content (CEM II, CEM IV, LC3), fine aggregate system (dolomite and river sand fraction 0/2), fibers (AA microfibers, steel fibers), and superplasticizer dosage.

2.2. UHPC with Amorphous Metallic and Steel Fibres

Reference mixes (Table 1) were defined based on Amorphous Metallic fibres and steel fibres presented in Figure 1 and Figure 2 respectively. The fresh properties were determined with respect to the slump flow and fresh density. Mechanical properties were determined including the hardened density, flexural strength and compressive strength, Ultrasonic Pulse Velocity; and durability properties: including the vacuum saturated porosity, chloride migration, resistivity. The properties were determined at different curing times. Hardened properties of UHPC mixes were evaluated using standardized mechanical and physical tests on specimens of varying geometries. Prisms of 4×4×16 cm were tested for flexural and compressive strength in accordance with EN 196-1 and EN 12390-5.

Density and ultrasonic pulse velocity (UPV) were measured prior to mechanical testing to evaluate internal compactness and detect any structural anomalies. UPV measurements were performed using a 54 kHz transducer setup following EN 12504-4, providing indirect insight into the material's homogeneity and internal void ratio. Specimens were demolded after 24 hours and cured under moist conditions (20 ± 2°C, >95% RH) until testing ages.



Figure 1. Amorphous Metallic Fibres



Figure 2. Steel Fibres

Table 1. UHPC mix design

		R_AA1	R_AA2	R_S
Cement CEM IV	kg/m³	800	800	800
Water	kg/m³	191	191	191
Aggregate 0/2	kg/m³	1343	1343	1343
PCM	kg/m³	19	19	19
Fibres Type	Type	AA	AA	S
Fibre %	%	0.6	2	2
Fibre	kg/m³	46	160	160
SP %	%	3.8	4	3.8
SP	kg/m³	31	31	31
W/Binder Ratio	Ratio	0.24	0.24	0.24

Note: AA: Amorphous Metallic Fibres, S: Steel Fibres

Durability assessment covered electrochemical and physical permeability tests to evaluate ionic transport, pore connectivity, and long-term resistance to chloride ingress. Four complementary methods were adopted including direct durability indicator (Permeable porosity) and indirect methods (Chloride penetration):

- Permeable Porosity: Based on vacuum saturation and oven drying, this test quantifies total and connected porosity from the mass difference between saturated, surface-dry, and oven-dry states.
- ASTM C1202 (Rapid Chloride Permeability Test, RCPT): Cylindrical specimens (Ø100×50 mm) were subjected to a 60 V DC potential between 3% NaCl and 0.3 N NaOH cells for 6 hours, and current was recorded every 30 minutes. Total charge passed (coulombs) was calculated to classify chloride penetrability.
- EN 12390-18 / NT Build 492: The non-steady-state migration coefficient (Nssm) was determined under a 35 V potential for 24 hours, followed by visual measurement of chloride penetration depth (xd) using $AgNO_3$ spraying. This test provides a quantitative diffusion coefficient.
- Surface Electrical Resistivity: Conducted via four-probe Wenner configuration at different ages to track resistivity evolution as a proxy for microstructural refinement. Higher resistivity implies reduced ionic mobility and denser microstructure.

2.3. Recycled UHPC

A detailed literature review was conducted to evaluate the recyclability of cementitious materials, with a particular focus on Ultra-High-Performance Concrete (UHPC). Various recycling methods including mechanical crushing, thermal treatment, and chemical processing were reviewed, with mechanical crushing identified as the primary method for UHPC recycling.

The R_AA1 mixes developed in the previous phase, were crushed using a jaw crusher, through repeated cycles until a 0/2 fraction was obtained. The particle size distribution of the recycled aggregate was compared to the natural crushed dolomite aggregate. The recycled UHPC was divided in particle fractions and blended to approximate that of the natural aggregate.



Figure 3. Crushing of UHPC using a laboratory Jaw Crusher – repeated cycled.

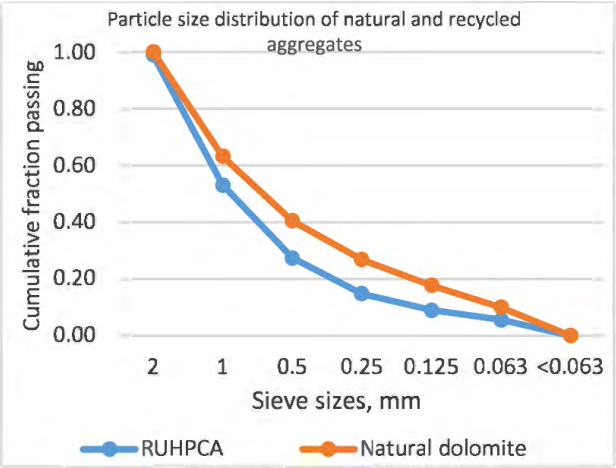


Figure 4. Particle Size Distribution

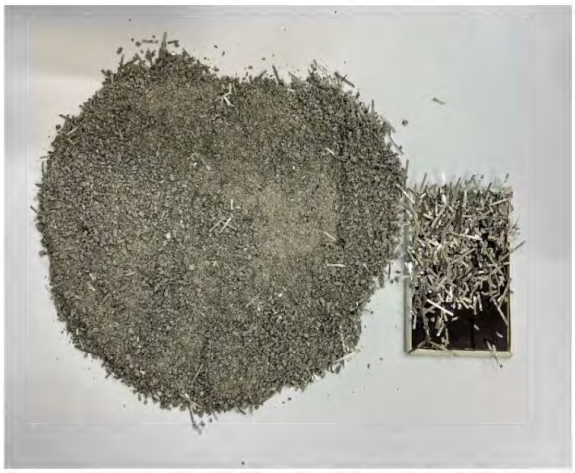


Figure 5. Magnetic separation of fibres

Mix designs with partial and full replacement of aggregates were developed as outlined in the table and cured in water. The fresh density and flow of the mixes developed were determined. Furthermore the mechanical properties (hardened density, flexural strength and compressive strength) were determined at 1, 7 and 28 days.

Table 2. Recycled UHPC mix design

		R0	**R25**	**R50**	**R75**	**R100**
Cement CME IV	kg/m³	800	800	800	800	800
Water	kg/m³	191	191	191	191	191
Aggregate 0/2	kg/m³	1343	1007	671	336	0
Recycled Aggregate 0/2	%	0%	25%	50%	75%	100%
Recycled Aggregate 0/2	kg/m³	0	336	671	1007	1343
SP %	%	3.8	3.8	3.8	3.8	3.8
SP	kg/m³	31	31	31	31	31
W/Binder Ratio	Ratio	0.24	0.24	0.24	0.24	0.24

3. Results and Discussion

3.1. UHPC Amorphous Metallic and Steel Fibres

UHPC based on CEM IV 32.5 was effectively produced through the first phase of the research. UHPC based on Amorphous Metallic fibres and Steel fibres was developed and the performance was assessed to determine the effectiveness of the fibres. Since brittle post-crack behavior was observed during experiments with AA fibers, samples containing 2% steel fibers were cast and tested. This adjustment ensured compliance with the standard requirements for UHPC. The R_AA1 mix had a fresh density of 2412.11kg/m^3 while the R_S mix had a fresh density of 2512.37 kg/m^3. Mixes R_AA1 (amorphous 0.6%) and R_S (2% steel fibres) reached a flow diameter of 260mm without bleeding or segregation. However, mix R_AA2 with 2% amorphous metallic fibres experienced a reduction in workability.

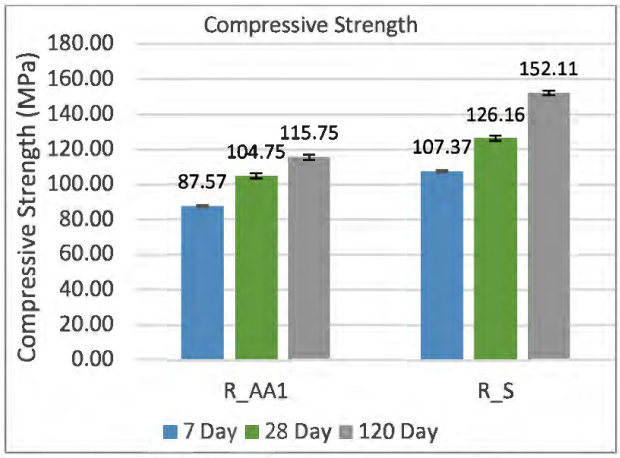


Figure 6. Compressive Strength (MPa)

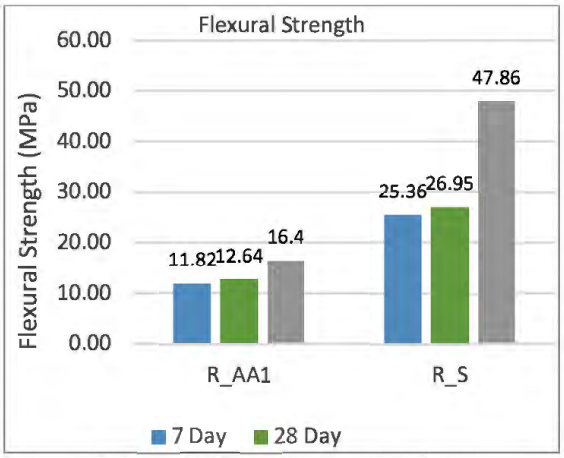


Figure 7. Flexural Strength (MPa)

The mechanical properties were determined with the compressive strength and the Flexural strength presented in Figures 6 and 7 respectively. The Steel fibre samples demonstrated an improved performance with higher compressive strength and flexural strength. Longer term performance was noted (120 days) associated with the presence of high percentage of pozzolanic inclusions in the CEM IV. The Density of R_AA1 and R_S mixes was 2.4t/m^3 and 2.53t/m^3 respectively at 28 days. The UPV value was determined at 28 days as 4878m/s and 5128m/s for R_AA1 and R_S mixes respectively. Compressive strength evolution displayed a characteristic UHPC trend, with rapid early-age hardening followed by gradual densification.

Flexural load–displacement tests were conducted on prismatic specimens (4×4×16 cm) according to EN 196-1 using a three-point bending configuration with a mid-span displacement control rate of 0.05 mm/min. Load and mid-span deflection were continuously recorded. Tests were carried out on the reference steel-fiber mix (R_S) at 7 and 28 days, and on the amorphous metallic fiber mix (R_AA2, 2% fibers) at 28 days. The tests aimed to evaluate crack initiation load, post-peak ductility, and overall flexural toughness. The R_S mix at 7 days achieved a peak load of approximately 10.82 kN at 808.00 mm mid-span deflection. The curve exhibited a sharp peak followed by gradual softening, typical of early-age UHPC where steel fibers partially bridge cracks but matrix stiffness dominates response. At 28 days, R_S showed an increased peak load of approximately 11.04 kN and higher energy absorption (~28196 kN·mm), indicating greater ductility and fiber–matrix bond strength after full hydration. The post-crack plateau extended over a wider displacement range, demonstrating enhanced toughness. The R_AA2 (2% amorphous alloy fibers) at 28 days exhibited a lower peak load (~6.79 kN) but a smoother load decay and moderate energy absorption (~2747 kN·mm). While peak load was reduced relative to R_S, the AA fiber system promoted stable, fine crack distribution, contributing to pseudo-ductile behavior despite the non-metallic reinforcement. Overall, flexural response improved significantly between 7 & 28 days for R_S due to continued hydration and fiber–matrix bond strengthening. The substitution of steel with amorphous fibers yields a more graceful post-crack response but lower ultimate capacity, suggesting potential for hybrid reinforcement strategies to combine ductility and strength.

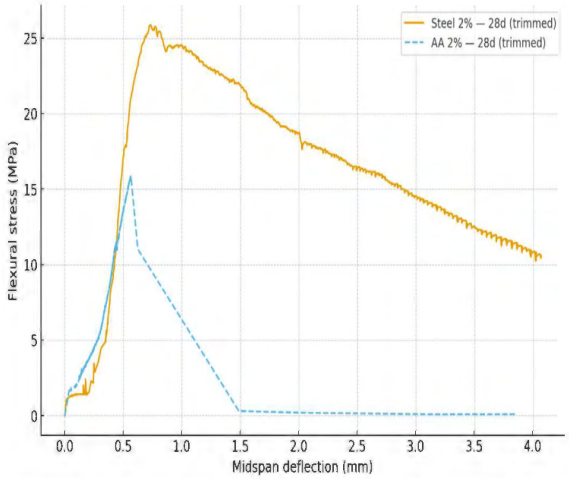


Figure 8. UHPC R_AA2 and RS (2%) 28 day Stress vs Deflection

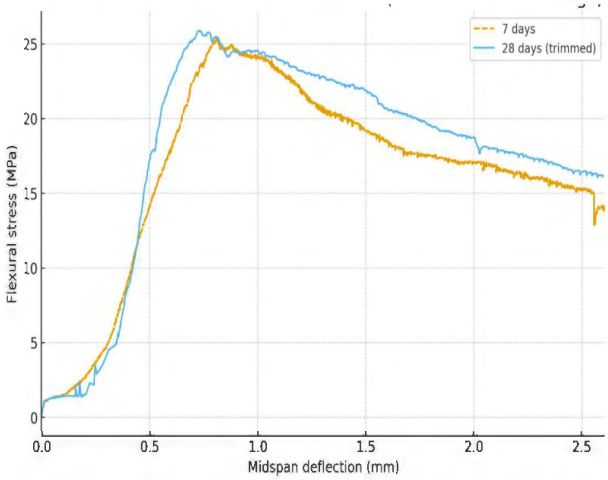


Figure 9. UHPC Steel Fibres RS (2%) 7 day and 28 day Stress vs Deflection

The durability properties were determined for the amorphous alloy fibre mix and the steel fibre mix with respect to both indirect (vacuum saturation porosity) and direct durability methods (chloride migration). The vacuum saturation porosity was noted to reduce over time as there is refinement in the UHPC microstructure. There is a clear and significant reduction in the Chloride migration coefficient determined through the EN 12390-18 Chloride ion penetration test (Table 4).

All durability indicators confirm the outstanding impermeability and microstructural refinement of the UHPC matrices. At 56 days, in the RCPT test (ASTM C1202), the R_AA1 mix exhibited a steady current rise from ~48 to 76 mA over 6 hours, corresponding to an estimated charge well below 1000 C, and classified as very low permeability. The EN 12390-18 test corroborated this, with a chloride penetration depth (xd) of only 2 mm and a migration coefficient of 0.57×10^{-12} m²/s, over an order of magnitude lower than conventional HPC. Permeable porosity results (PP = 15.6% for R_AA1) suggest moderate open porosity but likely closed pore networks, as confirmed by low chloride diffusion. Surface resistivity increased markedly with curing time, from ~17 kΩ·cm at 90 days to >40 kΩ·cm at 180 days, signifying continued hydration and pore refinement.

The R_S reference mixes, though strong mechanically and with lower permeable porosity, showed higher Chloride permeability (ASTM C1202) with estimated charge exceeding 1000 C, in the Low Chloride permeability category, and with lower resistivity (3–8 kΩ·cm), in the early stages (7 and 28 days) yet increasing to >20 at 120 days. Yet the R_S mix demonstrated a marked reduction in Chloride ion penetration (EN12390-18) reaching 0.94 $x\times10^{-12}$ m²/s.

The results suggest improved microstructural closure in the R_AA1 UHPC mix. Collectively, these results place the studied UHPCs firmly in the very low diffusion regime per international classification, predicting exceptional long-term durability even under aggressive chloride exposure.

Table 3. Permeable Porosity (Vacuum Saturation Method)

Mix	Age (days)	PP (%)
R_AA1	56	15.63%
R_S	7	10.79%
R_S	28	8.95%
R_S	56	6.95%
R_S	120	6.67%

Table 4. Chloride migration coefficient (EN 12390-18 Chloride ion penetration)

Mix Design	**Age** (Days)	**Nssm** (10-12 m2/s)
RAA_1	56	0.57
R_S	7	5.14
R_S	28	2.79
R_S	56	1,12
R_S	120	0.94

3.2. Recycled UHPC

The fresh density of the Recycled UHPC was determined together with the flow diameter as reported in Table. It is noted that the recycled aggregate does not result in a reduction in workability when substituting the crushed natural dolomite aggregate used in the UHPC. The mechanical and physical properties were determined after 7 and 28 days of curing. RUHPC demonstrated a slight reduction in density at small replacement percentages of natural aggregate (25%). The compressive strength of RUHPC is in the same range as the reference mix, as indicated in Figure 10. It is noted that while there is a reduction in strength for percentage replacement higher than 50%, the reduction is relatively low, suggesting the effective use of recycled UHPC aggregate as aggregate replacement in new UHPC.

The flexural strength up to 50% replacement of natural aggregate is noted to reduce with a significant reduction for 100% replacement. The UPV results indicate a correlation with the compressive strength values, with a reduction in performance but for the higher substitution levels.

Table 5. RUHPC Fresh density & flow diameter

	Fresh Density	**Flow**
	kg/m³	mm
R0	2387	275
R25	2365	290
R50	2316	270
R75	2254	285
R100	2219	285

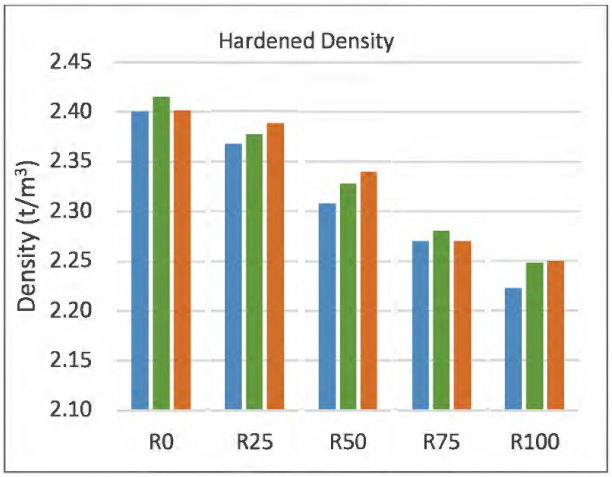


Figure 9. Hardened Density

Recycled aggregate mixes in general achieved competitive strength and UPV, indicating that reprocessed UHPC fine aggregate maintains strong particle integrity. Overall, the experimental mechanical data affirms that the studied UHPC formulations meet or exceed performance expectations for high-durability, low-porosity concretes.

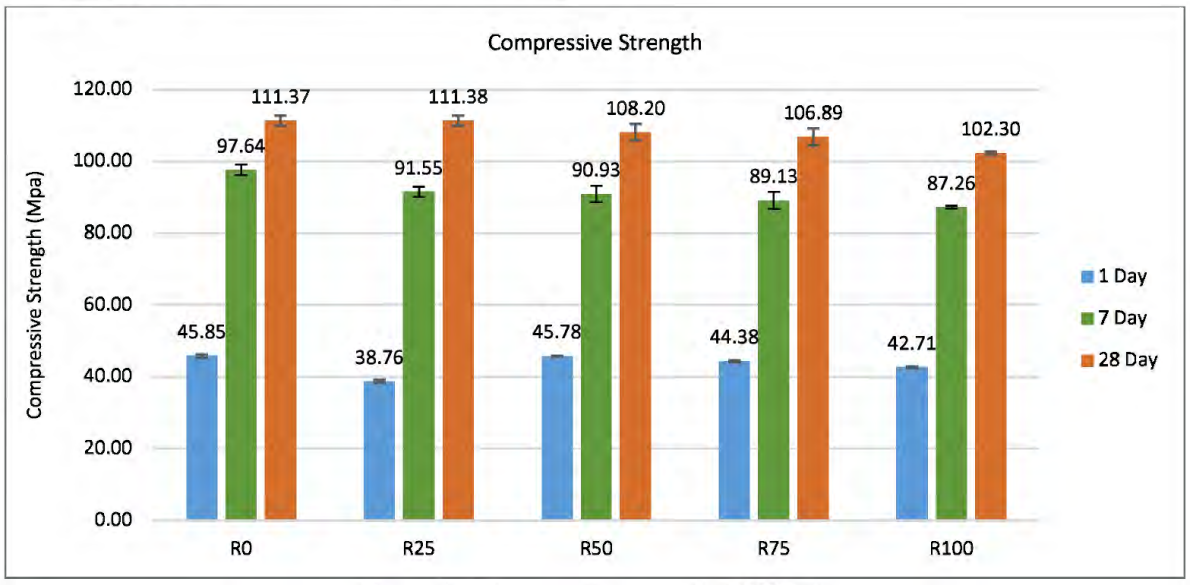


Figure 10. Compressive strength (RUHPC)

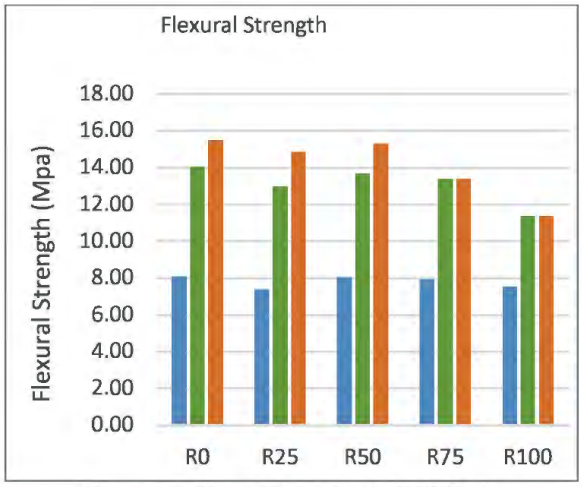


Figure 11. Flexural strength (RUHPC)

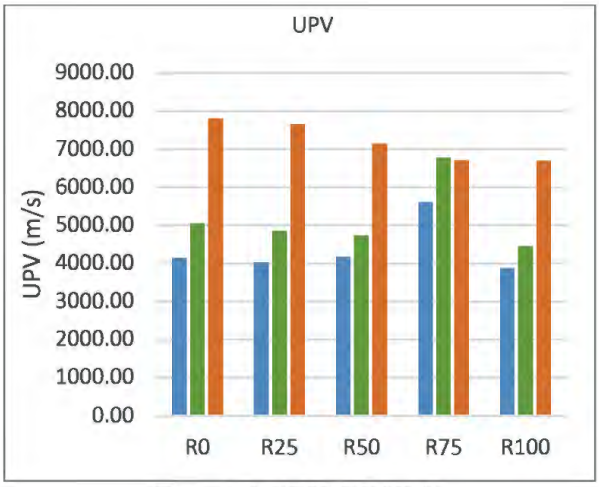


Figure 12. UPV (RUHPC)

4. Discussion and Conclusions

The research activity has demonstrated that UHPC can be effectively reprocessed at the end of its service life, supporting the principles of circular economy in the construction sector. By applying mechanical crushing and fiber separation techniques, valuable secondary materials were successfully recovered from aged UHPC elements and used as recycled aggregate in new low Carbon UHPC. UPC has been effectively produced with CEM IV having a low quantity of clinker and large quantity of pozzolan.

The initial laboratory validation of recycled aggregates indicates that UHPC waste can be transformed into usable resources, reducing the need for new natural materials and minimizing construction and demolition waste. These findings contribute to extending the life cycle of cementitious materials by enabling closed-loop recycling strategies.

Furthermore, the development and optimization of mix designs incorporating recycled UHPC aggregates help enhance resource efficiency and reduce the embodied environmental impacts associated with retrofitting interventions in heritage buildings. This early validation of UHPC recyclability offers practical methods for sustainable material management at the end of the life cycle of retrofitting materials.

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