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Exploring the feasibility of using recycled fines from diverse sources as partial cement substitutes in high-performance cementitious materials

Oussama Douidi [a,b], Ahmed Tafraoui [a], Pedro Serna [b], Abdelkadir Makani [a], Liberato Ferrara [c,*]

[a] Laboratory of Eco-materials: Innovations & Applications (EMIA), Civil Engineering Department, University of Bechar - Tahri Mohamed, Algeria
[b] Institute of Concrete Science and Technology ICITECH, Universitat Politecnica de Valencia, Spain
[c] Department of Civil and Environmental Engineering, Politecnico di Milano, Italy

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ABSTRACT

Advancing sustainable construction requires the development of durable materials while extending the life of end-of-life resources traditionally considered as waste. Construction and demolition waste represents a rapidly growing stream requiring effective recycling and valorisation strategies. Current directives promote the use of secondary raw materials to reduce environmental impacts and conserve natural resources. This study aims to reduce the environmental footprint of cementitious materials by repurposing fine fractions derived from diverse waste streams, including construction and demolition waste, recycled concrete, brick debris, and glass, as partial cement replacements in high-performance cement-based composites. A multi-scale experimental approach was adopted, starting with mortar mixtures to evaluate fresh properties, mechanical performance, and environmental behaviour, and subsequently extended to ultra-high-performance concrete formulations. Optimized ultra-high-performance concrete formulations achieved reduced cement content while maintaining superior performance and minimizing environmental impact. Results demonstrate that recycled fines can shift from disposal burdens to valuable resources, supporting circular-economy principles and enabling next-generation sustainable cementitious composites with enhanced technical performance and reduced environmental footprint.

1. Introduction

Since the beginning of the last century, concrete has become the most used construction material in the world, with nearly 30 billion tonnes consumed annually [1], making it possible to realize the more and more daring buildings and infrastructures that represent our modern cities and contemporary built environment. It is anyway also well known that this development has been accompanied by a likewise challenging-to-be-handled natural resource depletion and pollution in the form of Construction & Demolition Waste (CDW). This especially considering that these wastes often come in the form of bulky items that cannot be decomposed, whose management and disposal turn into significant socioeconomic issues, requires ambitious solutions integrated into a holistic vision aimed at enhancing the overall sustainability signature of the construction industry. The scenario is further complicated, if not worsened, when realizing that the amount of construction waste which is considered no longer useful or valuable to the first user has undergone a quick expansion during recent decades due to several circumstances, including rapid urbanization, the quick expansion of industrial zones, and the massive increase in population [2].

It is furthermore worth emphasizing that the steadily growing concern over managing the massive quantities of CDW, given their huge reusability potential, has also to deal with the necessity of setting-up and deploying a robust, reliable, and well-distributed supply chain of facilities capable of collecting, processing, and recycling these materials, and delivering them to end users such as construction companies, contractors, precast factories, or ready-mix concrete producers. All in adherence with one of the cornerstones of the cement and concrete industry's value

Abbreviations: CDW, Construction and demolition waste; RCA, Recycled concrete aggregate; SCM, Supplementary Cementitious Materials; UHPC, Ultra High Performance Concrete; SF, Silica Fume; RF1, Recycled Fines from CDW – source 1; RF2, Recycled Fines from CDW – source 2;. RBF, Fines from recycled brick; RCF, Fines from recycled concrete; RGF 1, Fines from recycled glass – source 1; RGF 2, Fines from recycled glass – source 2; $R_{UHPC}F$, Fines from recycled ultra-high performance concrete.

* Corresponding author.
E-mail address: liberato.ferrara@polimi.it (L. Ferrara).

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chain, ensuring the local availability of raw materials to minimize the environmental impact associated with transport and thereby enhance the overall sustainability of construction products, structural elements, and built infrastructure [3,4]. In this context, the availability of CDW can be assessed through its annual generation, which is immense. Recent global reviews identify CDW as one of the largest waste streams worldwide, estimating that between 10 and 12 billion tonnes are produced every year [5–10]. Following current solid-waste-management trends, this figure is projected to rise to around 27 billion-tones annually by 2050 [2]. The estimated quantities of CDW produced worldwide are illustrated in Fig. 1, which provides a clear overview of the reported statistics; although global data collection remains fragmented, this figure helps to contextualize the scale of construction and demolition waste generation.

Fig. 1 presents the reported estimates of construction and demolition waste (CDW) generation across world regions. It illustrates a clear dominance of Asia, driven primarily by China and India, while Europe and North America also contribute substantial quantities. Africa and Latin America are experiencing rapid growth in CDW generation, due to accelerating urbanization; however, their figures remaining anyway underreported because of limited and fragmented data collection. Consequently, the sum of regional estimates falls below the global total of 10–12 billion tonnes per year, reflecting discrepancies and undercounts caused by incomplete reporting in Africa, South Asia, and Latin America. This underlines both the scale of the challenge and the urgency of implementing effective waste-management policies. Managing this type of waste is further complicated by inadequate planning and insufficient regulations governing its disposal [2]. In fact, the increasing reliance on landfilling ever-growing volumes of solid waste not only encroaches on precious land but also causes serious social and environmental impacts, which are further exacerbated by weak inadequate oversight [33]. The destination of larger and larger areas to landfill can dramatically affect the availability of soil for agriculture and diminishes the space needed for housing and dwelling units as well as of other buildings and structures necessary for the world population to satisfy the evolving and growing societal demands. This, especially in developing countries, where it is fundamental to ensure the basic needs of a steadily increasing population in obeisance to United Nations Sustainable Development Goals [34,35].

Innovative approaches stimulate to take advantage of this waste in beneficial and constructive ways, including incorporating them into conventional and advanced construction materials, which promotes sustainable development in the construction sector and greatly aids in environmental preservation. Indeed, recycling CDW has been the subject of several researches into a variety of end-uses, ranging from downcycling into road sub-bases to upcycling into base and sub-base layers of urban pavements [36,37], and of course the production of aggregates. The latter has emerged as one of the most valuable technical and economic valorisation pathways [37,38] though, e.g., right now, in the EU, only 28% of CDW is reused or recycled [18,39,40].

Research on recycled concrete aggregates (RCA) consistently shows that replacing natural aggregates with recycled ones generally reduces mechanical strength and durability, mainly because of the higher water demand and greater porosity caused by the residual interfacial transition zone around the original aggregate particles [33,41–43]. These drawbacks significantly limit their use at high replacement levels. To improve and increase the usability of RCA in higher end applications, various treatment methods have been proposed, ranging from surface modification and chemical or mechanical conditioning to carbonation to nano-scale treatments, which aim to reduce porosity and enhance bond characteristics [44–47]. Although the afore-said treatments can improve the performance of RCA, their effectiveness remains strongly dependent on the quality of the parent concrete, and such procedures are often complex, costly, and energy-intensive, raising doubts about their overall environmental and economic viability [48]. Recognizing these limitations, the European Commission advocates for a strategy that prioritizes the appropriate selection and application of natural and recycled aggregates, avoiding arbitrary percentage-based incorporation targets that may lead to inefficient or counterproductive outcomes. As a matter of fact, the diversion of high-quality natural aggregates to low-value uses or procurement of recycled aggregates from distant locations may lead to considerable environmental and economic impacts caused by extended transport distances [49]. It is by the way worth remarking that during the recycling process of concrete waste, not only coarse aggregates are generated but also a fine fraction (<150 μm), which can account for up to 20 to 30% of the processed material [11,12,50]. However, this fraction cannot be directly introduced into concrete manufacturing, as it could lead to a negative effect on workability [51,52], and may further affect mechanical properties, including shrinkage and creep of the recycled aggregate concrete [42,53]. Consequently, targeted research is essential to identify suitable applications for these fines, enabling their appropriate valorisation and ensuring that the production of high-quality recycled aggregates remains both technically and economically viable.

In order to find productive uses for the aforesaid fine fraction, several researchers have investigated its incorporation into new cement-based materials. This has prompted studies such as those by Oksri-Nelfia [54] and Bordy [55], who suggested incorporating fines recovered from recycled concrete as a mineral addition in fresh concrete mixes. Building on this, other investigations demonstrated the feasibility of partially replacing cement with fines from recycled concrete, showing that is possible to reach up to 25% of cement volume replacement could be achieved without adverse effects on concrete performance [56]. Encouraged by these findings, some pilot projects extended the approach to ultra-high-performance concrete (UHPC): Borg et al. [57] and Ferrara et al. [58] reported that fines from recycled UHPC could be

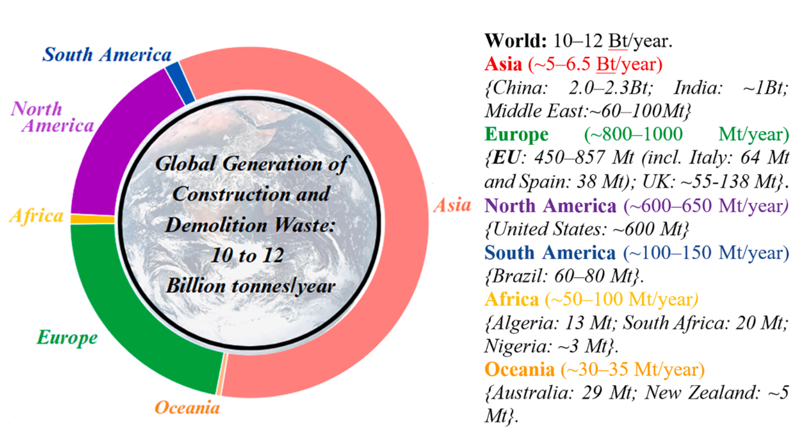


Fig. 1. Overview of the estimated annual statistics of CDW generation around world [2–32].

used as a cement substitute, at levels up to 30% by volume. Their findings showed comparable mechanical and durability properties, as well as similar self-healing capacity, which has been attributed to the substantial amount of unhydrated cement and unreacted binder still present in the original UHPC and carried over into the recycled fraction. These materials provide beneficial action when incorporated into new concrete mixtures, reducing the demand for fresh cement and adding value to the implementation of a circular economy in the production of advanced cement-based construction materials [41,59,60]. In line with this, Wang et al. [61] highlighted the potential of incorporating recycled concrete fines into ultra-high-performance concrete (UHPC) showing that replacing 10% of the cement resulted in a 28-day compressive strength of 133 MPa, exceeding the control by 3.9%. Moreover, incorporating recycled fines may enhance the particle packing density by reducing inter-particle voids, average particle size, and spacing, thereby helping to meet minimum paste content and rheological requirements needed to ensure optimal fresh-state performance [62].

To establish a clear framework for this study, a comprehensive bibliographic survey was conducted to examine how using fines from various recycled materials sources as cement substitution may affect the fresh-state properties and mechanical strength of cementitious composites. The following Fig. 2 illustrates the influence of different recycled fines on mechanical strength.

Fig. 2 shows the general trend reported in the literature for the effect of different recycled Fines on compressive strength. Most studies indicate that when construction- and demolition-derived fines, recycled concrete fines, or recycled glass fines are used as supplementary cementitious materials at moderate replacement levels (generally up to about 20–25%, and in some cases up to 30% by weight of cement), the resulting mixes exhibit comparable or only slightly reduced compressive strength relative to reference concretes. In certain cases, small substitution ratios even improve strength. However, once replacement levels exceed these thresholds, typically above 20–25% a clear downward trend in compressive strength is observed, with significant losses reported at higher substitution rates. These findings highlight the importance of optimizing replacement levels to balance environmental benefits with mechanical performance.

Concerning the influence of recycled fines on workability, Fig. 3 summarizes the main trends reported in the literature. Usually; low to moderate replacement levels (below 20% of binder mass), incorporating recycled concrete, brick or glass fines tend to preserves fresh-state performance, with only negligible or modest reductions in workability compared to reference mixes. Beyond these thresholds, however, a progressive loss of fluidity is typically observed, often requiring increased dosages of plasticizers or water-reducing admixtures to maintain target consistency. Particular care is needed because some recycled fines exert a stronger influence on workability due to their higher porosity, water absorption and especially their particle size, shape and morphology; coarser or more irregular particles tend to cause greater decreases in workability. The trends shown in Fig. 3 emphasize that the fresh-state behavior of mixes with recycled fines is both material- and dosage-dependent, highlighting the importance of optimizing both the type of recycled fines and its replacement level to achieve satisfactory workability.

Aside from these impacts, the literature documented further significant and multifaceted effects of recycled fines on the key characteristics of concrete behavior, which are multifaceted and call for careful evaluation. Their typically higher water absorption often requires adjustments to the mix design, for instance, recycled concrete fines may require about 1% additional mixing water for every 10% increase in replacement level [73]. Particle fineness is also critical, when particles are within the 0–250 μm range, their influence on performance is generally minor or negligible, whereas coarser fractions tend to increase porosity and negatively affect mechanical properties [62,64,69,73]. Moreover, the incorporation of recycled fines has been linked to a reduction in hydration heat [7,12,40,69], which directly affects setting behavior and typically prolongs the setting time of blended mixtures, a phenomenon widely reported in the literature [75,76,82,87,88]. This delay may be attributed to interactions between the recycled fines and hydration products, as well as the possible release of residual binders contained in the fines.

On the other hand, in a path that aims to enhance the environmental sustainability and improve the economic efficiency in construction practices, the adoption of high-performance concrete (HPC) and especially ultra-high-performance concrete (UHPC) is highly advised. Although UHPC typically requires up to 2 to 3 times more cement than ordinary concrete, its extended service life and superior durability offset the higher initial material demand, making it one of the most effective solutions for prolonging the lifespan of buildings and infrastructure [12]. Life-cycle analyses, such as those by di Summa et al. [4], confirmed its significant advantages in long-term cost and resource efficiency. Thanks to its outstanding mechanical performance, UHPC enables thinner and more resource-efficient structural elements, thereby mitigating the environmental impact of construction materials [12]. At the same time, the high binder content of UHPC creates a promising opportunity to incorporate recycled fines as partial replacements of cement, an approach that not only conserves raw materials but also aligns with sustainable development objectives. Understanding the effects of these recycled materials on UHPC performance is thus essential to optimise their use while maintaining consistent quality.

Producing high-performance concrete with reduced clinker content remains a central target of sustainable development, and the use of recycled fines represents an innovative pathway to this goal. Reusing construction waste as eco-friendly cementitious components delivers both environmental and economic benefits by cutting carbon emissions, energy use, and production costs, while simultaneously reducing reliance on conventional cement and thereby enhancing the overall efficiency of construction processes [81]. Notably, recent studies demonstrate that when strategically applied, certain recycled fines can foster the achievement of exceptional performance. For instance, Khan et al. [81] developed a UHPC with recycled glass fines maintaining self-compacting properties and reached compressive strengths exceeding 150 MPa while reducing cement content by about 16%. Other investigations confirmed comparable trends with recycled sand [89,90],

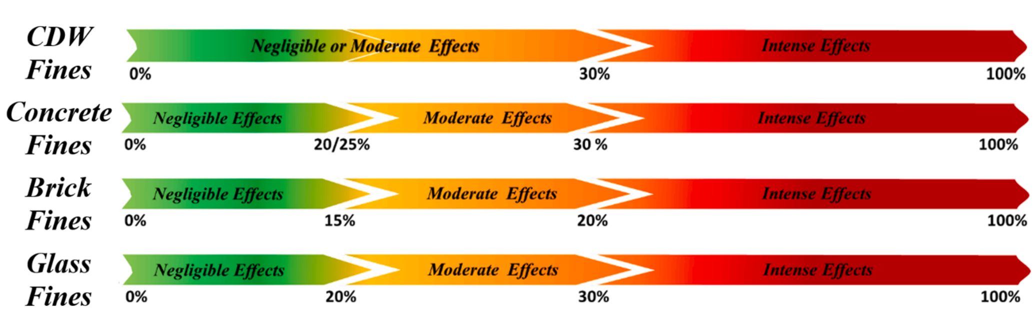


Fig. 2. Influence of different recycled fines on compressive strength [11,12,20,63–82].

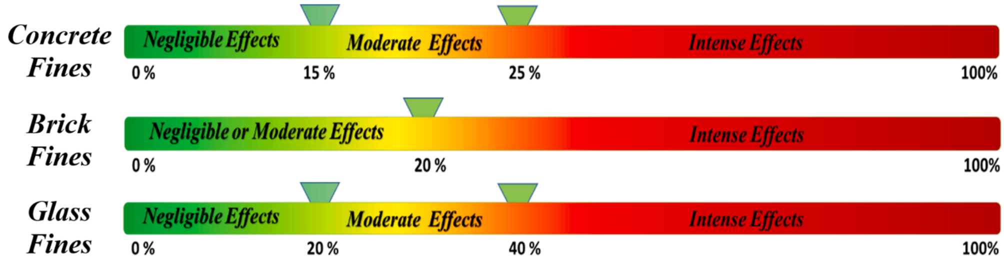


Fig. 3. Influence of different recycled fines on the workability [20,63,69,76,78,82–86].

glass cullet and hybrid fibers [91], and ceramic waste [92], reporting that UHPC can maintain or even surpass its mechanical and durability requirements when formulated with suitable recycled fines. These findings underscore the transformative potential of integrating recycled materials into advanced concrete formulations and highlight a viable route for reducing the environmental footprint of the construction industry.

In the framework described above, this study investigates reusing fine fractions derived from various waste sources including CDW, concrete, bricks, and glass as potential cement replacements and/or supplementary cementitious materials. A combined multi-objective optimization and experimental design approach is adopted to evaluate their incorporation into cementitious materials. These fines, recovered from the recycling of different waste streams has been used at their raw state without any additional treatment. The first phase focuses on incorporating these recycled fines into mortars and characterizing their influence on key performance parameters including workability, setting time, compressive strength, and flexural strength. The second phase scales the investigation up to UHPC formulations, with the ultimate aim of advancing optimization strategies to further reduce cement consumption while enhancing performance and, targeting workability while maximizing mechanical properties. The work begins with the acquisition and characterization of the various waste sources and building a comprehensive and consistent database to analyze their effects. These recycled fines are then incorporated into cementitious mortars at approximately 18% binder replacement by volume to assess their impact on workability, setting time, and mechanical performance, thereby evaluating the feasibility of producing cementitious composites that meet performance requirements while reducing the demand for fresh cement. Finally, the perspective of extending the use of these recycled fines in UHPC matrices represents an interesting possibility of upcycling the considered wastes into advanced applications, enhancing the environmental friendliness and sustainability of UHPC without compromising its performance.

2. Materials and methods

2.1. Materials

In the preparation of all the different investigated recycled-fine mortars, a Portland cement CEM I/A-L 42.5R SR was employed, which was supplied by the CEMEX factory in Buñol (Valencia, Spain); as per producer's specifications, the cement constituents are the clinker (95–100%) as well as some minor additions (0–5%), conforming to EN 197–1.

The natural sand used, was specifically selected to meet the required specifications for the production of high-performance concrete. It consisted of a blend of three sand fractions of different particle sizes to obtain distribution as close as possible to the one of the normalized sand.

Tap water from the Valencia aqueduct was employed together with the superplasticizer SIKA Viscocrete 20HE.

The control mortar mix proportions, reported in Table 1, were carefully optimized based on previous research and possible foreseen practical applications to ensure the desired properties of the final mortar, including mechanical strength and workability, while maintaining reliable performance. This reference control mixture was developed and validated through prior studies conducted at the ICITECH laboratory at UPV on the concept, design, and manufacturing of UHPC [93–96].

Table 1
Mix-design formulations of investigated mortars for 1 litre.

Materials	Control Mortar (g)	Mortar with recycled fines (g)
Cement	975	800
Recycled fines	-	175
Sand Coarse (2.0 - 4.0 mm)	225	225
Sand Medium (0.25 - 2.0 mm)	565	565
Sand fine (0 - 1.0 mm)	305	305
Water	170	170
Super-plasticizer	20	20

Together with the control mortar, eight mortar formulations were cast by replacing 18% by mass of cement with the recycled manufactured fines according to the mix compositions also reported in Table 1. All the mortars were prepared according to the specifications of EN196–1 and employing the mixing protocol hereafter detailed.

2.2. Recycled fines

The different fines used in this study have originated from different recycled material sources, as detailed further. The different CDWs were first of all collected and then the recycling process started by grinding them in three steps, consisting of crushing using a jaw crusher, grinding in a ball mill, then screening and finally sieving the obtained materials several times in order to obtain a fine powder in the required size fraction.

The employed recycled materials included:

- RECYCLED FINES – Source 1 (RF1): Fines were obtained from crushing and grinding of construction and demolition waste, and from further screening of recycled sand. Supplied by a recycling platform specialized in the treatment of different CDW located in Valencia, Spain.
- RECYCLED FINES – Source 2 (RF2): Fines were obtained from the same crushing and grinding process of construction and demolition waste, but after screening, the recycled sand was also subjected to a washing step to remove adhered impurities and soluble contaminants. Supplied by the same recycling platform in Valencia, Spain.

It is worth remarking that, as from information provided, construction and demolition waste used for producing RF1 and RF2 consists of a diverse mix of materials, including old concrete, masonry, brick, ceramic, roof tiles, wall and floor tiles, sanitary ware, glass, gypsum, and wood. Notably, high-content components such as brick, tiles, and sanitary ware may represent 20–30% of the total weight of recycled CDW, highlighting the heterogeneous nature and posing challenges to the potential of these materials for sustainable reuse [12,58].

- RECYCLED CONCRETE FINES (RCF): Fines came from crushing, grinding and sieving of concrete waste, specifically of laboratory concrete specimens which had been thrown away, and whose properties and origins are known and controlled (compressive strength lower than 40 MPa).
- RECYCLED ULTRA HIGH PERFORMANCE CONCRETE FINE (RUHPCF): Fines were obtained from crushing, grinding and sieving of Ultra-High-Performance Concrete with metallic fibers, obtained from own laboratory specimens (compressive strength higher than 120 MPa).
- RECYCLED GLASS FINES – Source 1 (RGF1): Fine recycled glass were obtained from the mechanical crushing and grinding of glass wastes after being collected, washed and dried to get finely a fine powder, received from a recycling platform in Valencia, Spain.
- RECYCLED GLASS FINES – Source 2 (RGF2): The recycled glass or cullet is a material generated from the glass waste during the recycling process, and consists of fine particles which cannot be recycled again in the production of glass [95] and would be otherwise destined to landfills [59]. The recycled glass fines 2 (recycled glass cullet) used in this study was obtained from a product supplied by the company FCC ámbito (Sagunto, Spain) and had to be further ground to be used in this investigation.
- RECYCLED BRICK FINES (RBF): The fines were derived from red brick waste were produced through a sequence of crushing, grinding, and sieving processes carried out in the ICITECH laboratory of the University Polytechnic of Valencia, Spain.
- SILICA FUME (SF): produced by the company ELKEM, used in this study as a reference commercial Supplementary Cementitious Materials to validate the approach and carry out a comparative analysis with "own" manufactured recycled mineral additions.

Each one of recycled fines has been employed in this investigation, as detailed earlier, is portrayed in three photos. These images illustrate the material's origin, a pre-use concrete powder form, and a microscopic view with two different pictures with magnification x100, as depicted in Fig. 4.

2.2.1. Physico-chemical characterization

- *Laser granulometry:*

All the employed recycled fines have been first of all analyzed by means of laser granulometry (Mastersizer 2000) to characterize their particle size distribution.

The obtained results are represented in Fig. 5, with further information provided in Table 2.

From the results of laser-analyzed particle size distribution, it can be observed that only the recycled glass fines (RGF1 and RGF2), and the silica fume SF exhibit a grain size distribution that complies with the boundaries for supplementary cementitious materials as outlined in

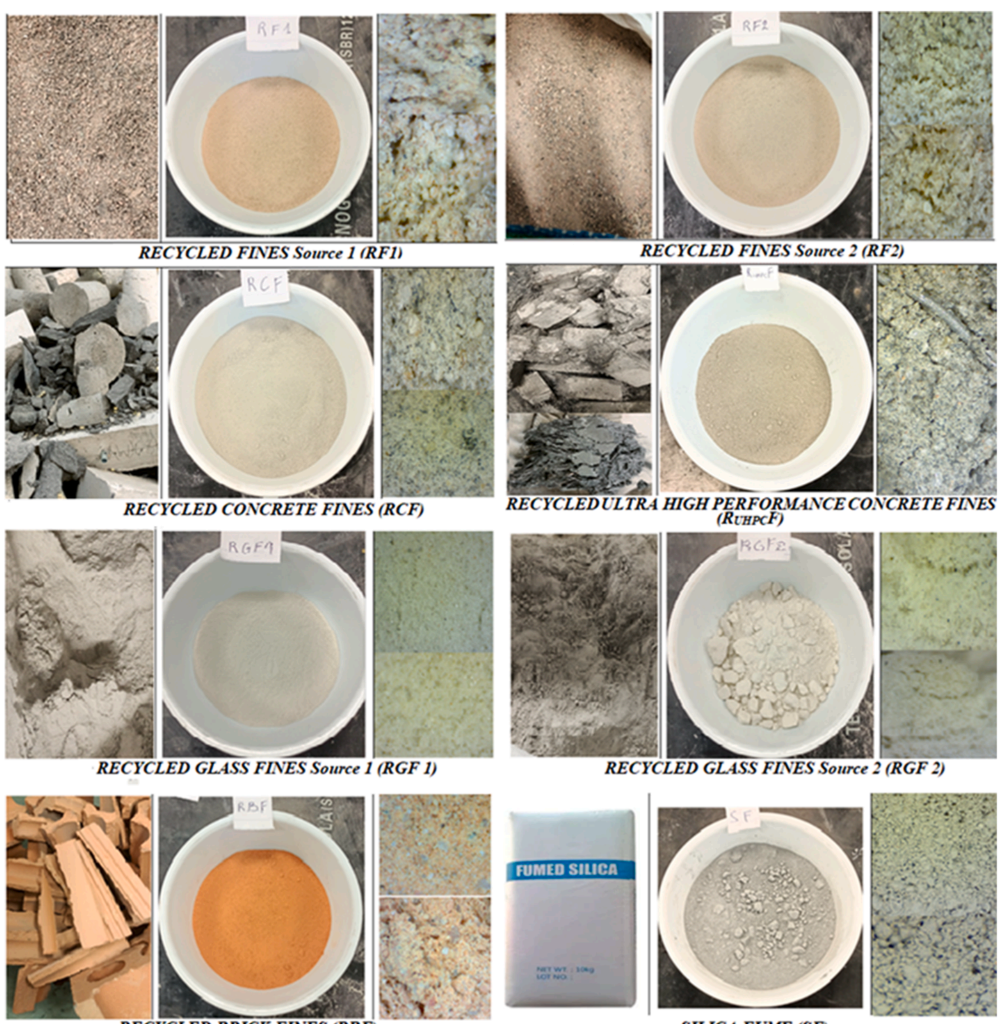


Fig. 4. Images of the recycled fines used in this study (Raw Material, Fine, Magnification*100).

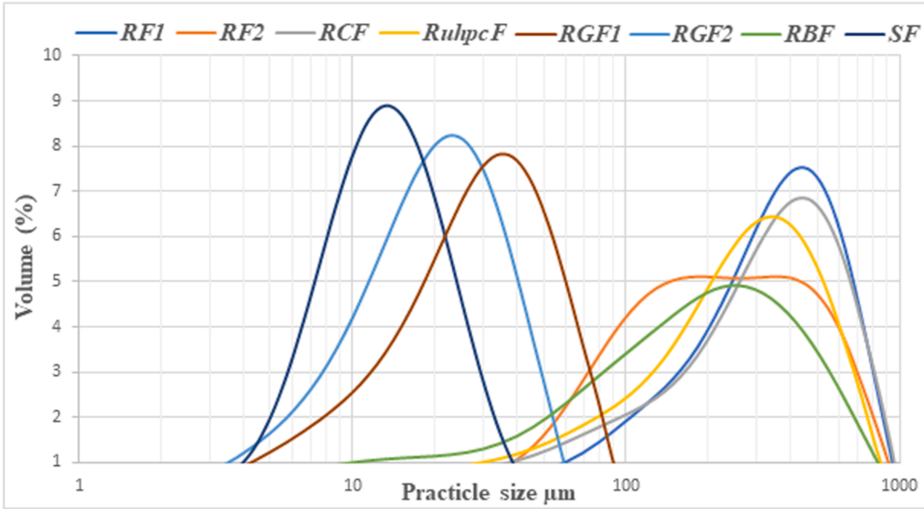


Fig. 5. Laser granulometry of the employed recycled fines.

Table 2
Information about the particle size of the fines.

Recycled fines	RF1	RF2	RCF	RBF	RGF1	RGF2	$R_{UHPC}F$	SF
Volume weighted average diameter (µm)	288.46	233.87	276.22	186.47	28.40	19.35	232.96	19.88
Uniformity	0.67	0.86	0.75	1.02	0.59	0.55	0.77	1.07
Specific surface area m^2/g	0.27	0.12	0.23	0.37	0.56	0.74	0.25	0.86

standard EN 197–1 (maximum allowable particle size of 150 µm). This outcome was expected, as these materials were produced through an industrial grinding process that resulted in an average particle size even lower than 50 µm. In contrast, the particle size distribution of Recycled Fines types 1 and 2, Recycled Concrete Fines, Recycled Brick Fines, and Recycled UHPC Fines skews towards the larger boundary, ranging from 10 to 1000 µm, with an average particle size of approximately 250 µm and with a notable fraction pushed towards the upper sieve size limit of 1000 µm. Although a broader granulometry can enhance filling capacity, it is important to notice that the grinding procedures employed for these materials were less efficient than industrial methods, having been conducted in a laboratory setting from test specimens or derived from coarse construction and demolition (C&D) wastes.

However, this could also be advantageous from an environmental sustainability perspective, as producing finer materials through extensive crushing and grinding typically requires higher energy input, thereby increasing the overall environmental footprint. In addition, the interfacial transition zone (ITZ) between recycled fines and the cement matrix plays a crucial role in governing the mechanical and durability properties of cementitious composites [97,98]. When recycled fines exhibit a relatively coarse particle size distribution, approaching the upper boundary of the fine fraction, they can behave as micro-aggregates in addition to acting as filler particles. For instance, studies have shown that recycled concrete fines with particle sizes up to approximately 250 µm, significantly larger than conventional fine fractions of around 125 µm do not substantially reduce the compressive strength of concrete [73]. Recent multi-scale and microstructural investigations using *in-situ* 4D CT and DVC techniques have further demonstrated that such coarse fines can develop a measurable and functionally relevant ITZ, allowing visualization of local density variations, microcracks, and bonding mechanisms between the recycled particles and the cement matrix [99,100]. This suggests that energy-intensive processing to produce very fine powders may not be necessary to achieve the desired material performance while simultaneously benefiting from a structurally significant ITZ.

- *Mineralogical composition*

Information on the mineralogical composition of the recycled fines was systematically gathered from previously published studies, main data has been derived from X-ray Diffraction analyses. These datasets were compiled and critically synthesized through a targeted bibliographic review to identify the principal crystalline phases associated with each material type. Table 3 presents the consolidated results, highlighting dominant oxide contents, secondary mineral phases, and trace components. This overview provides a sound basis for assessing the potential influence of each recycled fine on the hydration behaviour, workability, and mechanical performance of cementitious composites.

As shown in Table 3, the recycled fines display substantial mineralogical and chemical heterogeneity, reflecting the variability inherent to their source materials. CDW-derived fines and recycled concrete fines are generally dominated by silica and carbonates, with minor alumina, iron oxides, and traces of MgO, K_2O, and SO_3. Brick-derived fines exhibit elevated alumina and iron contents consistent with clay-fired products, whereas glass-derived fines are characterised by very high silica contents accompanied by sodium and calcium oxides typical of soda–lime glass. Silica fume, included as a benchmark SCM, displays the highest SiO_2 purity with only minor secondary oxides.

Although the compositions compiled in Table 3 are based on bibliographic sources rather than exclusively on analyses of the specific batches used, they remain representative of the major waste streams from which such fines are commonly produced. Their inherent variability can influence reactivity, water demand, and pozzolanic behaviour; however, the experimental results of this study indicate that such variability did not hinder mixture performance. The UHPC formulations incorporating the different recycled fines consistently achieved fresh-state and mechanical properties comparable to, or in some cases exceeding, those of the reference mixture. This demonstrates that, when appropriately selected and proportioned, recycled fines can be robustly integrated as supplementary cementitious materials despite compositional dispersion. To further address concerns regarding generalizability and reproducibility, it is important to note that the purpose of this study

Table 3
Typical mineralogical and chemical composition of the recycled fines.

Materials%	SiO_2 %	$CaCO_3$ %	Al_2O_3 %	Fe_2O_3 %	Na_2O %	CaO %	Additional Notes	Refs.
Recycled Fines From CDW	*30–70*	*17–30*	*6–19*	*2–6*	—	—	Traces of MgO, K_2O, SO_3 may be present.	[61,63,69,101–103]
Recycled Concrete Fines	*20–80*	*25–73*	*5–19*	*3–7*	—	—	Minor phases: portlandite, lime, iron oxides.	[11,12,19,20,54, 103–105]
Recycled Brick Fines	*49–70*	—	*~20*	*~8*	*1–3*	*2–5*	May also contain minor quantities of MgO, K_2O, SO_3	[20,100,106–108]
Recycled Glass-Derived Fines	*≥70*	—	*1–4*	*~1*	*10–16*	*7–13*	May contain MgO (2–5%) along with traces of other oxides.	[61,76,81,82, 109–112]
Silica Fume	*≥90*	—	*~1*	*~1*	—	*~3.9*	High-purity SiO_2 (92–96%); minor amount Al_2O_3 and CaO reported in advanced analyses	[61,81,112–114]

was to evaluate performance trends rather than to establish exact composition–property correlations. The consistency of the observed mechanical and environmental responses across mixtures indicates that the findings remain applicable to recycled fines with similar origins and processing routes. Overall, these findings further confirm the potential of recycled fines to be reliably integrated into UHPC systems, even in the presence of the compositional variability inherent to real waste streams.

2.3. Experimental test plan

The experimental program was designed to assess the fresh-state properties and mechanical performance of mortars produced with and without recycled fines. The procedure began with the preparation and mixing of the mortar batches. For each mixture, the dry constituents were weighed and placed into a laboratory mixer and blended for 30 s to ensure uniform distribution. Subsequently, two-thirds of the total mixing water was added, and mixing continued for an additional 90 s. Finally, the remaining water together with the superplasticizer was incorporated, and mixing proceeded for 15 min to obtain a homogeneous and workable consistency.

Fresh-State Performance Testing: Immediately after mixing, the fresh-state performance of the mortars was evaluated under both static and dynamic conditions in order to characterize their flowability and retention of workability over time. In the static condition, the mortar was left at rest between successive measurements, while in the dynamic condition it was kept under continuous low-speed mixing to simulate agitation during transport in a truck mixer. For each condition, the assessment started with flow-table tests on the fresh mortars, including the control mix, to determine their initial workability and its evolution with time. The mortar was placed into cylindrical molds (70 mm diameter, 60 mm height) and, within 15 s of filling, the mold was lifted vertically and the spread diameter was measured with a caliper along two orthogonal directions. The sample was then subjected to 15 strokes on the flow table with a standard tamping rod at a rate of about one stroke per second, as specified by EN 1015–3, after which the new spread diameter was recorded. This entire procedure was repeated at 0, 15, 30, 45 and 60 min after mixing to quantify the variation of fluidity over time and thus the mixture's ability to retain its fresh-state performance during a time period representative of hauling from a batching plant to a construction site.

Under the dynamic condition, the same protocol was applied but the mortar was maintained under continuous low-speed mixing (140 rpm) following the initial mixing stage, thereby simulating transit-mixer agitation typically experienced during transport. Flow-table tests were carried out at the same time intervals (15, 30, 45 min and 1 h of mixing) and using the identical measurement procedure to enable direct comparison between the two conditions. The resulting data provided insight into the influence of continuous mixing on the retention capacity of flowability and the resilience of the mixtures to transportation conditions. The entire spread-measurement process is illustrated schematically in Fig. 6. It shows the filling of the cylindrical mould with fresh mortar, the lifting of the mould to allow initial spreading, the measurement of the initial spread, the application of 15 flow-table strokes and the measurement of the final spread. These images visually summarise the procedure explained earlier and the sequence of operations carried out at different time intervals under both static and dynamic conditions to evaluate the retention of fresh-state properties.

In parallel with the flowability measurements, the setting time was evaluated using a Vicat needle apparatus in accordance with EN 196–3. For each test, the mortar was placed in the Vicat mould and the needle (cross-sectional area 1 mm^2; mass 300 g) was released without momentum to record its penetration depth. The initial setting time was defined as the first time the needle failed to reach the bottom of the specimen, leaving a recess of 4 $\pm$ 1 mm from the base plate, while the final setting time corresponded to the moment when the needle no longer penetrated the mortar.

Hardened Properties Testing: To assess the hardened properties, prismatic specimens with dimensions of 40 $\times$ 40 $\times$ 160 mm^3 were cast from each mix following EN 196–1. Six prisms per mixture were prepared for each mixture, demoulded after 24 h and then cured in a moist room at 20 $\pm$ 2 °C for 28 days. After curing, the specimens were tested for flexural strength and, on the resulting halves, for compressive strength. This comprehensive approach enabled the influence of recycled fines on both the fresh-state behavior and the mechanical performance of the mortars

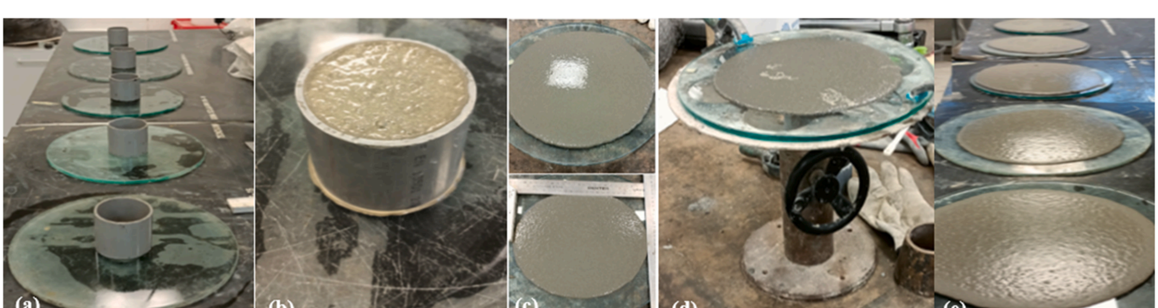


Fig. 6. Step-by-step illustration of the Process for spread diameter measurement: (a) filling the cylinder mould with mortar; (b) lifting the mould to allow spreading; (c) initial spread diameter measurement; (d) application of 15 strokes; (e) final spread diameter measurement.

to be assessed under conditions representative of practical construction practice.

At the same time, the density of the hardened mortars was determined on the $40 \times 40 \times 160mm^3$ prisms in accordance with EN 1015–10 (bulk density of hardened mortar).

For the UHPC mixtures, cubic specimens with 150 mm sides were produced for compressive strength testing. Four cubes were prepared and tested for each UHPC mixture, and the reported compressive strength values correspond to the average of the four specimens.

Environmental Assessment: The environmental analysis in this study was performed in accordance with the principles and framework of ISO 14,040 and the requirements and guidelines of ISO 14,044, complemented by the core rules for construction products set out in EN 15,804. The focus is on ultra-high-performance cementitous materials mixtures in which cement is partially replaced by different types of recycled fines, rather than on the design of structural elements. Within this framework, the environmental assessment adopts a sustainability-driven approach aimed at maximizing resource efficiency and promoting circularity in construction materials. For cementitious systems such as those investigated here, the goal is to achieve a optimal balance between environmental impact and mechanical performance, ensuring that the CO_2 reductions arising from lower cement content are not offset by the emissions associated with processing the recycled fines. Although no beams or other structural elements are manufactured in this study, the mechanical properties of the specimens remain essential indicators of potential performance; any substantial reduction in mechanical capacity would weaken both the practical feasibility and the environmental benefits of partial cement substitution. This approach allows the environmental implications of integrating different recycled fines into UHPC formulations to be assessed under controlled laboratory conditions, in line with internationally recognized life cycle assessment (LCA) methodology.

To complement this cradle-to-gate assessment, a performance-based environmental efficiency indicator is employed to capture the interplay between embodied carbon and mechanical performance. This metric provides a more insightful basis for comparing mixtures, as it accounts for the structural relevance of the material and highlights formulations that achieve environmental gains without compromising strength. It is computed by dividing the CO_2 emissions per unit volume of concrete (kg CO_2/m^3) by the corresponding compressive strength (MPa), thereby expressing the environmental burden relative to the load-bearing capability of each mixture. By normalizing environmental impact to mechanical performance, this indicator offers a robust evaluation of the true environmental efficiency of UHPC mixtures incorporating recycled fines.

3. Results and discussion

3.1. Fresh state properties

3.1.1. Flow-table spread diameter and its time evolution (without mixing)

The results of the evaluation of the mortar fluidity variation as function of time, measured through the spread diameter, before and after the application of the strokes and over a duration up to 60 min, at 15 min intervals, are reported in Table 4. Fig. 7 shows the variation of the spread diameter as function of the elapsed time, with reference to the initial measurement Fig. 7a) and after the application of the 15 strokes Fig. 7b).

Upon first sight of the results, it can be observed that, in general, each and all the investigated mortars were able to maintain their initial consistency while waiting for up to an hour after mixing. Concerning the initial spread, it can be observed that for the majority of recycled Fines, the flow diameter is comparable to the one of the reference mortar, except for the recycled glass fine 2 (RGF2) and silica fume (SF) formulations, which showed a decrease of about 20 to 25% in workability; anyway, even despite their reduced initial fluidity, also these mixtures were able to maintain similar fresh state performance over time. The reduced initial spread may be explained when considering material properties, since the recycled glass fine 2 (RGF2), composed of angular glass particles with a relatively low specific surface area, reduces lubrication, increases internal friction and viscosity, and leaves the mix drier due to its inability to absorb water. On the other hand, the silica fume (SF) is characterized by ultrafine particles and a high specific surface area, significantly increases water demand, acts as a microfiller, and may reduce the effective water-to-cement ratio, resulting in a stiffer, less workable mix.

Table 4
Evolution of the flow table spread diameter as a function of time elapsed from the end of mixing (measurements in mm).

Mix		0 min	15 min	30 min	45 min	60 min
Control (Cement)	Initial spread	245	230	225	220	210
	Spread after vibration	285	260	260	260	255
RF1	Initial spread	250	240	230	225	220
	Spread after vibration	295	280	280	275	270
RF2	Initial spread	245	240	235	235	230
	Spread after vibration	285	280	275	275	260
RCF	Initial spread	245	230	225	220	220
	Spread after vibration	280	260	260	255	250
RGF1	Initial spread	240	230	230	220	210
	Spread after vibration	270	260	250	240	240
RGF2	Initial spread	200	180	170	170	165
	Spread after vibration	230	210	200	200	195
SF	Initial spread	210	180	165	150	145
	Spread after vibration	240	205	195	185	180
RBF	Initial spread	250	230	220	215	210
	Spread after vibration	280	260	255	250	240
$R_{UHPC}F$	Initial spread	250	250	250	240	230
	Spread after vibration	295	285	280	280	270

The evolution of the spread as a function of the elapsed time shows a slight decrease in workability, limited to less than 20% even after a one-hour waiting period. Moreover, by applying the prescribed 15 strokes, the spread increased by 10 to 15%, and even after one hour, the flowability remained higher than the measurements without vibration at all elapsed times. Additionally, another notable aspect was noticeable regarding the apparent viscosity of the different mixtures, as some differences during flow were clearly noticeable, in line with previous observations related to the use of various cementitious materials [90]. While most mixtures spread easily, others, particularly the one containing RGF2, appeared visibly more viscous but still workable. Although not quantitatively measured, this variation in consistency was consistently noted throughout the mixing and handling process.

It is furthermore worth noting that, based on visual observations, all the mixtures appeared uniform and stable, with no visible signs of instability or segregation halos at the edges of the spread-flow patty. This stability is clearly evident in the images presented in Fig. 8.

The left panel (a) of Fig. 8 illustrates the standard flow table setup, including the truncated cone and spreading surface, while the right panel (b) presents representative images of the tested mortar mixtures under fresh state conditions. No mixture, whether the control or those incorporating recycled fines, showed signs of water bleeding, overflow, or segregation. Instead, each exhibited a uniform, cohesive, and stable flow behaviour, as confirmed by direct visual inspection during testing.

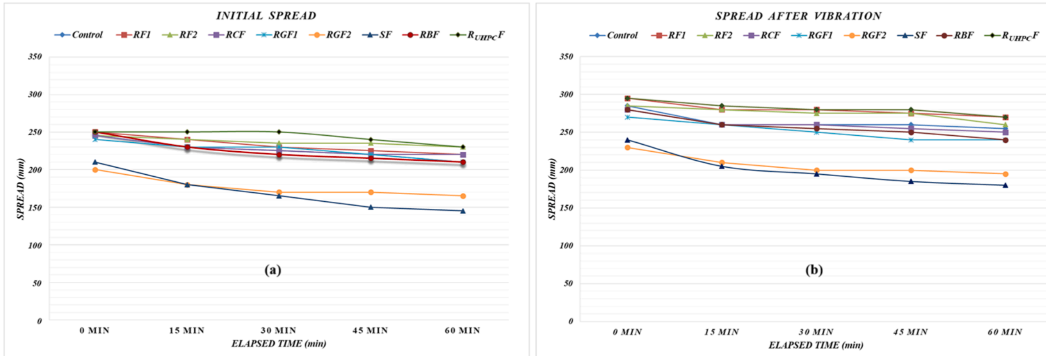


Fig. 7. The variation of fluidity as a function of setting time: a) Initial Spread; b) Spread by applying vibration (strokes Manual Shaking Table).

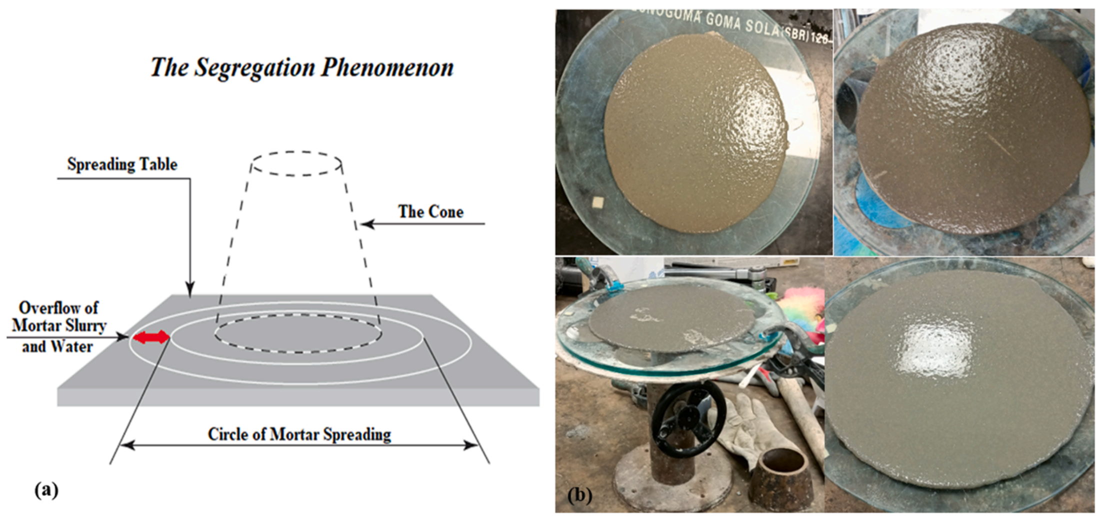


Fig. 8. Flow table setup and representative mortar mixtures: (a) Schematic of the flow table apparatus showing key components (cone, spreading table, overflow zone); (b) Photographs of fresh mortar samples during the spread-flow test, illustrating uniformity and stability across different mix designs.

3.1.2. Flow table spread diameter and its time evolution (continuous mixing)

The effect of continuous mixing on the retention of mortar flowability was assessed to evaluate the mixtures ability to withstand simulated transportation conditions. Following the initial mixing stage, each mixture was maintained at 140 rpm and its spread diameter measured at 15, 30, 45 and 60 min using the same flow-table procedure described previously.

Table 5 and Fig. 9 illustrate the evolution of the spread diameter, normalised to the initial value and after applying the prescribed 15 strokes. Across all mixtures including the control and those incorporating recycled fines, the flowability remained remarkably stable throughout the extended mixing period. No signs of water bleeding, segregation or overflow were observed, and the flow profiles stayed cohesive and uniform at all time intervals, demonstrating excellent retention of workability under simulated transportation conditions.

For all the investigated mixtures, except those made using recycled glass fine (RGF1, RGF2), the continuous mixing for up to 1 h had only a slight influence on the mixtures workability parameters. This confirms that the workability retention capacity of the investigated mixes over a 1-hour hauling time remains unaffected by the partial substitution of recycled fines (RGF), with no negative influence observed from the other investigated fines, as detailed above and further explained below.

In the case of recycled glass fines (RGF1, RGF2) continuous mixing caused a discernible drop in fresh-state performance and handling characteristics of fresh mortar compared to resting conditions. This behavior may be attributed to several specific characteristics of these glass particles, including their high specific surface area acting as seeds for cement hydration, the friction generated by their angularity and specific nature during mixing process, and their inability to absorb water. These factors increase internal friction, raise the temperature, and further accelerate hydration, making the mix progressively drier and less lubricated over longer the mixing time. Additional experiments demonstrated that increasing the superplasticizer dosage from 2% to 2.5% of the binder weight effectively preserved the fluidity characteristics of these mixtures under continuous mixing conditions.

When comparing the workability behavior of the mixture under the two different investigated conditions, respectively denoted as static conditions, where the mixtures were kept at rest for 1 h, and dynamic conditions, where slow continuous mixing occurred for the same duration, it can be observed that, in both cases, the fresh state performance has been similarly maintained despite slight variations. Additionally, the application of mild vibration has increased the spread without causing any visible signs of segregation in either condition. The overall behavior of mixtures when substituting various recycled fines was consistent across most cases, except for mixtures made up using recycled glass fines (RGF1, RGF2), where workability progressively decreased with prolonged mixing time.

The findings above confirm the potential of using various recycled fines as partial cement replacements in the manufacture of cementitious materials while maintaining desired fresh-state performance over a time frame complying with typical hauling and job site operations, encompassing typical circumstances of pouring conditions linked to the transport, installation, and placement on construction sites. For this

Table 5
The variation of the fluidity as a function of mixing time (measurements in mm).

materials/ mixing time		15 min	30 min	45 min	60 min
Control (Cement)	Initial spread	245	240	240	240
	Spread after vibration	285	280	280	280
RF1	Initial spread	250	230	225	220
	Spread after vibration	295	260	255	255
RF2	Initial spread	245	245	240	240
	Spread after vibration	285	280	280	280
RCF	Initial spread	245	240	235	235
	Spread after vibration	280	280	275	270
RGF1	Initial spread	240	230	200	90
	Spread after vibration	270	250	225	100
RGF2	Initial spread	200	215	90	70
	Spread after vibration	230	240	130	75
SF	Initial spread	210	215	220	220
	Spread after vibration	240	245	245	240
RBF	Initial spread	250	240	235	220
	Spread after vibration	280	280	270	250
$R_{UHPC}F$	Initial spread	250	250	250	240
	Spread after vibration	295	290	290	285

purpose, it can be noticed that the use of recycled fines as a cement replacement has proven effective. However, exceptions exist, notably with recycled glass fines (RGF1, RGF2), where adjustments or corrections, such as increasing the super-plasticizer dosage, may be required to counteract negative effects on workability.

3.1.3. *Setting time (VICAT)*

Building on the evaluation of flowability retention, the setting behavior of the mixtures was also assessed to characterise their transition from the fresh to the hardened state. The Vicat test results for all the investigated mixes are shown in Fig. 10.

All the employed recycled fines cause an increase in both initial and final setting times. This result aligns with expectations since the amount of reactive binder content (cement) has been reduced. Exceptions held in the case of the use of recycled concrete fines (RCF) and recycled glass fines 2 (RGF2), since they led to a shorter initial setting time, and in the case of using RGF2, also to a shorter final setting time. In the first case (RCF), the presence of unreacted material in the old interfacial transition zone may provide immediate reactivity. This behavior contrasts with the mixture utilizing RUHPCF, which likely exhibits slower reactivity due to the possible presence of certain components in the parent concrete composition, including different SCMs, which may affect the nature of the recycled fines and their intrinsic characteristics. As for RGF2, its high fineness, higher specific surface area, and capacity to act as a seed for cement hydration previously mentioned in the fresh-state performance might also explain the observed setting time behavior in this case.

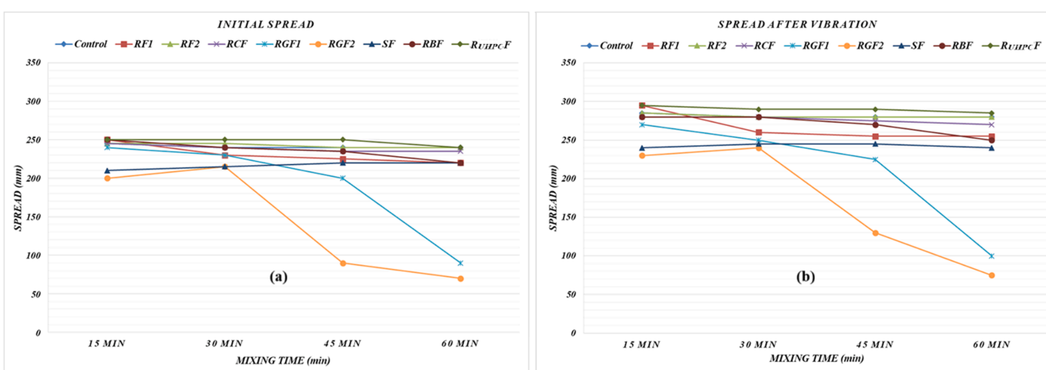
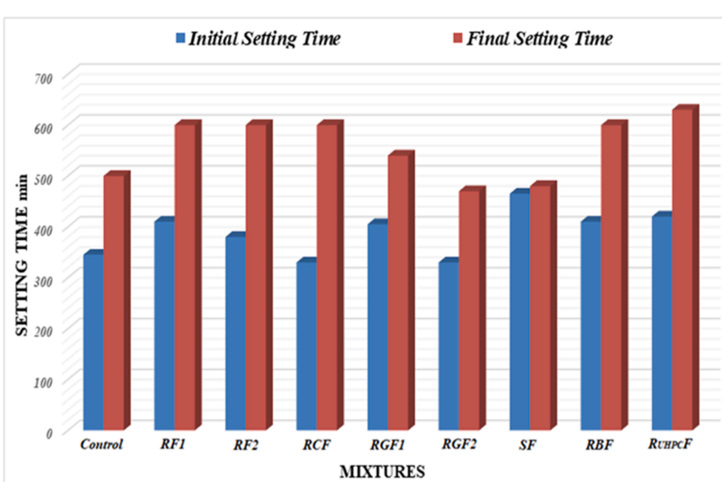


Fig. 9. The variation of the fluidity as a function of continuous mixing time: (a) Initial Spread, (b) Spread by applying vibration (strokes).



Materials	Initial Setting Time	Final Setting Time
Control	5h45mn	8h20mn
RF1	6h50mn	10h00mn
RF2	6h20mn	10h00mn
RCF	5h30mn	10h00mn
RGF1	6h45mn	9h00mn
RGF2	5h30mn	7h50mn
SF	7h45mn	8h00mn
RBF	6h50mn	10h00mn
$R_{UHPC}F$	7h00mn	10h30mn

Fig. 10. Mortar setting time of different mixtures.

3.2. Hardened state properties

After characterizing the fresh-state performance, attention was directed to the hardened properties in order to evaluate how the incorporation of recycled fines affects strength and density.

3.2.1. Compressive strength

The compressive strength values at 28 days for all the investigated mixtures are presented in Fig. 11. The results represent the average of twelve specimens (derived from the broken halves of the six prisms tested in bending) along with the corresponding scatter.

The use of different recycled fines can lead to a moderate reduction in mortar strength; however, these reductions usually remain limited below 10%, and in absolute terms always higher, or very close in the only lower case, to 100 MPa, indicating that the partial substitution of cement by recycled fines maintains acceptable strength levels for the production of high performance cementitious composites. The exception observed in the mix containing RGF2, where the compressive strength reduction reached 20%, may be attributed again to the angularity and high surface area of RGF2 particles, altering the packing density, thus compromising overall strength. In contrast, the mix incorporating silica fume exhibited a slight improvement in compressive strength compared to the reference mix. This quite well known enhancement may be attributed to the ultrafine particles of silica fume, which act as a micro-filler, refining the pore structure and strengthening the cement-aggregate bond, while its pozzolanic reactivity generates additional calcium silicate hydrate. Interestingly, the mix with recycled fines from ultra-high-performance concrete ($R_{UHPC}F$) achieved, among all the recycled fines mixes but the SF one, the value of compressive strength closest to the reference mix, confirming the beneficial effect, in this respect, of residual un-hydrated cement particles in the UHPC recycled fines that further react during the mixture curing.

3.2.2. Flexural strength

In Fig. 12, the flexural strengths results (average of six tests with related scattering) are presented for all the different investigated mixes.

The impact of different recycled fines as partial cement replacements on the flexural strength aligns closely with the trends observed in compressive strength results. Variations in flexural strength remained quite moderate, even insignificant across all mixtures, with only minor deviations in performance and with similar scatterings. The most pronounced reduction was observed in the mix containing recycled glass fines 2 (RGF2), as above, which experienced a flexural strength reduction in the order 10%. Notably, the mix incorporating fines from recycled ultra-high-performance concrete ($R_{UHPC}F$) as a cement substitute exhibited superior flexural performance by around 5% compared to the average results of the others mixtures, the presence of un-hydrated cement in the recycled fines contributing to enhance the paste to aggregate bond which may be ultimately responsible of the observed occurrence.

3.2.3. Mortar density

Finally, the density of the investigated mixtures was measured, and the results are presented in Fig. 13. The use of various recycled fines as partial cement replacements did not significantly affect the overall mortar density, with most mixtures exhibiting values close to the control (2.40 g/cm^3). Notably, as predicted in earlier comments, the RGF2 mixture exhibited the lowest density (2.32 g/cm^3), further reinforcing the consistency and validity of our observations regarding the influence of RGF2 on the overall mortar properties. The incorporation of recycled fines generally resulted in minor reductions in density, particularly for RGF2, which likely stems from its higher porosity and lower bulk density compared to other materials. This can be attributed to the presence of residual organic matter, microvoids, and irregular particle morphology in RGF2, which may hinder optimal particle packing and increase internal void space during compaction. In contrast, RF1 and RF2 showed densities nearly identical to the control, suggesting effective packing and minimal disruption to the matrix structure. Similarly, RCF, RBF, and $R_{UHPC}F$ exhibited only slight deviations, indicating that these materials do not significantly alter the compacted volume of the mortar.

These findings are consistent with the fresh-state behavior observed in previous sections, where RGF2 mixtures demonstrated increased water demand and reduced cohesion, both indicators of higher internal porosity. Lower density in hardened mortar may correlate with increased permeability and reduced compressive strength, highlighting the importance of pre-treatment and dosage optimization when using such materials. However, from a sustainability perspective, the slight reduction in density could be beneficial for lightweight construction applications, provided that long-term durability is maintained.

3.3. Environmental analysis of mixture production

A Life Cycle Assessment (LCA) was performed to evaluate the environmental impact of concrete incorporating waste-derived materials as

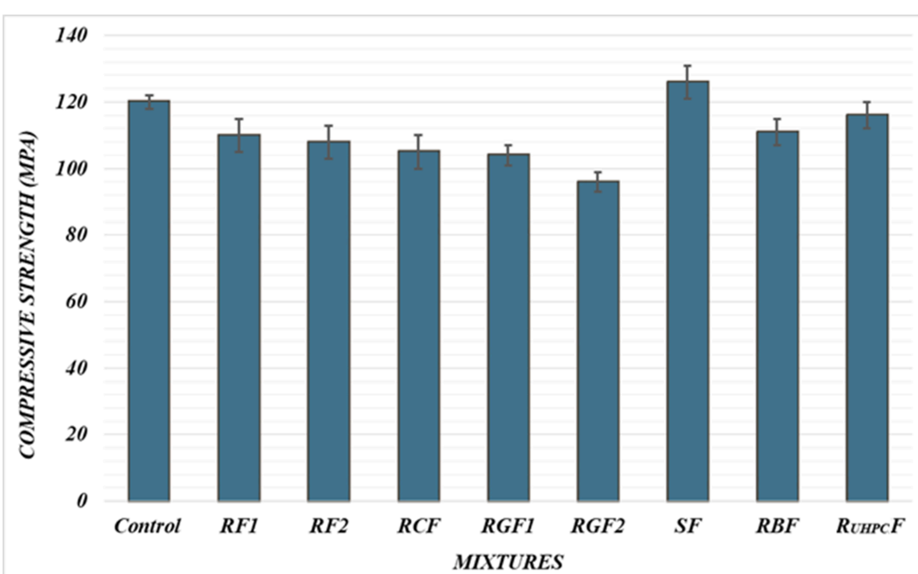
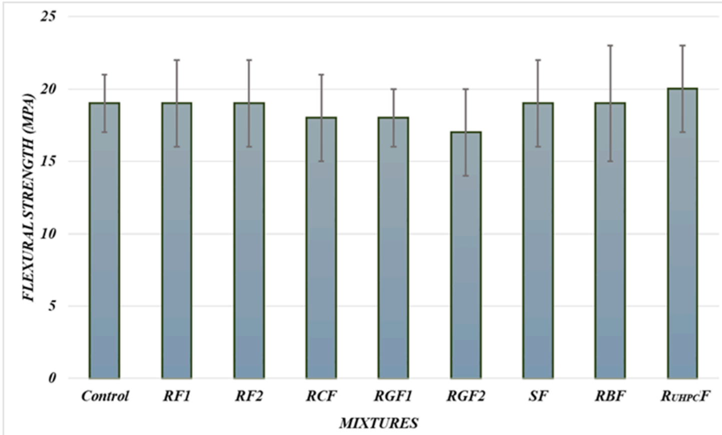


Fig. 11. The 28-days compressive strength for the investigated mixtures.



Mixtures	Flexural Strength (MPa)
Control	19 (±2)
RF1	19 (±3)
RF2	19 (±3)
RCF	18 (±3)
RGF1	18 (±2)
RGF2	17 (±3)
SF	19 (±3)
RBF	19 (±4)
RUHPCF	20 (±3)

Fig. 12. The 28-day flexural strength of the investigated mixtures.

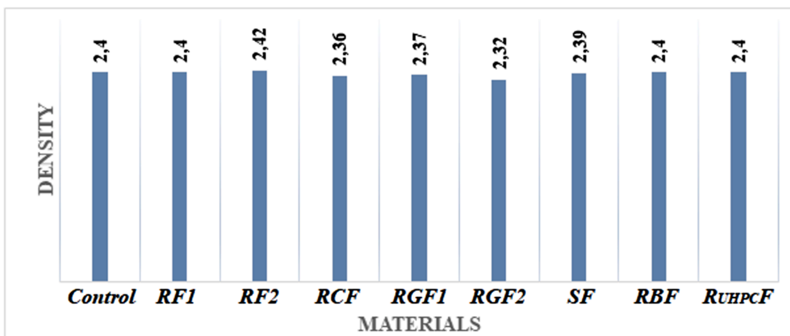


Fig. 13. Density of hardened mortar mixtures incorporating various recycled fines.

partial cement replacements. Although the LCA framework is, in principle, designed to provide a comprehensive evaluation of environmental effects across all stages of a material's life cycle, from raw material extraction to end-of-life, the assessment conducted in this study focuses on cradle-to-gate emissions. In this context, the analysis encompasses the stages from raw material acquisition to concrete production, without extending to the construction use phase or end-of-life scenarios.

The study involved a detailed inventory assessment quantifying inputs and outputs throughout the selected production chain boundaries. The corresponding environmental impacts were then calculated and interpreted within a sustainability-oriented framework, which assumes that high-performance cementitious materials should not only enhance mechanical and durability properties but also make it possible to design thinner structural elements and reduce maintenance needs over their service life, ultimately contributing to lower material consumption. A further objective is to promote the efficient valorisation of recycled materials and support circularity within the construction sector. For cementitious systems such as those developed here to represent genuinely sustainable alternatives, an optimal balance between environmental impact and mechanical performance must be achieved. In particular, the CO_2 savings derived from reducing cement content should not be offset by additional emissions associated with the processing of recycled constituents. Moreover, any decrease in mechanical performance may compromise structural efficiency and limit design optimisation. While the present work does not claim to resolve the complexity of this multi-criteria optimisation, it contributes to advancing the methodological framework by quantifying the embodied carbon footprint of various concrete mixtures incorporating different types of recycled fines. The environmental performance of each mixture was assessed following a consistent cradle-to-gate approach, aligned with ISO 14,040 guidelines, covering raw material extraction, processing, transportation, and concrete production stages. However, it is important to note that the emission factors collected from the literature do not always share identical system boundaries. Most datasets report cradle-to-gate emissions limited to basic material production, meaning that certain upstream processes such as waste collection, on-site sorting, secondary crushing or fine grinding of recycled materials, and internal transport within recycling facilities, may not be fully represented. To ensure methodological consistency, all mixtures were evaluated using the same system boundaries, and the LCA was designed as a comparative assessment rather than an absolute quantification of real-scale emissions. This approach guarantees that relative differences between mixtures remain meaningful and robust, even if some upstream processes are simplified or excluded.

The CO_2 emissions associated with the raw materials used in the investigated concrete formulations including cement, silica fume, recycled fines from construction and demolition waste (CDW), recycled glass fines, natural sand, water, and superplasticizer admixture were quantified in kilograms of CO_2 equivalent per cubic meter of concrete (kg CO_2 eq./m^3). According to the literature, the emission factors of these materials vary considerably, with cement being by far the most CO_2-intensive component. Depending on the cement type, production technology, energy source, and plant efficiency, cement production typically releases 600–950 kg CO_2 per tonne [102,107,110,115–118]. The production of silica fume, by contrast, is considerably less carbon-intensive, with reported emissions ranging between 14 and 30 kg CO_2 per tonne [110,117,118]. Regarding aggregates, the production of natural aggregates emits between 3 and 10 kg CO_2 per tonne [102,110,116–118]. Although the use of recycled aggregates can reduce these emissions by approximately 50%, the overall reduction in the carbon footprint of concrete remains limited since cement production dominates, accounting for more than 80% of total CO_2-equivalent emissions in concrete manufacturing [119,120]. This predominance arises from the clinkerization process, in which limestone decomposition and fossil fuel combustion at temperatures near 1450 °C generate substantial CO_2 emissions [121]. Nevertheless, the use of recycled aggregates can still achieve greenhouse gas reductions of up to 65% compared with natural aggregates, depending on local processing methods and transportation distances [104,122]. The production of recycled aggregates typically generates 3–7.7 kg CO_2 per tonne [101,123], while recycled fines tends to exhibit slightly higher emissions, usually between 5 and 10 kg CO_2 per tonne, due to additional crushing, grinding, and sieving steps [101,105, 124]. Similarly, recycled glass fines have been reported to produce emissions ranging from 7 to 18 kg CO_2 per tonne [110,111]. Finally, the production of chemical admixtures, particularly superplasticizers, is associated with substantially higher emission factors, typically between 1500 and 2500 kg CO_2 per tonne, due to their complex organic synthesis routes and high embodied energy [117,118,124–127].

Based on this data, Table 6 provides a comparative evaluation of the CO_2 emissions for each formulation, highlighting the extent to which partially replacing traditional cement with alternative supplementary materials reduces the overall carbon footprint of the mixtures. The control mixture exhibited the highest carbon emissions, reaching 889.1 kg CO_2 eq./m^3, with cement identified as the dominant contributor, responsible for approximately 94% of the total emissions, while the superplasticizer contributed about 5%. In contrast, mixtures incorporating recycled or supplementary materials demonstrated a noticeable reduction in embodied carbon. The mixture containing silica fume (SF) produced 742.1 kg CO_2/m^3, while those incorporating recycled glass fines (RGF1 and RGF2) yielded 741.4 kg CO_2/m^3. The formulations including recycled fines (RF1, RF2, RFC, and RFB) achieved a slightly lower value of 740 kg CO_2/m^3, corresponding to a reduction of 16.5 to 16.8% relative to the control mixture. The small variation among the different recycled supplementary cementitious materials (SCMs) indicates that all investigated alternatives contribute effectively to lowering the carbon footprint of concrete, with recycled fines providing a marginally higher benefit. These results highlight the environmental potential of integrating industrial by-products and recycled materials into concrete production as a viable strategy for reducing the sector's overall greenhouse-gas emissions.

3.4. Multi-criteria comparison of recycled-fines concrete mixtures

The effects of using different types of recycled fines as a partial replacement for the cement on various performance parameters are illustrated in the diagram shown in Fig. 14. This comparison provides a comprehensive evaluation of how incorporating alternative fines influences key mechanical and environmental properties.

The radar analysis in Fig. 14 provides a comparative visualization of various mortar formulations, illustrating the impact of incorporating different recycled fines as supplementary cementitious materials (SCMs) on key performance indicators, including compressive strength, flexural strength, flowability, density, and CO_2 emissions. The results indicate that the overall performance of the mortar has been maintained. Flowability remained largely unchanged in most cases, except for RGF2 and SF, where a reduction lower than 20% was observed, though the material still exhibited a good workable behavior. In terms of mechanical performance, flexural and compressive strengths remained stable across most formulations, with reductions generally lower than 10%. However, the mix with recycled glass 2 (RGF2) exhibited a more pronounced reduction of up to 20%, while silica fume (SF) contributed to an increase in mechanical properties. Regarding setting time, the behavior tends to be altered, often leading to prolongation and delays in hardening. From an environmental perspective, all mixtures demonstrated significantly lower CO_2 emissions, achieving a reduction of more than 16% compared to the control. Notably, recycled fines present a low-carbon alternative with a negligible CO_2 footprint less than 0.008 kg CO_2/kg; however, their incorporation may lead to a slight decrease in mechanical performance. This highlights the importance of material selection in optimizing sustainable concrete formulations.

By adopting alternative binders incorporating recycled fines, cementitious composites, even ultra-high performance ones, can achieve an effective balance between mechanical performance, workability and ecological responsibility. Among the tested mixtures, those containing recycled fines from CDW, glass or concrete exhibited only moderate reductions in strength, generally limited to about 10% relative to the control, which remains within acceptable limits for high-performance mortar applications; while maintaining satisfactory fresh-state properties. At the same time, the partial replacement of cement with these recycled fines reduced the binder-related CO_2 emissions by 18% compared with the control mix, representing a significant environmental gain. This strategy decreases the demand for virgin raw materials, mitigates the environmental impacts associated with extraction and processing, and promotes waste valorisation in line with circular-economy principles. Collectively, these findings demonstrate that recycled-fines UHPC-type mortars can provide a viable and fairly more sustainable route to high-performance cementitious materials, aligning mechanical reliability with improved environmental credentials. Moving forward, larger-scale trials and extended durability studies will be essential to confirm these benefits and to support the future of genuinely sustainable concrete manufacturing.

4. Integrated formulation and optimization of UHPC mixtures

4.1. UHPC mixture formulation and design strategy

The recycled fines retained for the detailed UHPC mix-design and optimisation phase were selected primarily on the basis of material availability, consistency and representativeness. In this study, sufficiently large and homogeneous quantities of CDW fines and glass fines

Table 6
The comparative analysis of CO_2 emissions in different mixtures.

Materials	CO_2 Emission Factor kg CO_2/kg	Control Mixture		Mixture containing SF		Mixtures containing RF		Mixtures containing RG	
		Quantity kg	Emission kg CO_2	Quantity kg	Emission kg CO_2	Quantity kg	Emission kg CO_2	Quantity kg	Emission kg CO_2
Cement	0.860	975	838.5	800	688.0	800	688.0	800	688.0
SF	0.020	-	-	175	3.50	-	-	-	-
RF	0.008	-	-	-	-	175	1.4	-	-
RG	0.016	-	-	-	-	-	-	175	2.8
Sand	0.006	1095	6.6	1095	6.6	1095	6.6	1095	6.6
Water	0	170	-	170	-	170	-	170	-
Super-plasticizer	2.200	20	44.0	20	44.0	20	44.0	20	44.0
Total CO_2 Emissions kg CO_2/m^3		889.1		742.1		740.0		741.4	

SF: Silica fume (SF), **RF:** Recycled fines 1 (RF1) / Recycled fines 2 (RF2) / Recycled Concrete fines (RCF) / Recycled Bricks fines (RBF)/ Recycled ultra-high performance fines ($R_{UHPC}F$) **RG:** Recycled glass fines 1 (RGF1) / Recycled glass fines 2 (RGF2).

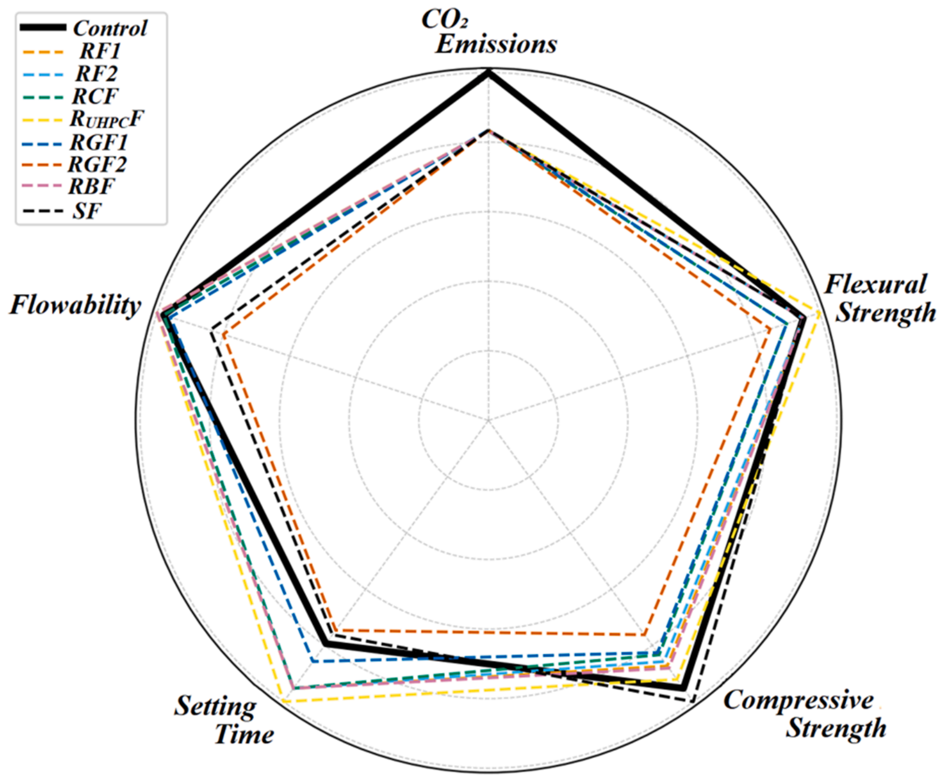


Fig. 14. The key performances comparison of the investigated mortar formulations.

could be sourced under controlled conditions, whereas other potential waste streams were obtainable only in limited amounts or with inconsistent properties. Restricting the experimental programme to these readily available streams ensured reproducible batching, statistically robust testing and meaningful comparisons, while still capturing the fine fractions most commonly generated by current construction and demolition practices. This pragmatic selection reflects logistical constraints rather than any prescriptive judgement on the suitability of other recycled fines, which remain of interest for future investigation once reliable supply chains are established.

4.1.1. UHPC mix design approach

Expanding on the previously studied mortar formulation, further testing and up-scaling efforts were undertaken to produce reinforced fibre UHPC mixes. The same original matrix mortar formulation was retained with a few adjustments made through the incorporation of micro steel fibers (10 mm length, 0.20 mm diameter) at a proportion of 160 kg/m^3, equal to about 2% by volume. The implemented mix-design adjustment aligns with the equivalent specific surface diameter concept proposed by Ferrara et al. [58], which optimizes the solid skeleton while mitigating the potential adverse effects of fibre inclusion. To address the problem of the significant amount of air bubbles present inside and on the surface of mortar specimens, an air-reducing admixture was introduced to eliminate entrapped air within the concrete mixture, with beneficial effects illustrated in Fig. 15. A little dose of air-trapped admixture proved sufficient to significantly reduce air content, as confirmed by the comparison between specimens with and without the admixture, shown in Fig. 15(a) and (b), respectively. Additionally, to overcome the challenges associated with fibre addition, the super-plasticizer dosage was slightly increased to counteract the workability loss and reduced fluidity associated with the addition of steel fibers. Table 7 reports the detailed mix proportions used to produce the fiber-reinforced UHPC investigated in this study, with details on the incorporated recycled fines.

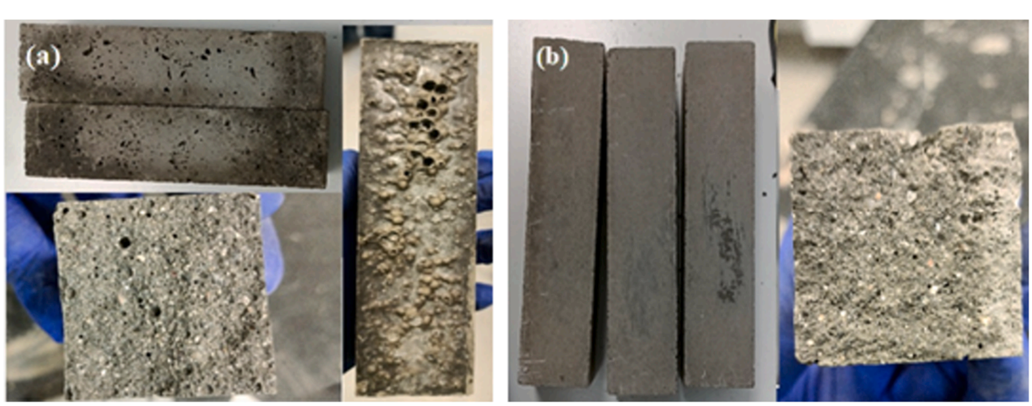


Fig. 15. Mortars specimens: a) before using trapped air admixture, b) after using trapped air admixture.

Table 7
Mix-designs of investigated UHPC mixes.

Constituent	Quantity (kg/m^3)	
	Control formulation	*SCM Formulation*
Cement	975	800
SCM (Recycled Fines)	-	175
Sand Coarse	225	225
Sand 0.8	565	565
Sand 0.4	305	305
Water	170	170
Super-plasticizer	25	25
Air-Reducer Admixture	4	4
Steel Fibers	160	160

SCM (Recycled Fines**):** Silica fume (SF), Recycled fines 1 (RF1), Recycled fines 2 (RF2), Recycled glass fines 1 (RGF1), and Recycled glass fines 2 (RGF2).

4.1.2. Evaluation of fresh-state properties

Table 8 summarizes the values slump flow diameter, measured using the inverted Abram's cone method, and the air content values measured using the air content meter for the investigated fibre-reinforced UHPC mixes.

The air content in the different UHPC mixes ranged from approximately 2.6% to 3.1%, which is excellent for concrete mixes, indicating a dense matrix which may be suitable for demanding applications. A slight increase in air content was observed with the incorporation of various recycled fines, though this change was minimal and did not affect the concrete performance. Notably, the preliminary mix prepared without the air-reducing admixture exhibited around 7% occluded air, highlighting the importance of the employed deairing admixture in controlling air content. Furthermore, concerning the workability results, all UHPC mixtures displayed high fluidity, remaining within the range expected for self-compacting concretes. The control formulation achieved a spread of approximately 790 mm, while mixtures incorporating various recycled fines as partial cement replacements showed insignificant effect on the concrete spread. A more pronounced decrease (about 7%) was observed with silica fume, attributable to its very high fineness and specific surface area, which increases water demand and slightly thickens the mix without compromising its self-compacting and self-levelling behaviour.

Visual inspection confirmed that all UHPC mixtures exhibits a high degree of homogeneity, with no visible signs of segregation, including the proper dispersion of fibers throughout the matrix, as shown in Fig. 16. This uniform distribution indicates the effectiveness of the adopted mixing procedure and formulation adjustments, such as the use of super-plasticizers and air-reducing admixtures in achieving a cohesive, highly workable UHPC. Moreover, despite fibre inclusion, the fluidity remained uncompromised, consistent with trends reported for fibre-reinforced high-performance concretes and confirming the robustness of the adopted fibre-inclusion method [58].

All slump-flow tests shown in Fig. 16 were conducted under identical conditions to ensure comparability. The mixtures were tested immediately after mixing at 20 ± 2 °C using the EN 12,350–8 procedure on a flat steel plate without vibration. The same cone dimensions, lifting time and measuring protocol were applied to both the control and recycled-fines UHPC mixtures. This uniform testing framework ensures that the differences observed in the spread profiles result solely from the material composition rather than variations in testing conditions.

Table 8
Trapped and slump-flow diameter of investigated UHPC mixes.

Formulation	Trapped air%	Slump flow diameter mm
Control	-	790
Silica fume (SF)	2.6	730
Recycled fines 1 (RF1)	3.1	780
Recycled fines 2 (RF2)	2.9	800
Recycled glass fines 1 (RGF1)	2.7	790
Recycled glass fines 2 (RGF2)	2.9	770

4.1.3. Assessment of hardened-state properties (Compressive strength)

Table 9 summarises the 28-day compressive strength values of the investigated fibre-reinforced UHPC mixes prepared with various recycled fines as partial cement replacements. The analysis of compressive strength results indicate that all mixtures achieved highly satisfactory performance across all concrete specimens, even considering the fact that the control mixture's achieved an impressive strength of approximately 133 MPa.

Among the tested formulations, the mix containing silica fume exhibited the highest performance, showing a strength increase of about 10% compared with the control. This improvement can be attributed to the high pozzolanic reactivity and microfiller effect of silica fume, which densifies the matrix and enhances its load-bearing capacity. In contrast, the partial replacement of cement with recycled fines led to moderate strength reductions; however, these decreases generally remained within an acceptable range (≤10% for most mixes). Only the mixture containing recycled glass fines 2 (RGF2) showed a larger reduction (~16%), likely due to its specific particle morphology and surface characteristics, which may slightly reduce packing density and bonding efficiency, thus introducing local stress concentrations under load.

Accordingly, despite these reductions, the overall performance of UHPC mixes manufactured with an equivalent binder made up by using recycled fines confirms the feasibility and efficiency of partially replacing cement with recycled materials, since with wise implementation; this approach may preserve key characteristics such as workability and compressive strength at promising levels for UHPC structural applications. These findings align with the preliminary mortar tests, confirming that recycled fines can effectively replace cement without compromising critical properties like strength and fluidity, even for demanding applications. This process demonstrates the potential to reduce cement usage sustainably while maintaining the performance of UHPC. With proper mix design adjustments, including admixtures and steel fibers, high-performance concrete can retain effectively its structural integrity and meet stringent performance criteria.

4.2. Optimisation

Building on the experimental results, a multi-objective optimization was performed to balance mechanical performance, cement reduction, and environmental sustainability. The observed reductions in compressive strength from partial cement substitution, although generally within acceptable ranges, could limit compliance with certain performance standards [128]. To address this, the optimization focused on the following explicit objectives: first, enhancing and maximizing compressive strength to maintain UHPC-level performance, ensuring that the optimized mix matches or surpasses the control formulation; second, minimizing cement content to reduce material consumption and support sustainable production; and finally, minimizing cradle-to-gate CO_2 emissions to further improve the environmental footprint of the mixture.

Formally, the mixture proportions were defined as a decision vector:

$$x = [x_c,\ x_r,\ x_s,\ w/b\ ,\ f,\ a\ ] \quad (1)$$

Where: x_c = Cement Content; x_r = Recycled Fines; x_s = Silica Fume; w/b = Water-to-Binder Ratio; f = Steel Fibre Content; a = Super-plasticiser Dosage.

The optimization objectives were expressed mathematically as:

$$\min J_1(x) = x_c,\ min\ J_2(x) = -f_c(x),\ min\ J_3(x) = CO_2(x) \quad (2)$$

Where each objective represents a key aspect of UHPC optimization:

$J_1(x)$: *Compressive Strength,* which is maximized to ensure the optimized UHPC mix matches or surpasses the performance of the reference control mix.

$J_2(x)$: *Cement Content,* which is minimized to reduce material

Fig. 16. Slump flow tests images of investigated UHPC mixes highlighting self-levelling behavior.

Table 9
The 28-days compressive strength of fibre-reinforced UHPC incorporating recycled fines as partial cement replacements.

Formulation	Compressive strength (MPa)
Control	133 *(± 5)*
Silica fume (SF)	147 *(± 3)*
Recycled fines 1 (RF1)	121 *(± 2)*
Recycled fines 2 (RF2)	120 *(± 3)*
Recycled glass fines 1 (RGF1)	119 *(± 3)*
Recycled glass fines 2 (RGF2)	111 *(± 2)*

consumption and environmental impact.

$J_3(x)$: *Cradle-To-Gate CO_2 Emissions,* which is minimized to improve the environmental footprint of the mixture.

Together, these objectives define a multi-objective optimization problem aimed at identifying mixture proportions x that simultaneously maximize compressive strength, minimize cement content, and reduce cradle-to-gate CO_2 emissions, while satisfying practical constraints such as workability, air content, and minimum strength requirements.

The optimization procedure systematically adjusted mixture proportions by progressively reducing cement and replacing it with recycled fines and silica fume, while maintaining a constant water-to-binder ratio and superplasticiser dosage. Each formulation was evaluated in terms of fresh-state properties, compressive strength, and CO_2 emissions. To quantify the combined mechanical and environmental performance, a performance-based environmental efficiency index, defined as compressive strength per unit CO_2 (MPa per kg CO_2/m^3), was calculated, enabling the identification of optimized formulations that achieve a balanced trade-off between high mechanical performance and low environmental impact.

The resulting optimal mix (cement 625 kg/m^3, silica fume 175 kg/m^3, recycled fines 175 kg/m^3) reduced cement content by 36% compared with the control (975 kg/m^3), while preserving or slightly exceeding the reference compressive strength (133 MPa). This substitution also resulted in a substantial reduction in CO_2 emissions and a clear improvement in performance-based environmental efficiency, demonstrating the effectiveness of the multi-objective optimization in achieving both sustainability and structural performance goals.

4.2.1. Optimised mix design

Table 10 provides detailed information on the optimized mix-design formulations which consistently include a fixed portion of silica fume, while an additional and equal portion of cement is replaced with various recycled fines.

Table 10
Optimised UHPC mixture formulation.

Constituent	Quantity (kg/m^3) *Optimised Formulations*
Cement	625
Silica fume SF	175
SCM (Recycled Fines)	175
Sand Coarse	225
Sand 0.8	565
Sand 0.4	305
Water	170
Super-plasticizer	25
Air-Reducer Admixture	4
Steel Fibers	160

SCM (Recycled Fines**):** Recycled fines 1 (RF1), Recycled fines 2 (RF2), Recycled glass fines 1 (RGF1),
and Recycled glass fines 2 (RGF2).

4.2.2. Fresh state properties of optimized UHPC mixes

The results of the fresh-state performance parameters, including slump flow diameter and air content, for the optimized UHPC formulations are summarized in Table 11. Upon analysing the results, it is noteworthy that the air content in UHPC increased from approximately 2.6% in the formulation containing silica fume SF to a range of 3.4%–4.0% in the case of the other optimized mixtures. Although this change is perceptible, the air content remained well within the acceptable range for concrete, ensuring material durability and overall performance. Regarding workability, the variations in slump flow diameter reveal that the optimized mixtures maintained always a high fluidity, moderately exceeding the levels achieved in the silica fume formulation. Notably, the mixtures fell within the extended range of self-compacting concrete, demonstrating excellent workability while maintaining excellent homogeneity, with no visible signs of segregation or other stability issues. The results also highlight the effectiveness of the optimization process, confirming that through a judicious selection and combination of

Table 11
The occluded air and the spreading of concrete optimisation mixture.

Formulation	Trapped air (%)	Slump flow diameter (mm)
Control	-	790
Silica Fume (SF)	2.6	730
Recycled Fines 1 + Silica Fume (RF1 + SF)	3.4	790
Recycled Fines 2 + Silica Fume (RF2 + SF)	3.5	790
Recycled Glass Fines 1 + Silica Fume (RGF1 + SF)	3.9	770
Recycled Glass Fines 2 + Silica Fume (RGF 2 + SF)	4.0	770

materials, it is possible to preserve critical parameters such as workability. This ensures the practical applicability of the mixes while meeting stringent construction requirements and supporting high-performance concrete applications.

4.2.3. Hardened state properties of optimized UHPC mixes (Compressive strength)

Similarly, the various blending of recycled fines with silica fume was assessed by examining the hardened state properties of the optimized mixtures, specifically through the evaluation of compressive strength. The results of this analysis are presented in Table 12.

Compressive strength values for the optimized mixtures reveals an evident improvement, when comparing the companion UHPC mixes with recycled fines only replacing cement to the optimized UHPC. The optimization process, which incorporates silica fume and recycled fines as a binary replacement of cement, results into a notable reduction of approximately 36% in total cement dosage, accompanied by a similar if not higher compressive strength at constant fresh state performance. This makes the use of the optimized mixtures advantageous on multiple fronts. From a performance perspective, they maintain comparable workability while achieving superior strength. Economically, the partial replacement of cement with recycled materials available at significantly lower costs may reduce the overall costs. Environmentally, this approach mitigates the adverse impact of cement production, a major contributor to greenhouse gas emissions, and promotes the reuse of inert waste materials, reducing harm to nature and surrounding ecosystems.

4.3. Environmental analysis

To substantiate this statement, the environmental impact of the investigated UHPC formulations has been assessed and quantified by calculating the CO_2 emissions associated with each constituent. A cradle-to-gate approach was adopted, encompassing emissions from raw material extraction through basic processing, as detailed in Section 3.3. To provide a more functionally meaningful evaluation, environmental efficiency was additionally assessed by normalizing embodied CO_2 emissions by the 28-day compressive strength (kg CO_2 per MPa·m^3). This performance-based indicator reflects the amount of CO_2 required to generate one unit of mechanical performance, offering a practical metric for comparing mixtures that differ in both environmental impacts and strength development.

From the analysis of Table 13, it can be observed that cement remains the dominant source of embodied carbon, accounting for approximately 60% of total emissions per cubic meter. Steel fibers constitute the second major contributor, representing nearly 32% (288 kg CO_2/m^3). These findings underscore the need for UHPC formulations capable of achieving high mechanical performance while incorporating reduced cement contents, and highlight the necessity of carefully assessing and optimizing steel fiber dosage to enhance UHPC sustainability while preserving mechanical performance. The results also highlight the reductions achieved by incorporating alternative cementitious materials. The UHPC control mix exhibited the highest embodied carbon, reaching 1194.1 kg CO_2/m^3. By reducing cement content by approximately 18% through the individual incorporation of recycled fines (SF, RF1, RF2, RGF1, and RGF2) led to average CO_2 reductions exceeding 12%, confirming the potential effectiveness of both industrial by-products and recycled fines in lowering the carbon footprint of UHPC production. However, when performance-based environmental efficiency is considered, the results become more nuanced. The findings reveal that, apart from the UHPC mix incorporating silica fume which enhanced both emissions reduction and mechanical strength, the mixes containing recycled fines, despite achieving comparable CO_2 reductions of about 12%, were concurrently associated with decreased mechanical performance. This trade-off translates into only a moderate advantage in terms of performance-based environmental efficiency, and in some cases, such as RGF2, even a disadvantage. These observations demonstrate that reductions in emissions per cubic meter do not necessarily translate into improved performance-based environmental efficiency, and emphasize the need for metrics that account for both environmental impact and mechanical response.

Table 12
28-days compressive strength of optimized mixtures.

Formulation	Compressive strength (MPa)
Control	133 *(± 5)*
Silica Fume (SF)	147 *(± 3)*
Recycled Fines 1 + Silica Fume (RF1 + SF)	143 *(± 3)*
Recycled Fines 2 + Silica Fume (RF2 + SF)	141 *(± 4)*
Recycled Glass Fines 1 + Silica Fume (RGF1 + SF)	135 *(± 4)*
Recycled Glass Fines 2 + Silica Fume (RGF2 + SF)	130 *(±3)*

This limitation motivated the adoption of an optimization strategy combining silica fume with recycled fines. The hybrid SF + RF system produced the most substantial CO_2 reduction, with embodied carbon decreasing to 898.0 kg CO_2/m^3, corresponding to nearly 25% reduction relative to the control. More importantly, the performance based environmental efficiency of this optimized mixture improved markedly, while the control UHPC required 8.98 kg CO_2/MPa·m^3, the hybrid SF + RF mixture required only 6.32 kg CO_2/MPa·m^3, representing an improvement of more than 29%. A similar trend was observed for the SF + RGF blend, which reached 6.79 kg CO_2/MPa·m^3, an improvement of more than 24% and superior to the case where silica fume was used alone (7.12 kg CO_2/MPa·m^3, around 20% improvement). These outcomes clearly demonstrate the synergistic effects of multi-component SCM systems, where combining industrial by-products with recycled fines yields benefits that surpass those of single-source replacements. The optimized hybrid mixtures therefore not only reduce embodied carbon more effectively but also deliver higher mechanical efficiency.

5. Discussions

The advancement of urbanization is accelerating the shift toward circular construction, where the recovery and valorisation of waste resources play a central role. A key challenge in this transition is not merely maximizing substitution rates, but identifying meaningful and technically viable thresholds that preserve or even enhance material performance prevalent [129]. In this context, the present study demonstrates that ultra-high-performance cementitious composites can successfully incorporate diverse recycled fines, including construction and demolition waste, recycled concrete, brick debris, and glass waste. Their integration through a careful and judicious incorporation approach ensured that mixture stability and fresh-state behavior remained uncompromised, and in several cases yielded improvements in mechanical response when materials were selected and proportioned through an optimization approach. These results confirm the feasibility of valorising heterogeneous waste streams within high-performance matrices, supporting sustainability goals while maintaining structural reliability.

A major contribution of this work is the identification of efficient strategies for reusing waste fines while ensuring optimal UHPC performance, together with a combined environmental mechanical evaluation that reveals how recycled and optimized mixtures can simultaneously reduce embodied carbon and maintain structural reliability. The cradle-to-gate assessment confirms that cement is the primary driver of embodied carbon accounting for roughly 60% of emissions per cubic metre, followed by steel fibres at approximately 32%. These findings highlight the necessity of designing UHPC mixtures that achieve target mechanical performance with significantly reduced cement contents and carefully optimized fibre dosages [130]. Incorporating recycled

Table 13
CO_2 emissions assessment of UHPC formulations incorporating recycled materials.

Material	Emission Factor kg CO_2/kg	Emission kg CO_2					
		Control	UHPC Mixes			Optimized UHPC	
			SF	RF	RGF	SF+RF	SF+RGF
Cement	*0.860*	838.5	688.0	688.0	688.0	537.5	537.5
SF	*0.020*	-	3.5	-	-	3.5	3.5
RF	*0.008*	-	-	1.4	-	1.4	-
RG	*0.016*	-	-	-	2.8	-	2.8
Sand	*0.006*	6.6	6.6	6.6	6.6	6.6	6.6
Water	*0*	0	0	0	0	0	0
Super-plasticizer	*2.200*	55.0	55.0	55.0	55.0	55.0	55.0
Air-Reducer	*1.500*	6.0	6.0	6.0	6.0	6.0	6.0
Steel Fibers	*1.800*	288.0	288.0	288.0	288.0	288.0	288.0
Total CO_2 Emissions kg CO_2/m^3		1194.1	1047.1	1045.0	1046.4	898.0	899.4
Réduction%		-	12.31%	12.49%	12.37%	24.80%	24.68%
Performance-Based Environmental Efficiency kg CO_2/ MPa.m^3		8.98	7.12	8.70	9.10	6.32	6.79

SF: Silica fume (SF), **RF:** Recycled fines 1 (RF1) / Recycled fines 2 (RF2), **RG:** Recycled glass fines 1 (RGF1) / Recycled glass fines 2 (RGF2).

fines proved highly effective in this regard, since the cement demand decreased substantially, yielding CO_2 reductions above 12% for mixtures with 18% substitution and approaching 25% when mixture optimization were applied allowing around 36% substitution. Optimized formulations by combining silica fume with recycled fines from CDW delivered more than a 29% gain in performance-based environmental efficiency, and over 24% in the case of recycled glass fines, without compromising, and in some cases exceeding, the strength of the reference UHPC. These findings clearly demonstrate the value of multi-component SCM optimisation as a pathway toward next-generation, low-carbon cementitious binders.

Beyond environmental gains, the enhanced mechanical efficiency of optimized mixtures has direct structural implications. Increased strength-to-emission ratios enable reductions in cross-sectional dimensions and overall material consumption in structural elements, translating into additional carbon savings at the structural scale. Furthermore, the improved matrix compactness and reduced entrapped air content observed in optimized mixtures are expected to enhance durability in the uncracked state, potentially prolonging service life and reducing maintenance and replacement demands. These long-term benefits amplify the sustainability advantages of UHPC incorporating recycled fines, extending their relevance well beyond the material level [131–135]. While the environmental model adopted here is based on cradle-to-gate emission factors and does not fully capture upstream processes such as waste transportation or grinding energy, the comparative conclusions remain valid given the consistent boundary conditions applied across all mixtures. Future research should refine this framework by integrating detailed transport scenarios, energy consumption for fine grinding, and the carbonation potential of recycled fines, which may further improve their net environmental contribution. Incorporating durability-driven metrics alongside environmental–mechanical indicators will also be essential for defining reliable substitution thresholds and ensuring long-term structural performance.

Overall, the results of this study demonstrate that the valorisation of recycled fines in UHPC presents one of the most effective strategies for producing high-performance concrete with substantially lower environmental impact. By reducing reliance on virgin raw materials, minimizing clinker content, diverting waste from landfills, and delivering competitive mechanical and durability performance, optimized hybrid UHPC systems emerge as promising candidates for next-generation low-carbon structural materials aligned with circular construction principles.

Future work will focus on durability tests (e.g., freeze–thaw, chloride penetration), real-scale validation, and enhancement of fines reactivity through chemical or thermal activation. Advanced microstructural analyses, such as 4D X-ray CT and Digital Volume Correlation, will be used to better understand interfacial zones, pore structure, and energy dissipation mechanisms. Sensitivity analyses considering processing energy, transport, and carbonation potential will further refine the environmental assessment and support optimized, low-carbon UHPC design.

6. Conclusions

This study demonstrates that fine fractions derived from construction and demolition waste, recycled concrete, brick debris, and waste glass can be effectively valorised as partial cement replacements in ultra-high-performance cementitious composites. Based on the experimental and analytical results, the following key conclusions are drawn:

(1) Recycled fines proved suitable as supplementary cementitious materials, maintaining mixture stability and homogeneity at substitution levels up to ~18%.
(2) UHPC mixtures incorporating recycled fines consistently preserved high fluidity, self-levelling behaviour, and resistance to segregation, even under weak vibration and simulated delays and transport periods of up to one hour, demonstrating that their fresh-state performance remains fully robust and operationally reliable.
(3) The incorporation of recycled fines typically resulted in delayed setting times and a slight increase in entrapped air, effects that can be effectively controlled through appropriate admixture strategies.
(4) Substitution of cement with recycled fines at levels up to 18% resulted in strength reductions of approximately 10%, while UHPC mixtures still achieved high compressive strengths. The control reached around 133 MPa, and strength losses in substituted mixtures were generally limited to within 10%.
(5) The optimization strategy combining recycled fines with silica fume enabled a 36% reduction in cement content while fully preserving concrete performance and, in some cases, exceeding the compressive strength of UHPC control.
(6) Replacing 18% of cement with recycled fines reduced total CO_2 emissions by over 12%, given that cement accounts for roughly 60% of cradle-to-gate emissions.
(7) Optimized UHPC mixtures, combining recycled fines with silica fume and replacing 36% of cement, nearly doubled the reduction, achieving almost 25% lower CO_2 emissions while maintaining or even enhancing performances.
(8) Performance-based environmental indicators showed that recycled fines from construction and demolition waste increased CO_2 efficiency per unit of strength by more than 29%, while recycled glass fines improved it by 24%. The optimized UHPC mixtures

achieved the best balance of low emissions and high mechanical performance.

These results demonstrate that recycled-fines-based UHPC offers a practical, high-performance, and sustainable pathway toward next-generation low-carbon construction, aligning circular economy principles with structural excellence.

CRediT authorship contribution statement

Oussama Douidi: Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Ahmed Tafraoui:** Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Pedro Serna:** Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abdelkadir Makani:** Visualization, Supervision, Project administration, Methodology, Investigation. **Liberato Ferrara:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Oussama Douidi reports financial support was provided by Directorate General for Scientific Research and Technological Development (D.G.R.S.D.T., Algeria). Liberato Ferrara reports financial support and article publishing charges were provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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