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Preliminary study on the fresh and mechanical properties of UHPC made with recycled UHPC aggregates

Marta Roig-Flores[a], Ruben Paul Borg[b], Cecilia Ruiz-Muñoz[a], Eduardo J. Mezquida-Alcaraz[a], Ester Giménez-Carbó[a], Albany Milena Lozano Násner[b] and Pedro Serna[a]

[a]Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, Valencia, Spain; [b]Faculty for the Built Environment, University of Malta, Msida, Malta

ABSTRACT

The recycling of construction and demolition waste material reduces disposal of material and also the consumption of resources, therefore promoting sustainability in construction. Ultra-high performance concrete (UHPC) is a relatively new material and its feasibility to be recycled needs to be verified. This work investigates the recyclability of UHPC disposed elements, including the production of recycled aggregates and fibres from UHPC. The feasibility of recycled aggregates and fibres at different replacement rates was evaluated through the assessment of rheological and mechanical properties of the newly produced UHPC elements. Concrete mixes with replacement of aggregates at 50% and 100%, displayed compression strength comparable to original UHPC, maintaining the original deflection-hardening response. However, their workability was slightly reduced when increasing the content of the recycled material. Mixes with recycled fibres experienced residual strength losses and behaved as deflection-softening materials in the case of complete replacement.

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Concrete; recycling; UHPC; workability; mechanical properties

1. Introduction

Ultra-high performance concrete (UHPC) is a special type of concrete with high compressive strength (around 140–200 MPa) and tensile strength (around 7–15 MPa), self-compacting properties and a ductile post-crack behaviour produced by high fibre contents (Yoo & Banthia, 2016). UHPCs are also characterised by excellent durability properties, including extremely low water permeability. UHPC composition includes high contents of binder (total binder content around 1000 kg/m^3), usually cement and silica fume, but often containing slags as well as a high content of steel fibres, which can range from 80 to 160 kg/m^3 or even higher.

At first glance, UHPC seems not environmentally friendly when compared to traditional concrete. However, due to its excellent mechanical and durability properties, the total volume of concrete needed can be significantly reduced when using a structural design adapted to the material properties. As a rule of thumb, around four times less volume of UHPC is needed than traditional concrete if the design is adapted to its properties (Serna et al., 2014), and then, less raw materials are needed. That means that UHPC is not necessarily more aggressive towards the environment than traditional concrete. However, both, traditional reinforced concrete and UHPCs use high contents of cement, aggregates, and steel, all of them with high environmental impact.

CONTACT Marta Roig-Flores marroifl@upv.es, roigma@uji.es Dpt. of Mechanical and Engineering Construction, Universitat Jaume I, Av. Vicent Sos Baynat, Castelló de la Plana, s/n 12071, Spain.

The UNEP Global Environmental Alert Service (GEAS) highlighted that sand and gravel are 'the largest volume of solid material extracted globally' (United Nations Environment Program [UNEP], 2014), which impacts natural ecosystems. In 2012, the consumption of aggregates was estimated to be >40 billion metric tonnes (Gt) a year, from where 25.9–29.6 billion tonnes corresponded to the building industry (UNEP, 2014). The consumption of aggregates in the building industry increased to 28.7–32.8 billion tonnes in 2017 (UNEP, 2019). In 2019, 50 billion tonnes of aggregates per year were needed, which made up an average of 18 kg per person per day (UNEP, 2019).

One of the ways proposed by UNEP to reduce the consumption of sand and gravel is the use of recycled or manufactured aggregates. In 2011, the report of the European Commission DG ENV 'Task 2 –Management of C&D waste' (Arcadis, BIO Intelligence Service, n.d.) estimated that, in the EU-27, the production of new concrete structures could potentially absorb up to 135 million tonnes (Mt) of recycled aggregates (i.e. 40–50% of waste concrete), considering that 10% of the concrete mix contained recycled aggregates.

The UNEP defines Recycled Aggregates as 'crushed rock, sand and gravels produced by sorting, crushing and screening of construction and demolition materials' and Manufactured Aggregates as 'crushed rock, sand and gravels substitutes produced from wastes from other industries' (UNEP, 2019).

The use of recycled or manufactured aggregates in UHPC has not been extensively investigated since UHPC is a relatively new material, and it requires good quality constituent materials in order to attain its excellent properties.

Most of the research about the use of recycled aggregates has focussed on traditional concrete types. Results published indicate that concretes produced with a high (or total) replacement of natural aggregates by recycled aggregates have generally lower workability (Etxeberria et al., 2007), lower compressive strength, and often form weak Interfacial Transition Zones (ITZ) (Yue et al., 2020), if compared with concrete produced with natural aggregates.

Nevertheless, recycled aggregates are being used worldwide in several civil engineering works. In Germany, around 87% of the excavated material (∼186 million tonnes) and 70% of construction waste (∼51 million tonnes) are recovered (Federal Ministry for the Environment, n.d.). Similarly, in the Netherlands and Denmark, 80% of the demolition waste is recycled, and the use is also increasing in Great Britain, where 10% of the aggregates used are recycled (Collins, 2003; Oikonomou, 2005). The percentages of aggregate replacement used in these countries are frequently between 20% and 40% since these values practically do not affect concrete fresh or hardened properties (Oikonomou, 2005). Despite its potential, the construction and demolition waste recovery rates are still lower than 50% in other countries (Tam et al., 2018), such as Brazil, China, Spain or the USA, among others. One factor that may be delaying the introduction of recycled aggregates in more construction works is the fact that in many concrete codes, recycled aggregates are often only allowed in their coarse fraction (>4 mm), or for non-structural applications (Tam et al., 2018). Other countries such as China and Japan have preliminary technical standards for recycled fine aggregates (Xiao, n.d.).

However, recycled aggregates have good potential to be used in high-strength, and high-performance structural concretes, ensuring proper mix design and quality control (Shayan & Xu, 2003). High-strength concrete (50–80 MPa) mixes with high contents of coarse recycled aggregates can be used in a wide range of applications, showing similar mechanical and durability properties to comparable mixes with natural aggregates (Limbachiya et al., 2000). The incorporation of recycled fine aggregates at replacements of 25% and 50% by mass in mixes with w/c ratios of 0.25 has shown some reductions in compressive strength (8–11% reduction) and in tensile strength (2–6%), when compared to their reference mix (Savva et al., 2021).

Since UHPC is composed of aggregates of small particle size (usually below 4 mm), recycled aggregates to produce new UHPC need to be in a similar size range. The replacement rates referred to in literature addressing the feasibility of recycled aggregates in UHPC cover values from 20% to 100% (Yu et al., 2019; Zhang et al., 2018), reporting reasonably good results. One study (Zhang et al., 2018) showed that increasing the replacement rates led a decrease in workability and compression strength, as well as to more ITZs in UHPC (weak points), and increased content of the old cement matrix. However, the mix with 100% replacement rate was still able to reach 140 MPa when subjected to autoclave curing and around 110 MPa in standard curing. Another study (Yu et al., 2019) used recycled aggregate with particle size between 0.06 and 5 mm obtained from a concrete dam to produce new UHPC. In that work, UHPC with recycled aggregates achieved practically the same compressive strength as for UHPC with natural

Table 1. Composition of original UHPCs.

Materials (kg/m^3)	Original UHPC Type A	Original UHPC Type B
CEM I 52.5	700	–
CEM I 42.5 R-SR	–	800
Microsilica	400	175
Natural sand (blend of 117/F, 103, 113)	817	–
Medium silica sand — 0.8 mm	–	Variable
Small silica sand — 0.4 mm	–	Variable
Silica flour	–	Variable
Water	231	Variable
Superplasticiser 1	64	–
Superplasticizer 2	–	Variable
Short steel fibres (13/0.2)	160	Variable
CA (Penetron)	5.6	Variable

aggregates. Regarding tensile and flexural strengths, UHPC with 40–60% replacement levels reached the best results, but all the mixes reached reasonably good strength.

Additionally, UHPCs have very high binder contents and low w/b ratio, and thus, after hydration, their matrices still have a considerably high amount of un-hydrated particles. Because that, recycled UHPC with very small particle size has also been proposed to replace cement and aggregates at the same time. This option was investigated (Wang et al., 2019), using recycled aggregates having a maximum size of 0.6 mm to substitute cement and sand. That study reported that the introduction of recycled aggregates increased the plastic viscosity of UHPC (due to the high absorption of the recycled aggregate) and reduced slump flow. Other properties that experienced some changes were early hydration process due to a nucleation effect, improved ITZ and capillary pores, which were altered by the inclusion of recycled particles (Wang et al., 2019).

In the case of manufactured aggregates obtained from other industries, promising results have been reported as well. Recycled aggregates obtained from the stone crushing or polishing industries (Yang et al., 2020), or from glass industry (Mousa et al., 2018; Soliman & Tagnit-Hamou, 2017), composed mainly of powder with calcite- or silica-based compounds, have been successfully introduced in UHPC to replace natural components of sizes below 0.75 mm. The use of recycled steel fibres processed from waste tires in UHPC has also been researched recently (Isa et al., 2020; Peng et al., 2014; Yang et al., 2019), obtaining promising results in terms of fresh and mechanical properties.

All these studies show the potential good performance of the recycled aggregates and recycled steel fibres to be used in UHPC. This study is a novel work investigating the potential of UHPC as construction and demolition waste, to be recycled and used as recycled aggregates and fibres to produce new UHPC. Specifically, this paper investigates the effect of replacing recycled aggregates and steel fibres in the fresh and mechanical properties (compression, flexural and tensile strengths) of UHPC.

2. Materials and methods

2.1. Obtaining the recycled compounds

The UHPC materials that were recycled to obtain the recycled aggregate can be classified in two categories, A and B. UHPC type A contained only one mix design, with cement type CEM I 52.5 R from Calacem, microsilica from BASF MasterRoc MS 610, and natural silica aggregate 117/F, 103, 113. UHPCs type B included various mix designs, with cement type CEM I 42.5 R-SR from Lafarge, undensified microsilica from Elkem, silica flour from Sibelco and controlled size aggregates of sizes 0.8 and 0.4 mm. Superplasticiser Glenium ACE 442 was used in the original UHPC type A and Sika ViscoCrete 20HE in the original UHPCs type B, to obtain the self-compacting property of UHPC. In the two UHPC types, short steel fibres (13/0.2) were used. The composition of the original materials is detailed in Table 1.

The original UHPC mixes had a compressive strength of between 130 and 150 MPa and were collected from previous experimental campaigns of different purposes. One hundred kilograms of UHPC Type A and two tonnes of UHPC Type B were collected.

Type A original UHPC was crushed at a laboratory level (Figure 1(top row left)) using a jaw crusher (Pascal Engineering) operating at a power of 750 W. After crushing, the material passed through a

Figure 1. Top row: laboratory crushing device (left) and magnetic belt device (right). Bottom row: elements of the recycling plant, (1) hopper to receive the specimens, (2) jaw crushing machine, (3) magnetic conveyor belt, (4) sieves for the classification of the material.

purposely designed and manufactured magnetic belt (Figure 1(top row right)) devise to extract the fibres from the crushed UHPC. The material was finally sieved into separate portions.

Type B original UHPC was crushed at the industrial level, in a waste treatment plant of the company 'Gestión y Reciclaje Belcaire' in Moncofa (Castelló). The process comprised a jaw crusher, a magnetic conveyor belt to separate steel fibres (Figure 1(bottom row)), and finally a belt with sieves. The crushing process was repeated two times to reduce the size of the resulting aggregates.

2.2. Properties of the recycled aggregates

The size distribution curves of the new aggregates obtained directly from crushing are presented in Figure 2. Size distribution was evaluated four times following EN 932-6, three times following the dry procedure and once following the wet procedure. The four curves obtained are very similar, with a continuous size distribution of aggregate mainly comprised between 0.5 and 4 mm. Figure 2 shows the size distribution curves obtained for the recycled aggregate from UHPC Type A and Type B (dry and wet methods). Figure 2 also includes the size distribution curves of the sands used in the original UHPC aggregates for comparison purposes: the blend of natural sands used as original aggregates in UHPC Type A and medium and small sands in UHPC Type B. The results show that the two recycled aggregates are very similar to one another, with Type A having slightly smaller maximum size (2 mm) than Type B and Type B having higher contents of the fraction between 0.125 and 0.6 mm. When compared with the reference sands used in the original UHPCs, the two recycled sands have a more continuous size distribution. In order to compare the results of the mixes with the recycled aggregates with the mixes with reference aggregates, the recycled aggregates were further sieved and classified to obtain a more similar size distribution.

The two recycled aggregates obtained from UHPC, Types A and B, were sieved and classified to obtain fractions with controlled size distribution for optimising the mix designs.

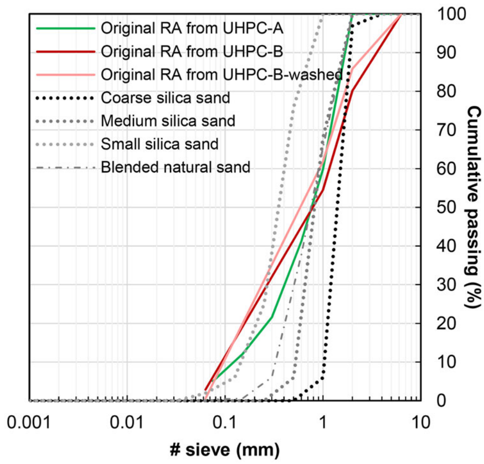

Figure 2. Size distribution of the recycled aggregates (RA) obtained just after crushing, compared with the reference sands.

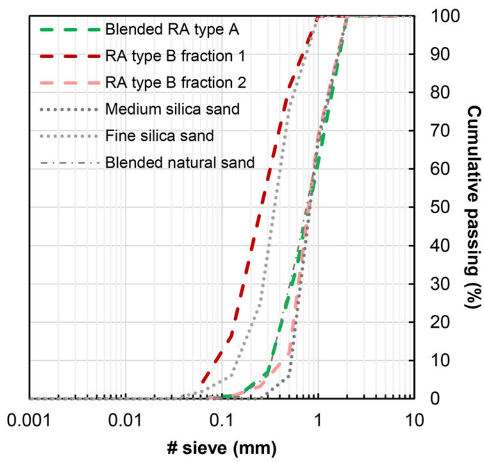

Figure 3. Crushed recycled UHDC aggregate and blended aggregate.

Recycled aggregate Type A was sieved and classified in the following four fractions: (i) $<$0.3 mm, (ii) 0.3–0.6 mm, (iii) 0.6–1 mm and (iv) 1–2 mm, and the resulting materials were blended to obtain aggregate with a similar particle size distribution to the blend of natural aggregates used in the original UHPC. The aggregate obtained for each fraction and the new blended recycled aggregate are presented in Figure 3.

Similarly, the recycled aggregate obtained from UHPC Type B was sieved and classified in four fractions: (i) $<$0.2 mm, (ii) 0.6–1.5 mm, (iii) 2–4 mm and (iv) 4–6 mm. The aggregates obtained for each respective fraction are presented in Figure 4. The aggregate fractions of 2–4 and 4–6 mm were discarded in order to target a UHPC similar to the original UHPC. The largest fraction (4–6 mm), which was discarded, also had a high volume of fibres still attached in the aggregates and was, therefore, the fraction then used to obtain the recycled fibres for this study.

Figure 5 shows the particle size distribution curves of the aggregates obtained from UHPC Type A, already blended, and compared with the size distribution curve of the reference aggregate used in the original UHPC mix. Figure 5 also displays the size distribution of fractions 1 and 2 obtained from UHPC Type B, which will be used for the replacement of the small and medium sands, respectively. The recycled aggregate Type A and fraction 2 of the recycled aggregate Type B show very similar size distribution and are also very similar to the natural aggregates and medium sand size distributions.

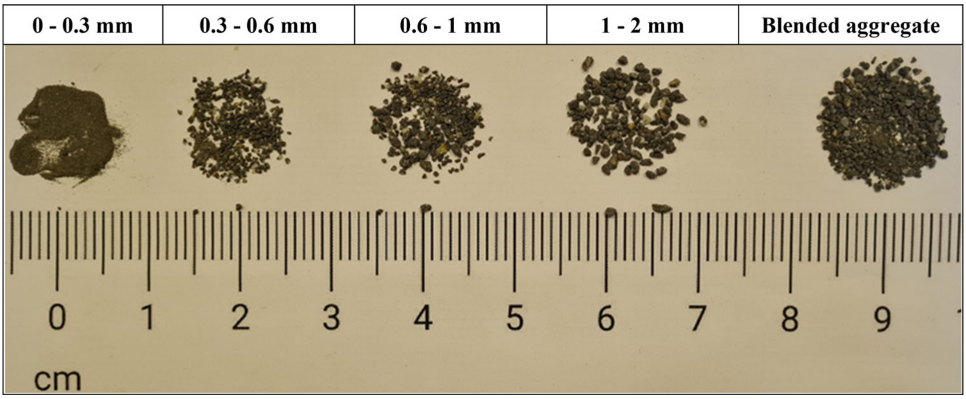

Figure 4. Example of resulting aggregates after sieving and classifying in different sizes. Lines in the scale pictures are in mm.

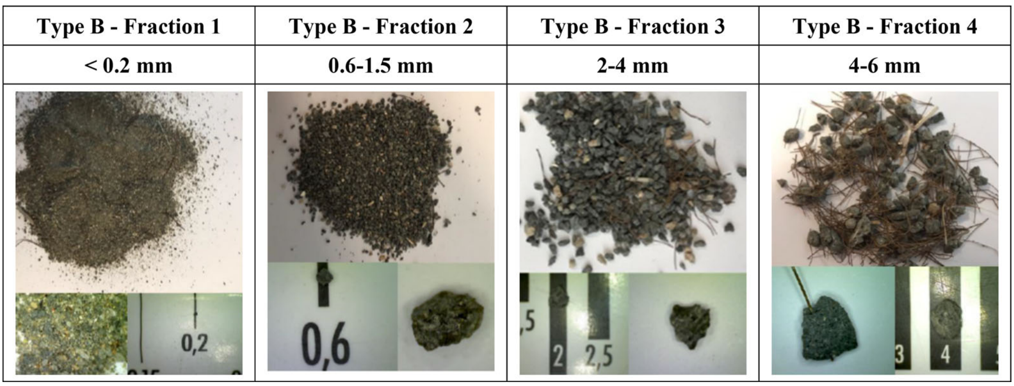

Figure 5. Size distribution curves of the recycled aggregates (RA) after sieving and classifying compared with the reference sands.

2.3. Obtaining the recycled fibres

Recycled steel fibres attached to the aggregates were removed through a purposely built electromagnetic equipment in the case of Type A aggregate in the laboratory. Steel fibres were also separated through an electromagnetic industrial setup in the case of Type B aggregate. The aggregates obtained from the recycling plant were further separated in the laboratory to obtain additional recycled fibres by using a magnet. Figure 6 shows the different steel fibres, as used in the original state (left), after the separation at the plant (middle) and after further separation at the laboratory (right).

The fibres obtained after this process contained a certain number of aggregates that were completely attached to the fibre and could not be separated using the magnet. The percentage of fibres and aggregates was grouped into smaller representative fractions of 260 g each, by manually separating the two materials using pliers. The results indicate that 52.6% of the weight of recycled steel fibres, corresponded to the contribution of aggregates firmly attached. An additional dosage of recycled fibre was added in order to correct this percentage of aggregates attached; the equivalent dosage of the recycled aggregates of size 2 (Figures 4 and 5) was reduced accordingly.

2.4. Recycled UHPC mixes

Two families of Recycled UHPC (RUHPC) were produced in this work. On the one hand, RUHPCs Type 1, which aimed to reproduce original UHPC Type A in Table 1; and on the other hand, RUHPCs Type 2, which aimed to reproduce one of the UHPCs used in Type B in Table 1. The base mix design considered for each type is displayed in Table 2.

Figure 6. Original fibres (left), fibres separated at the recycling plant (middle) and fibres separated from the aggregates at the laboratory (right).

RUHPCs Type 1 tested include the reference mix, with the original mix design, together with 50% and 100% replacement (by weight) of the aggregates. These mixes have been named as R1-0, R1-50, R1-100, where the second number indicates the replacement rate of the aggregates.

RUHPCs Type 2 tested different combinations of recycled small and medium fractions of the sands as well as the recycled fibres. These mixes have been named as R2-0, R2-s50, R2-m50, R2-f50, R2-s100, R2-m100, R2-f100, R2-all50 and R2-all100. The naming criterion includes the type of material replaced ('s' for the small fraction of the sand, 'm' for the medium fraction and 'f' for the fibres), and the percentage replacement.

Table 3 presents all the combinations studied in this work. Within each RUHPC group, constant water to binder ratio (w/b) was used for all the mixes. The superplasticiser content was not modified in order to report the effects of the recycled aggregates on the workability.

Mixes of the type RUHPC-1 were produced in accordance to the following mix protocol using a high speed pan mixer: (1) cement, microsilica and crystalline admixture were placed in the mixer and mixed for 2 min; (2) half of the mix water was added to the mixture and the mix restarted for 2 min; (3) aggregates were added to the mix, and a solution of the remaining water including superplasticiser was added immediately; (4) mixing for 30 min until a self-compacting mix was obtained and (5) addition of the fibres. Mixing continued up to 45 min.

The concrete mixer to produce all RUHPC-2 was an Eirich intensive mixer. The mixing process used consisted on the following steps: (1) dry mixing during 4 min at 300 rpm (sand, cement, microsilica, flour); (2) addition of water and mixing 3 min at 120 rpm and (3) addition of superplasticiser and mix 12 min at 120 rpm.

After casting, all specimens were covered with a plastic sheet to avoid moisture loss. Specimens were de-moulded after 24 h from casting and were stored in a standard humidity chamber at 20 °C and 95% relative humidity until testing time.

2.5. Methodology

Slump flow, compressive strength and flexural strengths were tested experimentally for the 12 mixes to analyse the feasibility of using these recycled materials to produce new UHPC.

Compressive strength was tested in RUHPC-1 mixes using prisms of 40 mm side, obtained after performing the flexural test in prisms of size 160 × 40 × 40 mm. This property was tested in RUHPC-2 mixes using cubes of 100 mm side, as per EN 12390-3:2009. In all the mixes with replacement of aggregates, four cubes were tested at 7 days and four cubes at 28 days, in order to evaluate if there were any effects on the rate of strength acquisition by the un-hydrated cement particles contained in the recycled aggregates. In the mixes with replacement of fibres, compression strength was tested at the age of 28 days using four cubes per mix. This was decided due to the relatively small amount of recycled fibres recovered, in order to produce more prisms to test in flexion, which provides more information about the performance of the fibres.

Regarding flexural strength, this property was tested in RUHPC-1 mixes at the age of 28 days in prisms of size 160 × 40 × 40 mm, through three-point bending test. This property was tested in RUHPC-2 mixes at the age of 28 days in prisms of square cross-section specimens with 100 mm depth and 500 mm length

Table 2. Reference mix designs for RUHPCs of Type 1 and Type 2.

kg/m^3	RUHPC R1-0	RUHPC R2-0
CEM I 52.5	700	–
Cement 42.5 R-SR	–	800
Microsilica	400	175
Superplasticiser 1	64	–
Superplasticizer 2	–	30
Water	231	160
Silica Sand 117 /F (NA)	286	–
Silica Sand 103 (NA)	409	–
Silica Sand 113 (NA)	122	–
Silica sand – medium	–	565
Silica sand – fine	–	302
Silica flour	–	225
Steel microfibres	160	160
CA (Penetron)	5.6	–

Table 3. Combinations of replacement rates and recycled materials investigated in this work.

		Aggregate type					
		Natural		Recycled		Fibre type	
	Mix	Medium	Small	Medium	Small	New	Recycled
RUHPC-1	R1-0	100%				100%	
	R1-50	50%		50%		100%	
	R1-100			100%		100%	
RUHPC-2	R2-0	100%	100%			100%	
	R2-s50	100%	50%		50%	100%	
	R2-m50	50%	100%	50%		100%	
	R2-f50	100%	100%			50%	50%
	R2-s100	100%			100%	100%	
	R2-m100		100%	100%		100%	
	R2-f100	100%	100%				100%
	R2-all50	50%	50%	50%	50%	50%	50%
	R2-all100			100%	100%		100%

through a Four-Point Bending Test (4PBT). Six prisms were tested in the reference concrete to characterise the mix. Two specimens were tested in the mixes where only aggregates were replaced since no differences were expected in the flexural strength when using new fibres. Four specimens were tested in the mixes where fibres were replaced.

The four-point bending test was performed with the span between the two supports at 450 mm, and the two loading points were separated at 1/3 of the total span. In order to measure the vertical displacement, two LVDTs were placed in the middle of the span, on both sides of the prism, and their values were averaged. During the test, the load was applied at a constant velocity of 0.05 mm/min until maximum load.

Tensile response and modulus of elasticity were obtained from the 4PBT using the simplified inverse analysis (IA) method proposed in literature (López et al., 2015, 2016; Mezquida-Alcaraz et al., 2021). This constitutive model is defined as a function of the parameters: elastic modulus (E), cracking strength (f_t), ultimate cracking strength ($f_{tu} = \gamma \cdot f_t$) and its associated strain (ε_{tu}); crack opening at the intersection of the line that defines the initial slope to the w axis (w_0). Tensile properties and elastic modulus of the mixes were obtained following this method.

3. Results

3.1. Workability

The slump flow test was performed for all the mixes, and in all cases, the recycled UHPCs obtained have self-compacting behaviour with slump flow values >550 mm (Figure 7). In all the RUHDC-2 mixes, the slump flow was larger than 650 mm including the case of 100% replacement of aggregate. In all the RUHPC-2 mixes, slump flow was measured after pulling out Abram's cone. The results obtained indicate

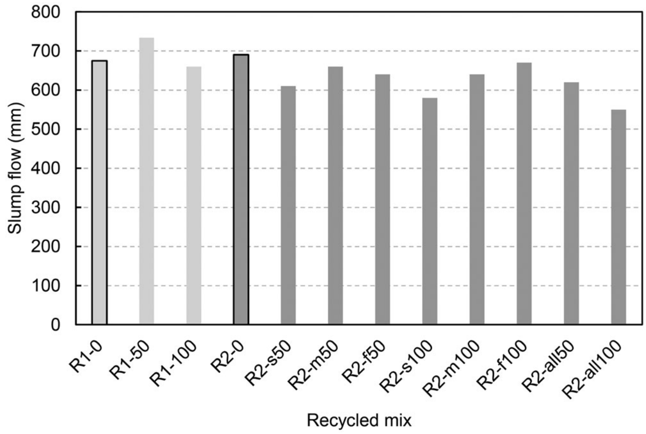

Figure 7. Slump flow test results for the recycled UHPC mixes of the family R1 (light grey) and R2 (dark grey) with the different replacement rates. The reference mixes have a black outline (R1-0 and R2-0).

that 50% of replacement of aggregates or fibres does not have a severe negative impact in the workability of the mix. When increasing the replacement rate of aggregates or fibres to 100%, slump flow experienced a reduction of around 10–15% (with the exception of the mixes R1-100 and R2-f100). This reduction was the highest in the mix with total replacement of the aggregates and fibres (R2-all100), in which slump flow was reduced by 21%. Despite the reduction of the slump flow, the mixes were flowable, and specimens could be cast following the usual procedure for self-compacting concrete. All the R1 mixes can be classified as self-compacting concretes type SF2 (slump flow between 660 and 750 mm), as per EN 12350-8. Most of the R2 mixes, that is, R2-s50, R2-f50, R2-s100, R2-m100, R2-all50 and R2-all100 fall into the category of self-compacting concrete type SF1 (slump flow between 550 and 650 mm), while the reference R2-0 and the two mixes R2-m50, R2-f100 can be classified as type SF2.

Figure 8 shows some images of the mixes during the slump flow test as examples to display the absence of segregation for all mixes developed in this research. The picture in Figure 8(left) displays one of the mixes with 100% of the replacement of the aggregates, with minor agglomerations, while Figure 8(middle) shows a mix with 100% of the replacement of the small fraction of the sand, with no signs or segregation nor agglomerations. Similar results without agglomerations were obtained in the mixes derived from R2 replacing the medium size sand. However, minor agglomerations of recycled fibres interlocked with aggregates were detected in the mixes with recycled fibres (Figure 8(right)).

The results of fresh properties indicate that aggregates and fibres recycled from UHPC are suitable to produce new UHPC in terms of maintaining the self-compacting properties of the concrete. For the higher replacement rates, the lower workability can potentially be compensated by using an extra amount of superplasticiser.

3.2. Compression strength

Figure 9 shows the results of compression strength for all the mixes tested at the ages of 7 and 28 days. The graph shows, in bars, the average value obtained and the limits indicate the standard deviation obtained. The results show similar results of compressive strength when replacing the commercial sand and fibres by the recycled materials, with a slightly higher variation of results in the mixes with the replacement of 50% of sand (R1), 50% of medium sand or 50% of fibres (R2-m50 and R2-f50, respectively). One of the mixes with 100% of fibres (R2-f100) obtained even higher strength than its reference, reaching 147 MPa. Similarly, the mix R1-100 with 100% of recycled aggregates also achieved higher compression strength than its reference R1-0, reaching 159 MPa at 28 days. The results obtained in series R1-0, R1-50, R1-100 at 28 days show first a decrease and then an increase with increasing contents of recycled aggregates, however, this did not happen at the age of 7 days nor in the R2 series, and thus, given the standard deviation values displayed in Figure 9, this variation can be attributed to the intra-batch variability. The higher strength in the R1 series compared to the R2 series are considered to be

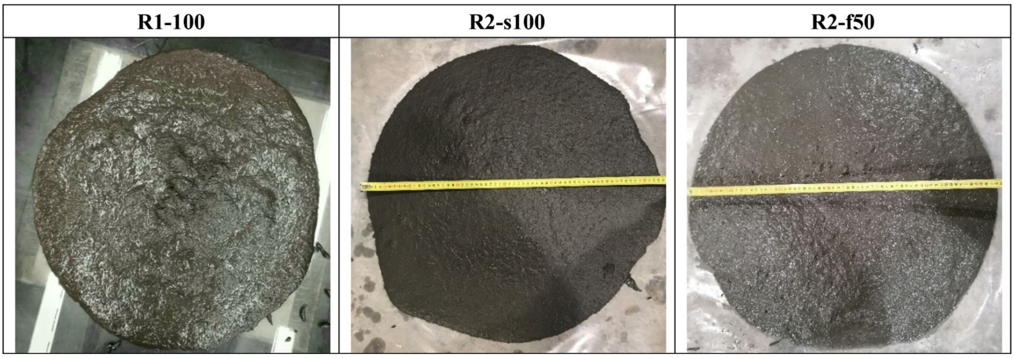

Figure 8. Examples of the slump flow test on the produced mixes.

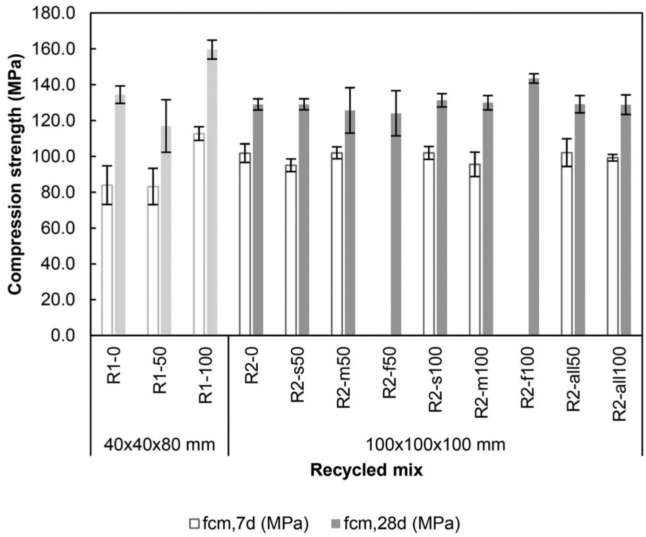

Figure 9. Average and standard deviation values of compressive strength of RUHPC-1s (light grey) and RUHPC-2s (dark grey) at 7 (bars with outline) and 28 days (filled bars).

produced by the smaller size of the specimens (Fládr & Bílý, 2018). In a whole, the compression strength results of UHPC with recycled aggregates are very similar to their reference UHPC.

3.3. Flexural strength

The maximum flexural strength values obtained in RUHPC-1 and RUHPC-2 mixes are displayed in Figure 10. The results indicate that increasing the replacement rate of the recycled aggregates reduces the flexural strength obtained through the three- and four-point bending test (3PBT and 4PBT) for the two prism sizes tested. There is a significant effect of the size of the specimen and test setup, which causes the RUHPC-1 mixes to present higher flexural strength, than RUHPC-2 mixes. In any case, the results obtained show that replacing the aggregates reduces only slightly the flexural strength in the mixes with complete replacement of steel fibres R2-f100 and R2-all100, and in R2-all50. The rest of the mixes show responses within the typical variation levels obtained (such as in the series RS-s100, with highest average result but also higher dispersion), and therefore, this is not considered to be a significant difference.

The experimental nominal stress versus displacement curves obtained in 4PBT for the reference UHPC R2-0 and the eight recycled mixes of the R2 group are shown in Figure 11, obtained from two or four specimens from the same batch. Two specimens were tested for the mixes that replaced aggregates and four for the mixes that only replaced fibres. The results are organised in three graphs, Figure 11(top)

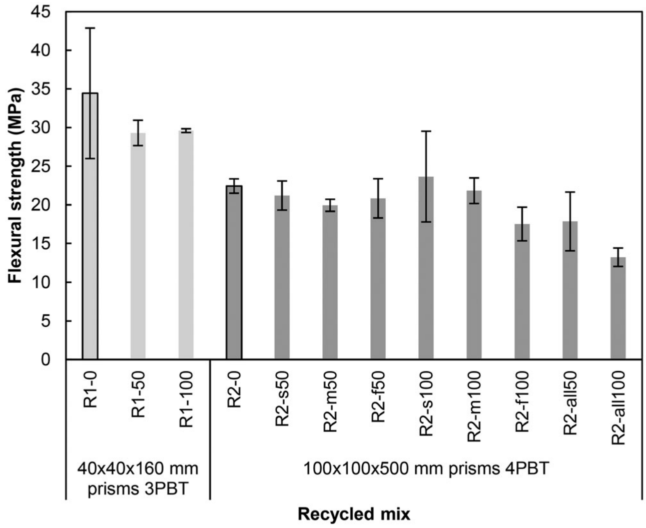

Figure 10. Maximum flexural strength obtained in UHPC-R1 (light grey) and UHPC-R2 (dark grey) mixes. The reference mixes have a black outline.

shows the results obtained when replacing only the commercial sands by the recycled sand. Figure 11(middle) shows the results obtained when replacing only the commercial fibres by the recycled fibres, and Figure 11(bottom) shows the results obtained when replacing simultaneously the commercial sands and fibres by the recycled components. In the three graphs, the results of the reference UHPC (from eight specimens) are displayed in a grey area as a reference, to see the extent of the variations obtained.

As expected, almost all mixes exhibit deflection-hardening behaviour due to the high volume of fibre used. The mixes that show deflection-softening behaviour are those with complete fibre replacement by the recycled fibres. The results show that the mixes where the two commercial sands were replaced by the recycled sands while maintaining new fibres show very similar strength and ductility than the reference curves, with stress peaks between 20 and 25 MPa. Similar results were also obtained when substituting 50% of the fibres by recycled fibres. However, when using 100% fibres replacement, the performance in 4PBT was clearly decreased, and it was further decreased when all the three recycled compounds were used at the same time at a 100% ratio, not displaying the ductility which is typical of these UHPC mixes.

3.4. Tensile strength through IA

Table 4 presents the tensile parameters of the base UHPC type 2, obtained by IA, and the coefficient of variation (CV). Table 5 presents the tensile parameters of RUHPCs of type 2. The results show that the parameters obtained when using recycled aggregates and new sound fibres are similar to those obtained with the reference UHPC. However, when replacing the fibres by the recycled fibres, the mechanical performance is reduced, more noticeably in the case of a complete replacement of the fibres. It is worth mentioning that this decrease in mechanical response was not obtained through the compression strength test. A specific row in Table 5 is indicated with an asterisk since the specimen had an inadequate mechanical response for the evaluation of the tensile parameters through IA.

4. Discussion

The results in this experimental investigation indicate that UHPC can be recycled to obtain new constituents to produce UHPC. Recycled aggregates obtained by crushing, sieving and classifying the material to obtain sizes similar to those of natural aggregates (fractions comprised between 1.5 and 0.063 mm), can be exploited to produce UHPC with comparable properties to reference mixes.

Slump flow was only slightly reduced when increasing the replacement of recycled compounds and the self-compacting properties that are characteristic of UHPC materials were maintained. The

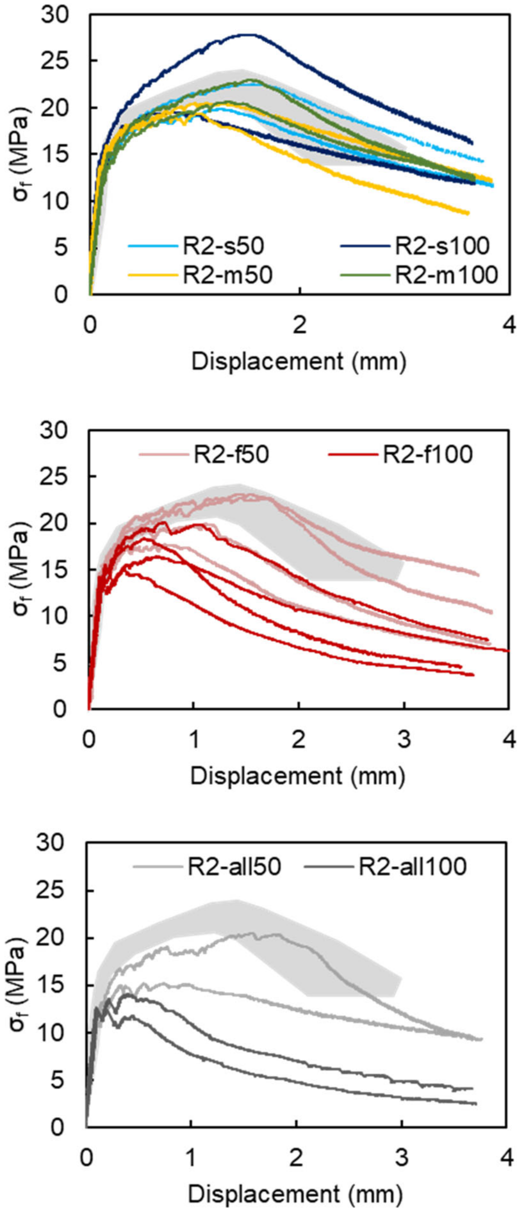

Figure 11. Stress–displacement curves for the recycled mixes compared to the reference mix (grey area).

Table 4. Tensile parameters of base UHPCs obtained from six prisms of the same batch through IA.

Mix		f_t (MPa)	f_{tu} (MPa)	ε_{tu} (‰)	E (MPa)	ω_o (mm)
R2-0	Avg.	9.94	8.26	4.71	50217	2.68
	CV (%)	1.64	5.46	16.52	2.65	15.83

compression strength obtained ranges between 110 and 160 MPa at 28 days, reaching values of typical UHPCs, even with complete replacement of aggregates and fibres. These results are similar to those reported in literature when using recycling traditional concrete elements to produce UHPC, achieving comparable compressive strength to that obtained when using natural aggregates, and especially for replacement rates around 50% (Yu et al., 2019). The replacement of aggregates by crushed recycled UHPC may have influenced the mechanical properties of UHPC due to the presence of un-hydrated

Table 5. Tensile parameters of RUHPC obtained through IA.

Mix	f_t (MPa)	f_{tu} (MPa)	e_{tu} (‰)	E (MPa)	ω_o (mm)
R2-s50	8.45	7.46	3.98	50700	3.24
	9.47	8.44	5.69	49800	3.63
R2-m50	9.73	6.84	2.62	51800	3.04
	9.27	7.56	3.99	49500	4.08
R2-f50	9.59	7.09	2.96	54700	2.77
	9.71	8.48	5.25	51900	3.39
	9.76	7.02	0.61	53700	1.55
	10.00	8.31	5.06	50100	2.97
R2-s100	9.67	11.43	6.07	56100	2.29
	9.55	7.81	1.40	49400	3.05
R2-m100	8.40	7.95	5.05	47000	2.83
	8.84	9.00	5.92	48000	2.61
R2-f100	7.96	6.00	0.72	57200	1.03
	8.65	7.33	1.46	53300	1.30
	7.76	6.48	1.71	45400	1.81
	8.85	8.00	2.32	49900	2.14
R2-all50	7.62	7.68	6.78	50100	2.56
	6.27	5.81	2.64	45900	3.34
R2-all100	a	a	a	a	a
	7.49	5.73	0.73	46100	0.97

[a]IA not applicable.

particles, presumably by improving its strength through their continuing hydration. This may have compensated any possible losses produced by the use of recycled aggregates, however, this hypothesis cannot be confirmed by the results of this study. The size of the aggregates studied was not small enough to be feasible as simultaneous replacement of both cement and aggregates. However, at the same time, this limited the potential decrease in workability, as was reported in other studies, where the replacement of small particles below 0.6 mm to substitute cement and sand led to an increase in the plastic viscosity of UHPC (Wang et al., 2019). All these results highlight the importance of the size distribution of the recycled aggregate particles in obtaining the desired response in UHPC.

The constitutive tensile law obtained from the values calculated through IA was very similar to the reference mix only in those mixes with no replacement of the fibres. When replacing the aggregates, the ultimate tensile strength values obtained range between 7 and 10 MPa and the ultimate tensile strain values obtained were in the range between 3‰ and 5‰ (Figure 12(left)).

In contrast, when replacing fibres by the recycled fibres, a significative decrease in the tensile constitutive law of the material was observed. This decrease is seen because of the smaller ultimate values (both σ and ε) when increasing the replacement rates, until values of 6 MPa and $<$1‰ of ultimate strain were reached when replacing all the UHPC constituents at the same time (Figure 12(right)). Thus, UHPC with partial or complete replacement of recycled fibres is more likely to display strain-softening behaviour. With the complete replacement of aggregates and fibres, it is also likely to display deflection-softening behaviour. Globally, when increasing contents of recycled fibres obtained from old UHPC, the new recycled UHPC will have a more brittle response than UHPC with new fibres. Additionally, the process for obtaining the recycled fibres is less time-effective than the recycling process for the aggregates, since only a small fraction of fibres is recovered, and frequently the latter is heavily attached to some old UHPC elements (slightly more than 50% of UHPC strongly attached). These results indicate some current limits for the usefulness of the process used for recycling fibres from UHPC to be used in new UHPC.

From 1997, when the first bridge made of UHPC was built in Canada (Blais et al., n.d.), the developments on UHPC and the number of structures built with this material experienced a considerable growth (Graybeal, n.d.) and its use has been progressing recently in several countries. In fact, in 2013, USA and Canada had around 55 bridges with UHPC elements, Europe around 15 and Australasia around 23 (Blais et al., n.d.). In 2020, only Switzerland had about 150 UHPC constructions, most of them in the bridge domain, and Malaysia had more than 120 UHPC bridges (all of them built since 2010) (Graybeal et al., 2020). In France, UHPC is being used primarily in façade cladding elements or roofing panels but its use it is expected to be expanded to other domains (Graybeal et al., 2020). However, other countries such as the UK show limited use of UHPC up to 2019 (Budd et al., 2019). Despite the growth that the use of UHPC has experienced, the

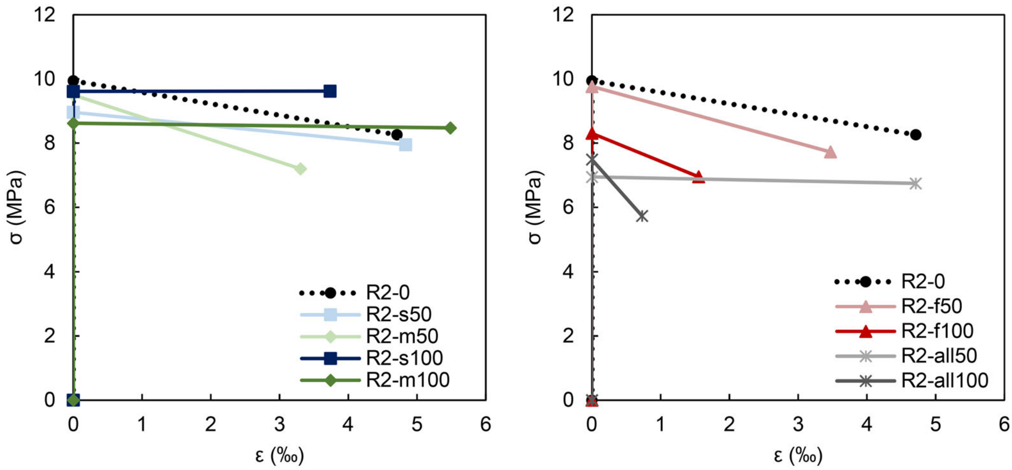

Figure 12. Average σ–ε laws for each recycled UHPC mix obtained after from inverse analysis to prisms tested to 4PBT.

recyclability of this material will be of higher relevance in those countries with higher number of applications in UHPC, and for the internal circularity in precast plants that work with UHPC in any country.

5. Conclusions

The outcomes of this study demonstrate that recycling UHPC as construction and demolition waste is feasible at laboratory scale and also at industrial scale. The resulting recycled sands displayed a great potential to be used for producing new UHPC with excellent fresh and hardened properties. Specifically, it was demonstrated that:

- UHPC can be recycled entirely to obtain aggregates and fibres to produce new UHPC. The recycling process of UHPC is easily adaptable to the current existing processes to recycle construction and demolition waste. No technical difficulties were found during the process, neither at laboratory scale nor at an industrial scale.
- The use of UHPC as a recycled aggregate to produce RUHPC can be wholly accepted with little to no changes in the mix designs to obtain fresh and hardened properties similar to UHPC made with new or natural compounds. This conclusion applies for high replacement ratios of natural aggregates of the medium and small fractions. Slump flow values obtained were generally higher than 550 mm, and compression strength was higher than 115 MPa for all the groups tested.
- The use of recycled fibres to produce new UHPC is also feasible for replacement rates of 50% obtaining deflection-hardening mixes with only slight decreases in workability. Mixes with complete replacement of steel fibres obtained reduced workability, strain- and deflection-softening responses, as well as a slight tendency to produce agglomerations of fibres.

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ORCID

Marta Roig-Flores http://orcid.org/0000-0002-1067-1276
Ruben Paul Borg http://orcid.org/0000-0002-5298-4609
Cecilia Ruiz-Muñoz http://orcid.org/0000-0003-4777-6423
Eduardo J. Mezquida-Alcaraz http://orcid.org/0000-0002-8370-1341
Ester Giménez-Carbó http://orcid.org/0000-0002-2856-4081
Albany Milena Lozano Násner http://orcid.org/0000-0002-9982-9016
Pedro Serna http://orcid.org/0000-0001-8754-1165

References

Arcadis, BIO Intelligence Service. (n.d.). IEEP, Directorate-General for Environment (European Commission) – *Service contract on management of construction and demolition waste* – SR1 Final Report Task 2. https://doi.org/10.1038/081073a0.

Blais, P. Y., Senior, P. E., Le Groupe, P., Sherbrooke, T., Canada, Q., Couture, M., Operations Manager, P. E., Bolduc, B., & Beauce, S.-M. (n.d.). *Precast, prestressed pedestrian bridge World's first reactive powder concrete structure*.

Budd, O., Pottle, S., & Stacy, M. (2019). *UHPC in the UK*.

Collins, R. (2003). Recycled concrete. *Advanced Concrete Technology*, *4*, 1–13. https://doi.org/10.1016/B978-075065686-3/50294-9

Etxeberria, M., Vázquez, E., Marí, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research*, *37*(5), 735–742. https://doi.org/10.1016/j.cemconres.2007.02.002

Federal Ministry for the Environment. (n.d.). *Nature conservation and nuclear safety – Construction waste* | BMU. Retrieved November 30, 2020, from https://www.bmu.de/en/topics/water-wastesoil/%0Awaste-management/types-of-waste-waste-flows/construction-waste/

Fládr, J., & Bílý, P. (2018). Specimen size effect on compressive and flexural strength of high-strength fibre-reinforced concrete containing coarse aggregate. *Composites Part B: Engineering*, *138*, 77–86. https://doi.org/10.1016/j.compositesb.2017.11.032

Graybeal, B. (n.d.). *Ultra-high performance concrete: A state-of-the-art report for the bridge community*.

Graybeal, B., Asce, M., Brühwiler, E., Kim, B.-S., Toutlemonde, F., Voo, Y. L., & Zaghi, A. (2020). *International perspective on UHPC in bridge engineering*. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001630

Isa, M. N., Pilakoutas, K., Guadagnini, M., & Angelakopoulos, H. (2020). Mechanical performance of affordable and eco-efficient ultra-high performance concrete (UHPC) containing recycled tyre steel fibres. *Construction and Building Materials*, *255*, 119272. https://doi.org/10.1016/j.conbuildmat.2020.119272

Limbachiya, M., Dhir, R., Limbachiya, M. C., Leelawat, T., & Dhir, R. K. (2000). Sustainable construction using concrete view project materials and structures/use of recycled concrete aggregate in high-strength concrete. *Materials and Structures*, *33*(9), 574–580. https://doi.org/10.1007/BF02480538

López, J. Á., Serna, P., Navarro-Gregori, J., & Camacho, E. (2015). An inverse analysis method based on deflection to curvature transformation to determine the tensile properties of UHPFRC. *Materials and Structures*, *48*(11), 3703–3718. https://doi.org/10.1617/s11527-014-0434-0

López, J. Á., Serna, P., Navarro-Gregori, J., & Coll, H. (2016). A simplified five-point inverse analysis method to determine the tensile properties of UHPFRC from unnotched four-point bending tests. *Composites Part B: Engineering*, *91*, 189–204. https://doi.org/10.1016/j.compositesb.2016.01.026

Mezquida-Alcaraz, E. J., Navarro-Gregori, J., & Serna-Ros, P. (2021). Direct procedure to characterize the tensile constitutive behavior of strain-softening and strain-hardening UHPFRC. *Cement and Concrete Composites*, *115*, 103854. https://doi.org/10.1016/j.cemconcomp.2020.103854

Mousa, M., Cuenca, E., Ferrara, L., Roy, N., & Tagnit-Hamou, A. (2018). Tensile characterization of an "Eco-friendly" UHPFRC with waste glass powder and glass sand. *RILEM Bookseries*, *15*, 238–248. https://doi.org/10.1007/978-94-024-1194-2_28

Oikonomou, N. D. (2005). Recycled concrete aggregates. *Cement and Concrete Composites*, *27*(2), 315–318. https://doi.org/10.1016/j.cemconcomp.2004.02.020

Peng, G. F., Niu, X. J., & Long, Q. Q. (2014). Experimental study of strengthening and toughening for recycled steel fiber reinforced ultra-high performance concrete. *Key Engineering Materials*, *629–630*, 104–111. https://doi.org/10.4028/www.scientific.net/KEM.629-630.104

Savva, P., Ioannou, S., Oikonomopoulou, K., Nicolaides, D., & Petrou, M. F. (2021). A mechanical treatment method for recycled aggregates and its effect on recycled aggregate-based concrete. *Materials (Basel)*, *14*(9), 2186. https://doi.org/10.3390/ma14092186

Serna, P., López, J. Á., Camacho, E., Coll, H., & Navarro-Gregori, J. (2014). *Footbridge over the Ovejas ravine in Alicante: An economical alternative made only of ultra-high-performance fibre-reinforced concrete (UHPFRC)*. Am. Concr. Institute, ACI Spec. Publ. 2014 July (pp. 435–450). https://doi.org/10.35789/fib.bull.0079.ch41

Shayan, A., & Xu, A. (2003). Performance and properties of structural concrete made with recycled concrete aggregate. *ACI Materials Journal*, *100*, 371–380. https://doi.org/10.14359/12812

Soliman, N. A., & Tagnit-Hamou, A. (2017). Using glass sand as an alternative for quartz sand in UHPC. *Construction and Building Materials*, *145*, 243–252. https://doi.org/10.1016/j.conbuildmat.2017.03.187

Tam, V. W. Y., Soomro, M., & Evangelista, A. C. J. (2018). A review of recycled aggregate in concrete applications (2000–2017). *Construction and Building Materials*, *172*, 272–292. https://doi.org/10.1016/j.conbuildmat.2018.03.240

United Nations Environment Program (UNEP). (2014). *Sand, rarer than one thinks*. United Nations Environment Program (UNEP), 2012, 1–15. https://wedocs.unep.org/bitstream/handle/20.500.11822/8665/GEAS_Mar2014_Sand_Mining.pdf?sequence=3&isAllowed=y

United Nations Environment Programme. (2019). *Sand and sustainability: Finding new solutions for environmental governance of global sand resources*. https://www.unenvironment.org/news-and-stories/press-release/rising-demand-sand-calls-resource-governance

Wang, X., Yu, R., Shui, Z., Song, Q., Liu, Z., Bao, M., Liu, Z., & Wu, S. (2019). Optimized treatment of recycled construction and demolition waste in developing sustainable ultra-high performance concrete. *Journal of Cleaner Production*, *221*, 805–816. https://doi.org/10.1016/j.jclepro.2019.02.201

Xiao, J. (n.d.). *Springer tracts in civil engineering recycled aggregate concrete structures*. http://www.springer.com/series/15088

Yang, J., Peng, G. F., Shui, G. S., & Zhang, G. (2019). Mechanical properties and anti-spalling behavior of ultra-high performance concrete with recycled and industrial steel fibers. *Materials (Basel)*, *12*(5), 783. https://doi.org/10.3390/ma12050783

Yang, R., Yu, R., Shui, Z., Gao, X., Xiao, X., Fan, D., Chen, Z., Cai, J., Li, X., & He, Y. (2020). Feasibility analysis of treating recycled rock dust as an environmentally friendly alternative material in ultra-high performance concrete (UHPC). *Journal of Cleaner Production*, *258*, 120673. https://doi.org/10.1016/j.jclepro.2020.120673

Yoo, D. Y., & Banthia, N. (2016). Mechanical properties of ultra-high-performance fiber-reinforced concrete: A review. *Cement and Concrete Composites*, *73*, 267–280. https://doi.org/10.1016/j.cemconcomp.2016.08.001

Yu, L., Huang, L., & Ding, H. (2019). Rheological and mechanical properties of ultra-high-performance concrete containing fine recycled concrete aggregates. *Materials (Basel)*, *12*(22), 3717. https://doi.org/10.3390/ma12223717

Yue, G., Ma, Z., Liu, M., Liang, C., & Ba, G. (2020). Damage behavior of the multiple ITZs in recycled aggregate concrete subjected to aggressive ion environment. *Construction and Building Materials*, *245*, 118419. https://doi.org/10.1016/j.conbuildmat.2020.118419

Zhang, H., Ji, T., Zeng, X., Yang, Z., Lin, X., & Liang, Y. (2018). Mechanical behavior of ultra-high performance concrete (UHPC) using recycled fine aggregate cured under different conditions and the mechanism based on integrated microstructural parameters. *Construction and Building Materials*, *192*, 489–507. https://doi.org/10.1016/j.conbuildmat.2018.10.117