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Ultra-High Performance Concrete: Recycling and Issues

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Abstract

Ultra-high performance concrete (UHPC) is used in infrastructure due to the outstanding mechanical and durability properties. On the other hand, infrastructures reach an end of life and all materials must be restored, replaced or recycled. Two years old UHPC was conventionally crushed with some difficulties, due to the high steel fibres content and strength, to prepare aggregates (0-32 mm). Some aggregates still contained fibres. A concrete with compressive strength class C 30 / 37 was taken as a reference and a mixture with 50% addition of UHPC recycled aggregates was prepared. The blend with 50% UHPC aggregates exhibited a reduction of the strength at 28 days at 40 MPa as compared to the reference mixture with 68 MPa. The modulus of elasticity was reduced to 25'295 MPa. The reference mixture showed 36'709 MPa. The chloride migration was 10.3 x 10^{-12} m^2/s for the UHPC recycled concrete and 8.2 x 10^{-12} m^2/s for the reference. The water permeability of the recycled mixture with UHPC aggregates showed a higher value of 11.7 g/m2h as compared to 8.3 g/m2h of the reference. The values correlated with the higher saturable porosity 17.2% of the recycled UHPC mix. Thus, the recycling of UHPC needs a modified demolition and crushing procedures as for conventional concrete. The addition of UHPC aggregates in conventional concrete does not necessarily improve the performance. Adjustments in the aggregate preparation and mix design are required to allow the use of recycled UHPC aggregates within cementitious systems.

Keywords: UHPC, recycling, mechanical performance, durability

Introduction

The ultra-high performance concrete (UHPC) was recently developed and combines the main positive characteristics of cementitious materials in order to achieve high mechanical performance and durability. The use of finer particles is one of the components that contributes to achieve high compressive strength up to 150 MPa after 28 days of hydration (Akhnoukh & Elia, 2019). A close relationship between strength and porosity is also clear (Odler & Röbler, 1985) and the reduction of the pore size is a major concern in this type of material. The close packaging of very fine raw materials, low water / cement ratio ranging around 0.2 and the addition of superplasticizers (Park et al., 2005) all contribute to high strength. A rapid strength development is often observed. After 2 days of hydration the compressive strength may already be above 100 MPa. At 7 days, the strength reaches 140 MPa and after 28 days the values are close to 170 MPa for commercially used UHPC (Paglia & Antonietti, 2023). The microstructure of UHPC mainly consists of unhydrated cement clinker particles, quartz sand, and hydration products, such as C–S–H (Sorelli et al., 2008). The very dense microstructure is due to the reactive mineral admixture that consumes the CH and reacts to CSH. In this manner the interfacial zone along the aggregates does not exhibit well formed crystalline CH as for conventional concrete (Reda et al., 1999). The homogenization of the microstructure with quartz sand is also a relevant factor for the strength (Richard & Cheyrezy, 1995). The addition of high amounts of steel fibres introduces a high ductility into the material (Russel & Graybeal, 2013) and particularly enhances the toughness (Zollo, 1997).

On the other hand, the specifically chosen UHPC ingredients, the high content of cement of over 800kg/m3 (Perry, 2018) arise relevant questions about the sustainability of this cementitious material. This in spite of the thinner sections than can be produced as compared to the material ingredients and quantities of conventional concrete. However, these latter components are more widespread worldwide and exhibit significantly lower costs.

Nonetheless, attempts are made to increase the sustainability of UHPC. Highly reactive belite cement in place of CEM I 52.5 R is used, but it gives lower early strength (Singh, 2004). A

supplementary cementitious material, such as silica fume with 0.2 μ particle size, a by-product of the ferro-silicon industry, added in a range 20-30% of the cement may provide a UHPC with 200 MPa (Chan & Chu, 2004). Metakaolin deriving from the calcination of natural clays may only partially affect the strength with lower values of around 7% (Tafraoui et al., 2009), but the wider availability and lower costs can make it a valid sustainable alternative. The fly ashes and the ground granulated blast furnace slags or combinations of them may also be used as a partial cement replacement with satisfactory properties (Yazici et al., 2009), although the changes forced by the reduced CO_2 emission requirements lower the potential use of these two materials. Meanwhile, all high temperature curing regimes that promote even higher strength as well as the preparation works for nano-particles (Sanchez & Sobolev, 2010) seems further away from more sustainable targets. The risk husk ash partial cement replacement is able to maintain the main characteristics of UHPC (Van Tuan et al., 2011). Refined quartz sand with diameter below 1 mm can be substituted by recycled glass, limestone (Yang et al., 2009), and basalt aggregates (Wang et al., 2012) to achieve similar performances. Steel fibres enhance the ductility and toughness depending also on their shape (Kim et al., 2011). The direct tensile strength after 35 days of hydration of commercially available UHPC reaches 8 ± 3.6 MPa. The values vary depending on the fiber quantity and spatial orientation. The strength increases when a high amount of fibers is oriented towards the tensile direction. The fibers are partially bent and rarely broken after the tests. The tension is transmitted across the fibers and the cracks proceed over the fibers within the cement matrix and along or across the aggregates (Paglia et al., 2022).

On the other hand, the relative recent development of UHPC did not yet frequently faced replacements of the material. Therefore, the aim of the work is to analyze the recycling issue that may arise from the demolition of such an ultra high strength material and the opportunity to recycle the crushed aggregates to produce a cementitious material.

Experimental Procedure

A two years old UHPC stored in the atmosphere was used to prepare the aggregates. The material was placed in a conventional crushing device equipped with a magnet at the top of the transportation conveyor belt (Figure 1 left). The magnet was able during the transportation procedure of the material to remove a relevant part of the fibres (Figure 1 centre). Nevertheless, many fibres remained entrapped within the high strength aggregates (Figure 1 right).

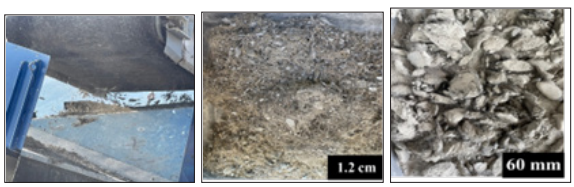

Figure 1: Crushing procedure (left), fibres separation (centre) and UHPC crushed aggregates (right).

A reference mixture of concrete with compressive class C 30 / 37 resistant to freeze and thaw and a mixture with the addition of 50% recycled UHPC concrete aggregates were prepared with a 340 kg/m^3 cement dosage (Table 1).

Mixture properties	Reference mix with natural aggregates CPN G	CPN G mix + 50% recycled concrete aggregates UHPC
CEM I 42.5 N	340 Kg	340 Kg
Water content	139	189
Aggregates (0/32 mm)	1610 Kg	805 Kg (Natural) + 805 (Recycled UHPC)
Fly ash	50 Kg	50 Kg
Air entrapping agent	0.2% (mass cem.)	0.2% (mass cem.)
Superplasitcizer	1% (mass cem.)	1% (mass cem.)
Aggregates absorption	15	50

Table 1: Concrete mix proportions.

The compressive strength, modulus of elasticity, porosity and water permeability, accelerated carbonation, chloride penetration and the freeze / thaw resistance were measured (Standard SN EN 206 - Concrete - Specification, performance, production and conformity, + A2, 2021).

Results and Discussion

The recycled UHPC aggregates exhibit a variable granulometry and a general chipped-angular geometry due to the high strength of the crushed UHPC material (Figure 2 left). The recycled UHPC mixture shows the natural aggregates with a relatively smooth and rounded surface that help the workability, while the UHPC recycled aggregates exhibit a chipped angular shape (Figure 2 centre), typically seen for tunnel TBM excavation machines natural aggregate residues.

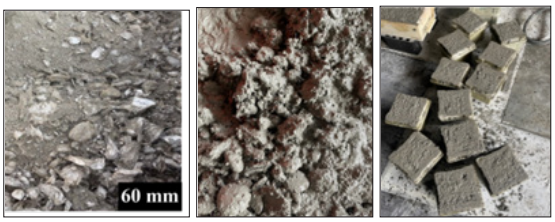

Figure 2: Crushed UHPC aggregates (left) and fresh mixture of 50 % natural and 50 % UHPC aggregates. Note the presence of fibers (centre). Cube specimens 150 mm casting (right).

The blends in the fresh state indicate variable results with respect to the density and air content that may be caused by the inhomogeneous presence of the UHPC aggregates within the recycled mixture (Table 2). The workability of the recycled UHPC mix was acceptable, although the presence of fibers in some UHPC recycled aggregates made the sample casting a little more difficult, but feasible (Figure 2 right).

Blend type	Density [Kg/m³]	Air Content [%]	w/c Ratio	Walz Index
Reference mix with natural aggregates	2348	4.8	0.39	1.05
Mix + 50% recycled concrete aggregates UHPC	2311	1.5	0.41	1.04

Table 2: Fresh state blends parameters.

The mixtures exhibit in the hardened state a mean compressive strength after 28 days of hydration of 68.9 MPa for the reference mixture and 40.3 MPa for the blend with 50% recycled UHPC aggregates (Figure 3 left). A significant decrease in strength is observed. This in spite of the presence of fibres hooked in the UHPC aggregates that might act as an additional strength reinforcement feature. In this concern, it is not possible to assume that the recycled ultra-high strength aggregates may behave as natural aggregate, in spite of their strength. In fact, the crushing procedure and the presence of residual fibres, partially distorted them and created microcracks in the UHPC aggregates (Figure 3 right).

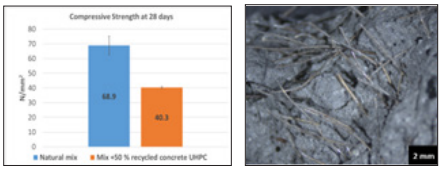

Figure 3: Compressive strength (left), modulus of elasticity (centre-left), microcracks on recycled UHPC aggregates (centre-right) and lack of crack filling (right) after 28 days hydration.

These cracks are difficult to fill with the new cementitious material (Figure 4 left) and the strength is reduced. The modulus of elasticity also indicates after 28 days a lowering of the mean value from 36'709 MPa for the reference mix to 25'295 MPa for the recycled UHPC mix (Figure 4 right).

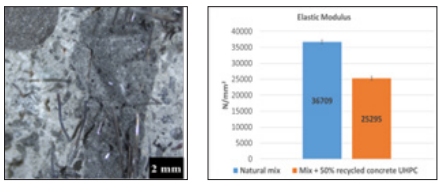

Figure 4: Lack of crack filling with the new concrete (left) and modulus of elasticity (right).

The chloride penetration indicates a mean value of 8.2×10^{-12} m²/s for the reference blend and 10.3×10^{-12} m²/s for the recycled UHPC concrete (Figure 5 left). The slight increase in the chloride permeability correlates with the water permeability, which exhibits an increase to 11.7 g/m²h for the recycled UHPC mix (Figure 5 right). In this concern, the reduced chloride penetration of the recycled aggregates seen in some conventional 100% recycled aggregate concrete (Paglia et al., 2022) and the increased potential binding capacity is no longer seen in UHPC recycled concrete. This is due to the extreme low permeability of the UHPC aggregates that reduces the surface area and the contact points of the cementitious material with the chlorides, thus reducing the potential binding capacity.

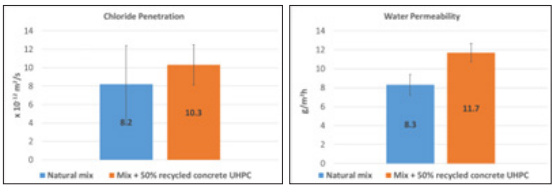

Figure 5: Chloride penetration (left) and water permeability (right) of the blends.

The saturable porosity, namely the porosity in contact with the surface that allows the ingress of detrimental agents, exhibits higher values for the recycled UHPC concrete (Figure 6 left). This fact correlates with the higher chloride penetration and water permeability. The high saturable porosity exhibits a direct relationship with the lower resistance to water and chloride penetration, while the higher total porosity (Figure 6 right) shows a direct correlation with the lower compressive strength.

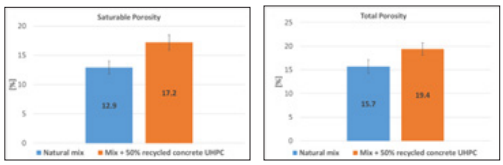

Figure 6: Saturable (left) and total porosity (right) of the blends.

The higher saturable porosity of the recycled UHPC concrete also promotes a higher CO_2 penetration and carbonation (Figure 7 left). Similarly, the resistance to freeze and thaw is significantly higher for the reference mixture as compared to the recycled UHPC concrete (Figure 7 right). The higher dishomogeneity of the recycled UHPC concrete structure lowers the resistance to cyclic freeze and thaw deformation and the dishomogeneous presence of fibers partially attached to the UHPC aggregates are not capable to increase the ductility of the samples and reduce the scaling of the surface.

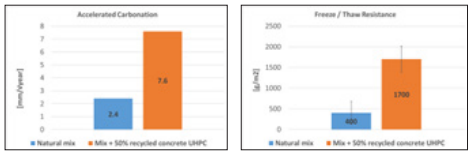

Figure 7: Accelerated carbonation (left) and freeze / thaw resistance (right) of the blends.

Conclusions

The ultra-high strength concrete was tested with respect to its recycling capability. The demolition of such a high strength cementitious material on site is not as easy task and conventional crushing procedures with the presence of a magnet are not ideal to produce recycled aggregates completely free of fibres. The addition of 50% by mass of recycled UHPC high strength aggregates decreases the general mechanical and durability

properties of the concrete. Therefore, alternative special demolition and crushing techniques should allow to better separate the fibres from the ultra-high strength cementitious crushed aggregates. In addition, some preparation works may be required to better shape the aggregates, unless the fine gradation resulting from the fibre sorting procedure does not require additional adjustment techniques. All these procedures may exhibit a conflict with today's sustainability targets, in spite of the supplementary cementitious material cement binder replacements that may be used to produce UHPC.

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