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Investigation of lab and pilot scale electric-pulse fragmentation systems for the recycling of ultra-high performance fibre-reinforced concrete

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Abstract

Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) such as LafargeHolcim Ductal® is a new concrete product that incorporates large amounts of fine metal fibres, and is designed to have multiple advantages over traditional concrete products. These fibres, while providing additional strength, represent a new recycling challenge as they may block or increase wear of conventional mechanical apparatus, or be broken during processing rendering them unusable. High voltage electric-pulse fragmentation (EPF) systems such as those produced by SELFRAG AG use repeated electric discharges to selectively fragment composite materials along phase boundaries, overcoming compressive strength and preventing damage to metallic fibres. Initial tests in a laboratory scale system at a range of specific energy levels up to 60 kWh/t showed that Ductal® sample with a compressive strength of 170 MPa was amenable to EPF with good recovery rate of the steel fibres, which were fully liberated in the 0/2 mm product size fraction. Upscaled tests were performed on two Ductal® samples with compressive strengths of 170 and 210 MPa respectively using the ‘Pre-Weakening Test Station’ (PWTS), a continuous EPF system. Tests with specific energy levels up to 27 kWh/t showed similar results for both Ductal® samples: fibre liberation correlates with increasing specific energy input up to a plateau at about 13 kWh/t where increased energy produces little to no additional breakage. About 60% of fibres were recovered after just one treatment step performed at 13.4 kWh/t. These promising results obtained at pilot-scale indicate that this technology is suitable for UHPFRC recycling and fibre recovery, and that scaling-up the process to a commercial level is technically feasible.

Keywords: Recycling; Ultra-high performance fibre-reinforced concrete; Electric-pulse fragmentation; Selective fragmentation

1 Introduction

Developed in recent decades, Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) has many advantages over traditional concretes, including very high mechanical performance, ductility, and durability. According to the French UHPFRC standard (The reference (NF P 18-470, 2016) should be included here.), UHPFRC is characterized by a compressive strength starting from 130 MPa, with a minimal tensile strength defined as 6 MPa. These attractive characteristics have enabled architects and engineers to build remarkable structures such as bridges, stadiums, and architectural façades.

UHPFRC is a composite material containing a high cement content, mineral admixture (usually silica fume), fine sand (with an absence of coarse aggregate), steel fibres, and a very low water/binder ratio ensured by the use of superplasticizers (Máca et al., 2013; Hussein and Amleh, 2015; Afroughsabet et al., 2016). Fibres are either metallic, organic or synthetic but steel fibres are the most commonly used for structural and non-structural purposes (Afroughsabet et al., 2016).

Due to its outstanding properties, a tremendous amount of work has recently been performed on the formulation and application of UHPFRC (Afroughsabet et al., 2016; Yoo and Yoon, 2016). However, there are only few studies regarding the end-of-life recycling of UHPFRC or even conventional fibre-reinforced concrete (FRC). In particular, Kunieda et al. (2014) and Topçu and Baylayli (2016) investigated the recycling potential of ordinary FRC (compressive strength < 50 MPa) made with steel and polypropylene fibres and just polypropylene fibres respectively. Kunieda et al. (2014) showed that it is possible to recover the fibres by using a jaw crusher, similar to those used for recycling ordinary concrete, and that the fibres were completely liberated in the size fractions lower than 5 mm. The recycling behavior of UHPFRC was only studied by Sedran et al. (2011) on a commercialized UHPFRC product called BSI/Ceracem® which included calcined bauxite aggregates and developed a compressive strength around 210 MPa. Sedran et al. (2011) found that using a jaw crusher was not efficient for UHPFRC recycling but the combination of an impactor and a gyratory crusher allowed liberating fibres in the size fraction 0/3 mm, which could then be extracted with a magnet.

Although currently the amount of UHPFRC waste is relatively low due to its recent introduction to the construction industry, it is nevertheless essential to investigate the processes that would be implemented for its recycling. The recovery and recycling of the steel fibres for production of new UHPFRC is crucial as this is an expensive component which could then contribute to reduce the high production cost of new UHPFRC (Yoo and Banthia, 2016; Huang et al., 2017). This study investigates electric-pulse fragmentation (EPF) as a potential breakthrough technology for liberating the steel fibres contained in Ductal® UHPFRC. Main differences between the Ductal® and the BSI/Ceracem® UHPFRC are the following (Maten, 2011):

(i) Possible heat treatment during hydration, especially applied to Ductal®, in order to reduce creep and shrinkage deformations.

(ii) Maximum aggregate size : while Ductal® materials only contain very fine sand (<1 mm), Ceracem® includes up to 7 mm-sized ultra-hard aggregate (but at a rather low content).

EPF involves generating highly energetic electrical pulses (150–750 J/pulse) with a very fast voltage ramp-up time (<500 ns) and applying them to materials immersed in a process liquid. Dielectric liquids such as water, are more resistive than solids when the pulse rise time is kept below 500 ns forcing discharges through the immersed material (Bluhm et al., 2000). The plasma channel formed during the discharge causes explosive expansion along the discharge pathway (electrodynamic fragmentation), and the collapse of the plasma channel produces a shock-wave that propagates through the material (electrohydraulic fragmentation).

The high selectivity of the process arises from the way the electricity and shockwaves interact with physico-chemical properties of the material, discontinuities in electrical permittivity and conductivity at phase boundaries locally enhance the electric field forcing the discharge channels to these boundaries. The combination of the shock wave with acoustic discontinuities concentrates tensile stress at phase interfaces (Andres et al., 1999; HISER, 2016). The concentration of energy and stress at phase boundaries causes selective breakage, and allows full liberation of components from the feed material.

Laboratory tests on various ores show very high liberation rates (Andres et al., 1999; Andres et al., 2001; Dal Martello et al., 2012; Wang et al., 2012a; Bru et al., 2017). If the ore contains metalliferous phases on or near the particle surface, these can guide the discharge across the particle surface instead of through the particle, losing part of the pulse energy to the water. If the metalliferous minerals occur inside the particle, the breakdown channels result in increased internal fracturing, a feature that can be exploited to preferentially remove metallic components or to weaken a material as demonstrated on construction grout by Zuo et al. (2015) and concrete by Parvaz et al. (2015). The efficiency of EPF for ordinary concrete recycling was proven at lab scale (Iizasa et al., 2010; Inoue et al., 2012; Touzé et al., 2017) and pilot scale (Bru et al., 2017). Its applicability to the selective fragmentation of UHPFRC waste has not yet been studied but since it contains metallic fibres in a mineral gangue then promising results are expected.

This work aims to study the efficiency of EPF technology for the up-cycling of Ductal® UHPFRC by selectively liberating steel fibres from the sand/cement paste in order to recycle both fractions into new concrete products with similar mechanical properties to those made using raw materials. In particular, the steel fibres could be used to make new UHPFRC and the fine fraction could be used either to make new UHPFRC or to make new standard concrete.

Initial tests were performed at small batch-scale on a SELFRAG Lab system in order to explore the fragmentation mechanisms prior to up-scaled to tests on a continuous throughput pilot system. The continuous pilot scale system allowed assessing the repeatability of this kind of treatment, testing the influence of the operating parameters on the process performances at conditions close to the industrial ones, and investigating the robustness of the technology when treating two types of UHPFRC materials.

2 Materials and methods

2.1 UHPFRC samples

The UHPFRC samples used in this study were cast by LafargeHolcim R&D center and are classified as Ductal® concrete (Ductal G2 FM). The samples were manufactured from a proprietary premix including 150 kg of 14 mm long steel micro-fibres per a cubic meter (6.4% mass). The premix had a maximal particle size below 1.0 mm. Two kinds of Ductal® concrete samples were manufactured from the same premix by applying two different curing methods: one was manufactured without any treatment after demolding whereas the other one was manufactured with a heat treatment at 90 °C and 100% relative humidity for 48 h after demolding. The compressive strength after 28 days of two Ductal® concretes were 170 MPa and 210 MPa, respectively. These samples were crushed in a jaw crusher with a closed-side setting of 100 mm and sieved in order to get samples in the size fraction 5/40 mm.

2.2 Experimental set-up for lab scale tests

The lab scale EPF tests were conducted using the 'Lab', a laboratory scale device for the batch processing of material, manufactured by SELFRAG AG, Switzerland (Fig. 1). The equipment is designed to process samples of up to approximately 1 kg with a top particle size of 40–45 mm in a 4 L vessel filled with de-mineralised water. The working electrode is immersed in the upper part of the vessel, while the bottom of the vessel constitutes the counter electrode. The apparatus produces high voltage electric discharges between the two electrodes. The operating parameters that can be changed are the voltage (90–200 kV), electrode gap (10–40 mm), pulse repetition rate (1–5 Hz) and number of electric pulses (1–1000).

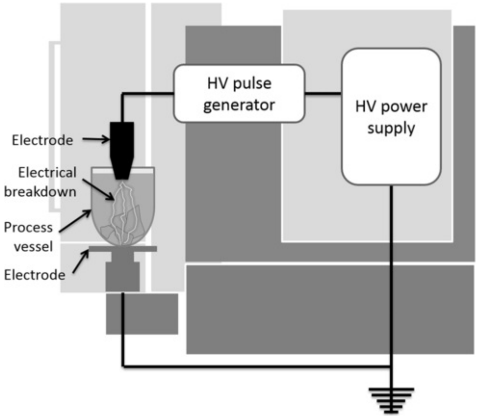

Fig. 1 Schematic of the SELFRAG Lab machine.

The objective of the lab scale tests was to investigate the influence of the generator energy (also called specific energy for a given sample mass – in kWh/t) on the fragmentation of the samples. As shown in Eq. (1), generator energy is dependent on the voltage and number of pulses applied since the capacitance is fixed at 37.5 nF for the lab machine. The voltage was set at 150 kV because preliminary tests have shown that lower voltage values result in a lower discharge probability, where the set number of discharges is not reached by the machine due to electrical field strength being too low to reliably produce discharges as also observed by van der Wielen (2013). As voltage and capacitance were fixed, generator energy was modified by adjusting the number of pulses.

$$E_{gen} = n\,0.5\,CU^2 \tag{1}$$

where E_{gen} represents generator energy (J), n is number of pulses, C is capacitance (F) and U is pulse voltage (V).

As it has been shown that when several particles are placed in the batch vessel then the energy is not evenly distributed among all particles (Shi et al., 2013), single-particle tests were conducted on samples with a size of about 40 mm.

Seven specific energies were investigated (from 1.2 to 60 kWh/t) with an electrode gap of 40 mm and a pulse rate of 5 Hz. These tests were performed on both Ductal® samples with an individual particle mass of about 100–200 g.

2.3 Experimental set-up for continuous pilot scale tests

The pilot scale continuous tests were performed with the SELFRAG Pre-Weakening Test Station (PWTS), a first of its kind EPF plant designed to continually process material at up to 1 t/h, material and application dependent. The PWTS (Fig. 2) consists of a pulse generator, a processing zone, and a process vessel filled with de-mineralized water. Material is fed into the process zone via a metal plate conveyor with a 5 mm spacing between each plate (Fig. 3) which acts as the counter electrode. The process zone is immersed in water and material is transported through this area by the conveyor where it passes below a disk-shaped upper electrode which discharges through the material onto the conveyor (Fig. 3). The operating parameters which can be changed are the voltage (50–200 kV), the capacitance (10–150 nF), the electrode gap (10–80 mm), the pulse repetition rate (1–100 Hz), the polarity (positive or negative), and the belt speed. The generator energy input can be calculated for the PWTS from given parameter setting with the same equation as for the Lab machine (Eq. (1)), adjusting the speed of the conveyor so that all material receives a comparable number of discharges.

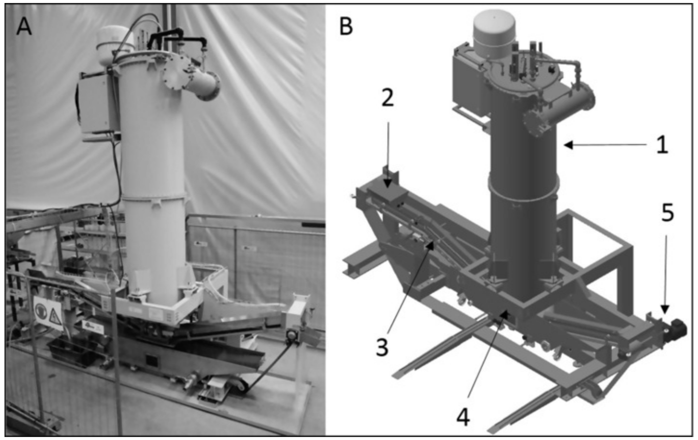

Fig. 2 A: The SELFRAG PWTS; B: 1: High voltage pulse generator; 2: feed in hopper; 3: conveyor belt; 4: process zone; 5: feed out.

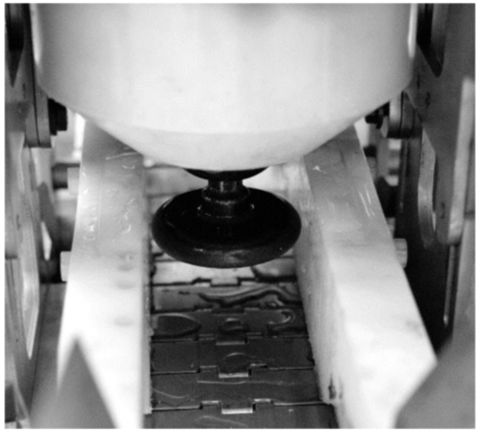

Fig. 3 PWTS process zone.

The EPF performance (as defined by the selectivity of the fragmentation), was evaluated through a series of tests, each performed on a mass of 3 ± 0.2 kg of sample with size between 5 and 40 mm. All tests were performed at 150 kV, a capacitance of 80 nF, a pulse repetition rate of 10 Hz, and an electrode gap of 50 mm. The specific energy (kWh/t) which relates to the generator energy input for a given sample mass, was controlled by varying the conveyor belt speed which influences the material residence time in the processing zone and therefore the number of pulses which are discharged into the sample. After each test, the water vessel was cleaned to recover all the fine particles.

Three test series were performed:

- The first series aimed to assess the repeatability of the PWTS. Tests were carried out at a specific energy of 5 kWh/t on Ductal® sample with a compressive strength of 170 MPa. Four replicates were performed.
- The second series aimed to study the influence of the specific energy. Tests were performed on Ductal® sample with a compressive strength of 170 MPa at a specific energy of 1.1, 5.0, 13.4 and 27.5 kWh/t.

- The objective of the third series was to study the influence of the UHPFRC compressive strength. Tests were conducted on the two Ductal® samples at a specific energy of 1.1, 5.0 and 13.4 kWh/t.

2.4 Characterization methods

The particle size distribution of the sample before and after the treatment was measured by manual sieving in order to characterize the fragmentation. Since the treatment can weaken the sample (Wang et al., 2011), special care was used during sieving to avoid additional fragmentation. Nine sieves were used: 2 mm, 5 mm, 8 mm, 9.5 mm, 16 mm, 20 mm, 25 mm, 31.5 mm and 40 mm. The fibres content in a dedicated size fraction was measured by performing a magnetic separation manually.

3 Results and discussion

3.1 Characteristics of the liberated steel fibres

Magnetic separation was performed on two size fractions (0/2 and 2/5 mm) of fragments obtained after EPF in order to identify the liberation size of the steel fibres. The steel fibres in the 0/2 mm size fraction were liberated while the steel fibres in the 2/5 mm size fraction were still attached to mortar pieces (Fig. 4). The degree of liberation was evaluated by measuring the residual mortar content in the steel fibres fraction, performed by grinding the material in a planetary mill followed by sieving at 0.160 mm. This analysis gave a mortar content of about 4 wt% for the steel fibres recovered from the size fraction 0/2 mm and a mortar content of about 88 wt% for the steel fibres recovered from the size fraction 2/5 mm. There is then zero liberation of fibre in size fractions above 2 mm, as once fibres are liberated they fall into the 0/2 mm size fraction. Therefore, the fibre liberation size of 2 mm was considered in this study. The liberation size was also confirmed by a scanning electron microscopy analysis of the liberated and new fibres (Fig. 5). The image of the liberated fibres indicates a negligible quantity of mortar without any substantial deterioration of the fibre surface.


(a) 0/2 mm (b) 2/5 mm

Fig. 4 Steel fibres contained in the size fractions 0/2 mm (a) and 2/5 mm (b) obtained after PWTS (It is possible to replace "PWTS" by "an EPF continuous treatment performed"?) treatment at 5.0 kWh/t of Ductal® samples @ 170 MPa.

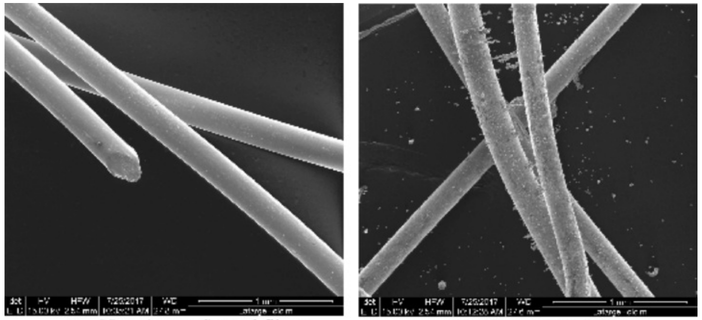
(a) New (unused) steel fibres (b) Liberated steel fibres

Fig. 5 Scanning electron microscopy analysis of the new (a) and liberated (b) steel fibres. The liberated steel fibres were obtained from the size fractions 0/2 mm of Ductal® samples @ 170 MPa after PWTS (It is possible to replace "PWTS" by "an EPF continuous treatment performed"?) treatment at 5.0 kWh/t.

3.2 Influence of the specific energy on the fragmentation with the batch equipment

The influence of the specific energy on the product size P50 (i.e. 50% passing size) after EPF is given in Fig. 6. There is an initial phase where little size reduction occurred (up to approximately 6 kWh/t), followed by a strong decrease in product size over a relatively small energy range, before levelling off in the high energy range (from about 20 kWh/t). Similar trends were reported by van der Wielen et al. (2013), Zuo et al (2015) and Bru et al. (2017). The initial phase can be explained by the fact that a threshold specific energy may be required to fully overcome particle strength and lead to the breakage of the majority of the particles. When a discharge occurs in a particle, micro-cracks are formed but more energy is needed to increase the micro-cracks density sufficiently to produce an interconnected fracture network until the particle's integrity is reduced to the point where it fragments completely (van der Wielen et al., 2013). The asymptote in fragmentation is due to the non-linear relationship between energy input and size reduction: after a certain energy input (specific to material), additional input causes little further breakage (Bru et al., 2017). Many authors have shown that the particle size of the sample has a strong influence on fragmentation (Wang et al., 2012b; van der Wielen et al., 2013; Zuo et al., 2015), coarser particles being far more susceptible to be broken or weakened than finer particles. According to van der Wielen et al. (2013), this may be due to the fact that a larger particle can provide the full bridge for a discharge from the two electrodes with then a relatively limited travel distance through the processing water which mean that almost all the energy is discharged in the particle. On the contrary, smaller particles are not be able to bridge the gap between electrodes fully and therefore the pulses may be required to jump from particle to particle several times, involving a longer total travel distance through water and then a larger portion of energy lost in the water and not available for fragmentation.

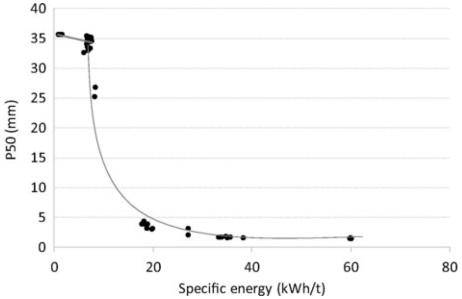

Fig. 6 Product size P50 as a function of the specific energy after batch treatment of Ductal® samples @ 170 MPa.

This change in breakage with energy correlates with the EPF breakage mechanisms reported by Zuo et al. (2015). Below a material specific energy threshold, the particle experiences 'surface breakage', and above, 'body-breakage'. Particles undergoing surface breakage remain intact or show only minor surface damage producing chips and fines even if micro-cracks can be generated. Particles undergoing body breakage often produce coarse fragments and fewer fines. In this case, when the specific energy is lower than 6 kWh/t, little size reduction of the main particle occurred, while the fineness of the products increased (highlighted with the evolution of the mass content of the size fraction 0/2 mm in Fig. 7) indicating that surface breakage is the dominant fragmentation type at this energy level. It was assumed by van der Wielen et al. (2013) that the particles accrue the damage necessary to produce the finer size distributions prior to actual size reduction. An increase in specific energy therefore increases the amount of body breakage leading to a decrease in the particle size distribution and most probably to a higher fibre recovery.

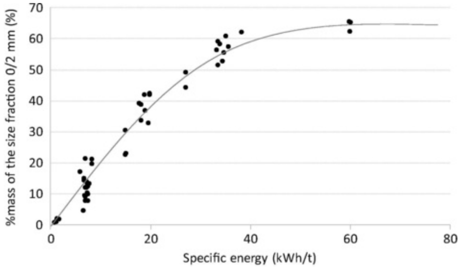

Fig. 7 Mass content of the size fraction 0/2 mm as a function of the specific energy after batch treatment of Ductal® samples @ 170 MPa.

When looking at the recovery rate of the fibres, Fig. 8 shows that it increased with the specific energy up to a value close to 70% at 60 kWh/t. A similar trend was observed for the mass content of the 0/2 mm size fraction as shown in Fig. 7, which confirms that it can be used as an analogue for fibre recovery rate since fibres are fully liberated in this size fraction. Moreover, Fig. 7 shows that there is a breakage limit of the machine. This is probably due to reduced breakage efficiency on smaller particles in the process vessel – the *feed size effect* (van der Wielen et al., 2013) where a greater feed particle size can result in greater size reduction. Sequential discharges in a closed system mean that with every discharge the 'feed' size decreases.

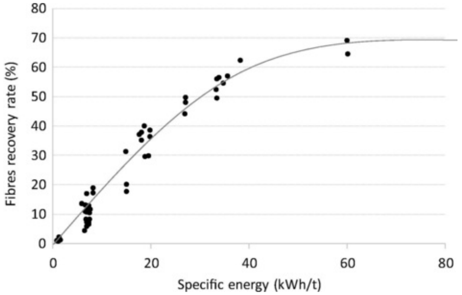

Fig. 8 Recovery rate of the fibres as a function of the specific energy after batch treatment of Ductal® samples @ 170 MPa (calculated with fibres in the size fraction 0/2 mm).

Fig. 7 shows that there is a strong dispersion of data for a given specific energy, which decreases with increasing specific energy. An increase in the specific energy leads to a decrease in the relative standard deviation of the 0/2 mm mass content (Table 1) which means that the breakage becomes more reliable with a higher number of discharged pulses. This is related to the single-particle mode combined with this material which is heterogeneous in shape. This variability should be decreased by using a continuous system as the PWTS.

Table 1 Mean, standard deviation and relative standard deviation of the mass content of the size fraction 0/2 mm at different specific energies after batch treatment of Ductal® samples @ 170 MPa.

Specific energy (kWh/t)	1.2	7.2	15.0	18.8	27.0	34.7	59.9
0/2 mm – Mean (%)	1.5	13.4	25.5	38.6	46.8	57.8	64.5
0/2 mm – Standard deviation (%)	0.6	4.2	4.4	3.8	3.4	3.3	1.7
0/2 mm – Relative standard deviation (%)	37.1	31.5	17.2	9.7	7.4	5.8	2.7

3.3 Results obtained with the PWTS operating at a continuous pilot scale

3.3.1 Repeatability of the PWTS treatment

The repeatability of the PWTS was evaluated by performing 4 replicates at a specific energy of 5.0 kWh/t on Ductal® sample with a compressive strength of 170 MPa. This specific energy was chosen since it corresponded to a strong dispersion of the results in the tests performed at lab scale. Fig. 9 displays the average particle size distribution of the fragments obtained after each test, with the standard deviation for each measured value. The scattering of results is small compared to the results obtained with the Lab machine, which can be explained by the continuous processing method and by the machine configuration. Indeed, the PWTS uses a large surface area disk electrode while the Lab machine uses a finger-shaped electrode which means that the PWTS has a less focused streamer initiation and a larger but less intense electrical field than the lab system. The probability of a particle being part of the discharge channels in the PWTS is then larger (Zuo et al., 2015). These results confirm the good repeatability of the EPF treatment with the PWTS.

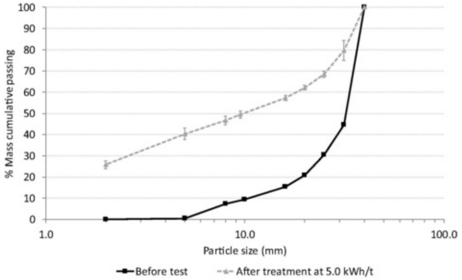

Fig. 9 Particle size distribution before and after an EPF continuous treatment (Is it possible to add (PWTS machine)?)at 5.0 kWh/t of Ductal® samples @ 170 MPa.

3.3.2 Influence of the specific energy on the selective fragmentation of UHPFRC samples

Tests were performed on the 170 MPa Ductal® sample at specific energies of 1.1, 5.0, 13.4 and 27.5 kWh/t. Since variables such as voltage and capacitance can affect the discharge probability (van der Wielen, 2013), the specific energy input to the sample was achieved by adjusting the speed of the conveyor belt transporting the sample. Modifying the conveyor speed controls the sample residence time in the discharge zone, and therefore the number of pulses received by the sample and hence the specific energy. Results related to the product size P50 after treatment are given in Fig. 10. A strong decrease in product size over a relatively small energy range (1–4 kWh/t) was observed, before an asymptote at around 10 kWh/t. This asymptote can be explained not only by a reduced breakage efficiency on smaller particles but also by the design of the metal plate conveyor. Indeed, the metal plates are spaced of 5 mm which means that material with a particle size below 5 mm can fall between the metal links and become mixed with other test material, leading to a limitation in size reduction. Similar trends were observed during the tests performed with the batch equipment (Fig. 6), except that the asymptote was reached at lower specific energy levels (10 kWh/t vs around 20 kWh/t with the batch equipment). Moreover, even if it was not possible to observe at pilot scale an initial phase where little reduction occurred, it is difficult to know if this is due to a very small initial phase or to no initial phase at pilot scale; it would have required more data at specific energies between 1 and 5 kWh/t.

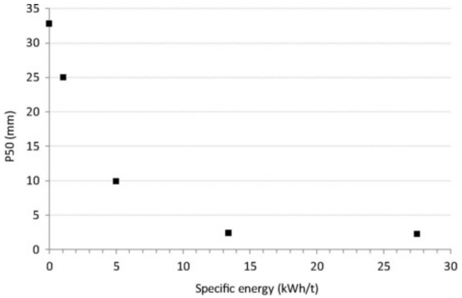

Fig. 10 P50 of the products after an EPF continuous treatment of Ductal® samples @ 170 MPa as a function of the specific energy.

The recovery rate of fibres, calculated with the liberated fibres i.e. the fibres contained in the size fraction 0/2 mm, is given in Table 2. It can be seen that the recovery rate of the fibres is about 30% after one run at a specific energy of 5.0 kWh/t and it increases with the specific energy up to a value close to 60% at 13.4 kWh/t. This stabilization in the fibre recovery rate can be explained by the breakage behavior at specific energies higher than 13.4 kWh/t, as observed in Fig. 10 and more precisely in Fig. 11, since fibres are liberated in the 0/2 mm size fraction. Indeed, Fig. 11 is related to the evolution of the mass content of the 0/2 mm and 0/5 mm size fractions and shows that they level off at about 50% and 75% respectively at a specific energy of 13.4 kWh/t. As explained before, the stabilization in the evolution of the mass content of size fractions under 5 mm is partly due to the design of the conveyor of the PWTS machine used in this study. This means that it could be possible to reach higher size reduction, and then higher fibre recovery rate, when using an EPF machine with another design of the conveyor belt. Increasing specific energy slightly increases the proportion of steel fibres in the 0/2 mm size fraction (Table 2).

Table 2 Steel fibres content in the size fraction 0/2 mm and recovery rate of the steel fibres as a function of the specific energy after an EPF continuous treatment of Ductal® samples @ 170 MPa.

	Specific energy (kWh/t)			
	1.1	5.0	13.4	27.5
Steel fibres content in the size fraction 0/2 mm (%mass)	8.0	8.3	9.2	9.7
Recovery rate of the steel fibres (%mass)	11.3	26.6	53.3	57.6

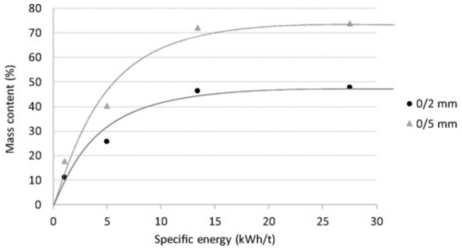

Fig. 11 Mass content of the size fractions 0/2 mm and 0/5 mm as a function of the specific energy after an EPF continuous treatment of Ductal® samples @ 170 MPa.

3.3.3 Influence of the UHPFRC compressive strength

Particle size distributions after continuous treatment of Ductal® samples with and without heat treatment, i.e. with a compressive strength of 170 and 210 MPa respectively, are quite similar at a given specific energy level (Fig. 12). This means that the heat treatment implemented for curing a UHPFRC, which led to two distinct compressive strengths, does not have a significant effect on the fragmentation induced by the PWTS. This lack of a significant correlation between compressive strength and particle size distribution after electric-fragmentation was also observed by van der Wielen (2013) and is due to a locally extensive stress regime created within the sample by the discharge where compressive strength is of little relevance. There is then a limited extent of crushing around a plasma channel due to pressures locally exceeding the compressive strength of material (van der Wielen, 2013).

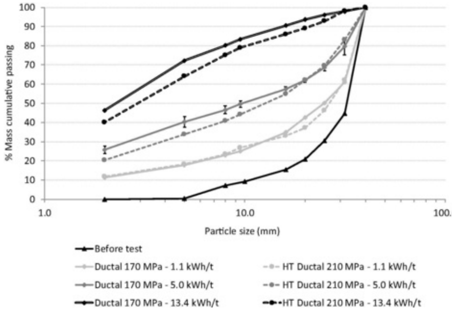

Fig. 12 Particle size distribution before and after an EPF continuous treatment performed at various specific energies for a Ductal® sample @ 170 MPa (without heat treatment) and a Ductal® sample @ 210 MPa (with heat treatment HT).

Results regarding the influence of the UHPFRC compressive strength on the steel fibres content of the size fraction 0/2 mm is given in Table 3. It seems that the UHPFRC compressive strength has only a slight influence on the liberation of the steel fibres. At a specific energy of 13.4 kWh/t, the steel fibre content is 9.2% and 8.3% for a 170 MPa Ductal® (non-heat treated) and 210 MPa Ductal® (heat treated) respectively. These results show that the studied electric-fragmentation process is a robust technical solution for the recycling of UHPFRC. This is very crucial for the implementation of this process since it could not be possible to sort all kind of UHPFRC waste.

Table 3 Steel fibre content in the size fraction 0/2 mm as a function of the specific energy after an EPF continuous treatment of Ductal® samples @ 170 MPa (without heat treatment) and of heat-treated Ductal samples @ 210 MPa.

Specific energy (kWh/t)	1.1	5.0	13.4	27.5
Ductal® sample @ 170 MPa	8.0	8.3	9.2	9.7
Ductal® sample @ 210 MPa (heat-treated)	7.2	7.2	8.3	

4 Comparison of lab and continuous pilot-scale epf(It would be better to write it in capital letters "EPF") systems

This work combined the use of two SELFRAG systems, the Lab batch machine and the PWTS continuous pilot system, in order to study the efficiency of electric-fragmentation technology for the selective liberation of the steel fibres contained in UHPFRC. This approach gave the opportunity to firstly investigate the feasibility of the electric-fragmentation technology and the mechanisms involved by performing tests at lab scale on a small amount of sample, and secondly to study its up-scaling with the continuous machine at pilot scale.

While the fragmentation mechanisms undergone by a sample treated in the lab and pilot machine are similar, the performance of the PWTS at a given specific energy is significantly better than the Lab machine, in terms of both the product size P50 and fibre recovery rate. This is most probably due to a higher electrical energy efficiency related to the continuous pilot machine PWTS since its generator is designed for energy efficient industrial operations, while the Lab system is designed for small scale studies and mineral liberation for geosciences research where energy input is largely irrelevant. This can also be explained by the characteristics of the treated sample, since only one particle block was used at lab scale, which decreased in size with each discharge, while a continuous feed of larger particles was used at pilot scale (feed size effect). Different settings of the lab and pilot machine like the capacitance (37.5 nF in the Lab machine and 80 nF in the PWTS) and pulse repetition rate (5 Hz in the Lab machine and 10 Hz in the PWTS) for example can also explain the observed differences.

5 Conclusions

Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) such as Ductal® represents a challenge to conventional recycling processes due to the high fibre content and high compressive strength which may increase wear of crushing apparatus. Moreover, malleable fibres may jam mechanical apparatus, or be broken during processing, decreasing the amount of reusable material. Tests performed with an electric-pulse fragmentation continuous pilot system showed that the electric-fragmentation of UHPFRC Ductal® samples allows the recovery of about 30% of steel fibres after just one treatment step performed at 5.0 kWh/t and this recovery rate reached about 60% when the treatment was done at 13.4 kWh/t. It was also observed that fragmentation is essentially unaffected by the compressive strength of the material, making electric-fragmentation a valid and robust process for the recycling of this material. These are initial results and as such the system process can be optimized, suggesting very promising results if a recycling loop was implemented as it would be for an industrial implementation. The next steps will be to perform tests with the products obtained after the treatment to check their suitability for making new UHPFRC and ordinary concrete, to perform tests with conventional crushers and to carry out techno-economic analyses in order to compare the two pathways.

6 Uncited references

NF P 18-470 (2016).

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References

Afroughsabet V., Biolzi L. and Ozbakkaloglu T., High-performance fiber-reinforced concrete: a review, *J. Mater. Sci.* **51**, 2016, 6517–6551.

Andres U., Jirestig J. and Timoshkin I., Liberation of minerals by high-voltage electrical pulses, *Powder Technol.* **104**, 1999, 37–49.

Andres U., Timoshkin I., Jirestig J. and Stallknecht H., Liberation of valuable inclusions in ores and slags by electrical pulses, *Powder Technol.* **114**, 2001, 40–50.

Bluhm H., Frey W., Giese H., Hoppé P., Schultheiβ C. and Sträβner R., Application of pulses HV discharges to material fragmentation and recycling, *IEEE Trans. Dielectr. Electr. Insul.* **7**, 2000, 625–636.

Bru, K., Touzé, S., Parvaz, D.B., 2017. Development of an innovative process for the up-cycling of concrete waste. In: HISER Conference, Delft, The Netherlands, 21–23 June 2017.

Dal Martello E., Bernardis S., Larsen R.B., Tranell G., Di Sabatino M. and Arnberg L., Electrical fragmentation as a novel route for the refinement of quartz raw materials for trace mineral impurities, *Powder Technol.* **224**, 2012, 209–216.

HISER, Electrofragmentation technology and its benefits for construction and demolition waste, *Newsletter* 2016, 2.

Huang W., Kazemi-Kamyab H., Sun W. and Scrivener K., Effect of replacement of silica fume with calcined clay on the hydration and microstructural development of eco-UHPFRC, *Mater. Des.* **121**, 2017, 36–46.

Hussein L. and Amleh L., Structural behavior of ultra-high performance fiber reinforced concrete-normal strength concrete or high strength concrete composite members, *Constr. Build. Mater.* **93**, 2015, 1105–1116.

Iizasa S., Shigeishi M. and Namihira T., Recovery of high quality aggregate from concrete waste using pulsed power technology, *Clean Technol.* 2010, 325–328.

Inoue S., Iizasa S., Wang D., Namihira T., Shigeishi M., Ohtsu M. and Akiyama H., Concrete recycling by pulsed power discharge inside concrete, *Int. J. Plasma Environ. Sci. Technol.* **6**, 2012, 183–188.

Kunieda M., Ueda N. and Nakamura H., Ability of recycling on fiber reinforced concrete, *Constr. Build. Mater.* **67**, 2014, 315–320.

Máca P., Sovják R. and Vavřiník T., Experimental investigation of mechanical properties of UHPFRC, *Procedia Eng.* **65**, 2013, 14–19.

Maten R.N., Ultra High Performance Concrete in Large Span Shell Structures, Master thesis, 2011, TUDelft.

NF P 18-470, Bétons fibrés Ultra Hautes Performances Spécification, performance, production et conformité, 2016, AFNOR French Standard Institute.

Parvaz, D.B., Weh, A., Mosaddeghi, A., 2015. A Pre-concentration Application for SELFRAG High Voltage Treatment. In: 14th European Symposium on Comminution and Classification (ESCC 2015), Chalmers University of Technology, Gothenburg, Sweden, 7–10 September 2015.

Sedran T., Durand C. and de Larrard F., An Example of UHPFRC, In: Toutlemonde F. and Resplendino J., (Eds.), *Designing and Building with UHPFRC* 2011, John Wiley & Sons.

Shi F., Zuo W. and Manlapig E., Characterisation of pre-weakening effect on ores by high voltage electrical pulses based on single-particle tests, *Miner. Eng.* **50–51**, 2013, 69–76.

Topçu, I.B., Baylavli, H., 2016. Recycling of Polypropylene Fiber Reinforced Concrete. In: 2nd International Conference on Civil, Stuctural and Transportation Engineering -ICCSTE16, Ottawa, Canada, 5–6 May 2016.

Touzé S., Bru K., Ménard Y., Weh A. and Von der Weid F., Electrical fragmentation applied to the recycling of concrete waste – effect on aggregate liberation, *Int. J. Miner. Process.* **158**, 2017, 68–75.

van der Wielen K.P., Pascoe R., Weh A., Wall F. and Rollinson G., The influence of equipment settings and rock properties on high voltage breakage, *Miner. Eng.* **46**, 2013, 100–111.

van der Wielen K.P., Application of High Voltage Breakage to a Range of Rock Types of Varying Physical Properties, Thesis Camborne School of Mine, 2013, University of Exeter.

Wang E., Shi F. and Manlapig E., Pre-weakening of mineral ores by high voltage pulses, *Miner. Eng.* **24**, 2011, 455–462.

Wang E., Shi F. and Manlapig E., Mineral liberation by high voltage pulses and conventional comminution with same specific energy levels, *Miner. Eng.* **27**, 2012a, 28–36.

Wang E., Shi F. and Manlapig E., Factors affecting electrical comminution performance, *Miner. Eng.* **34**, 2012b, 48–54.

Yoo D. and Banthia N., Mechanical properties of ultra-high-performance fiber-reinforced concrete: a review, *Cem. Concr. Compos.* **73**, 2016, 267–280.

Yoo D.-Y. and Yoon Y.-S., A review on structural behavior, design, and application of ultra-high-performance fiber-reinforced concrete, *Int. J. Concr. Struct. Mater.* **10**, 2016, 125–142.

Zuo W., Shi F., van der Wielen K.P. and Weh A., Ore particle breakage behaviour in a pilot scale high voltage pulse machine, *Miner. Eng.* **84**, 2015, 64–73.

Highlights

- The electric-pulse fragmentation technology was studied for the recycling of ultra-high performance fibre-reinforced concrete (here Ductal® concrete), and in particular for liberating the steel fibres contained in this concrete.
- Tests were firstly performed at small batch-scale in order to explore the electric-pulse fragmentation mechanisms and then a continuous throughput pilot system was used to investigate the feasibility and the robustness of the technology.
- With the pilot system, the recovery rates of the steel fibres were about 30% and 60% after just one treatment step performed at respectively 5.0 kWh/t and 13.4 kWh/t.

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- The electric-pulse fragmentation mechanisms were explored at small batch-scale.
- A continuous pilot system was used to assess the feasibility of the technology.

- 33% of the fibres were recovered after one treatment step performed at 5.0 kWh/t.

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