An example of UHPFRC recycling

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Summary

This paper presents some results concerning the recycling of a particular UHPFRC called CERACEM which includes calcined bauxite aggregate and a high content of steel fibers. It shows that the UHPFRC can be crushed and separated into sand and fibers. The recycled sand can be used in replacement of a river sand in self levelling concrete, with no loss of fluidity and no decrease in compressive strength. When replacing calcined bauxite in CERACEM by recycled sand, no workability change is observed and the loss in compressive strength is limited to 10%. Finally, recycled fibers have been used in Ceracem with no changes in the material properties. The study concludes that this UHPFRC can be completely and easily recycled in hydraulic materials, which makes it possible to consider serenely the use of this kind of UHPFRC in all its life cycle.

Keywords: recycling, ultra high performance fiber reinforced concrete, concrete mixture proportioning, calcined bauxite

1. Introduction

A new generation of concrete has appeared few years ago: Ultra High Performance Fiber-Reinforced Concrete (UHPFRC). They are characterized by a compressive strength higher than 150 MPa and a high volume of steel fibers providing them a noteworthy ductility. Their use is still marginal but the applications start to multiply: architectural thin elements (e.g. for frontage cover...), slender pre-stressed structural elements, sanitary appliances and even furniture.... A reference document [1] serving as a basis for use of these new materials in civil engineering was published in 2002, and many companies are involved in the development of their own UHPFRC. This confirms the increasing interest for this kind of material. As for recycling, two difficulties appear at a first glance: a high resistance versus its demolition on one hand, and the presence of fibers versus sorting, on the other hand.

LCPC has recently carried out a research on this topic within the Eureka European project called Innoconcrete, from December 2002 to June 2006. This project aimed at improving the knowledge on a particular UHPFRC developed by Eiffage company called CERACEM. Among other constituents, this UHPFRC includes calcined bauxite aggregate and a high content of steel fibers (around 190 kg/m3). It generally develops a compressive strength around 200 MPa without any thermal curing. The project was separated in different tasks aiming at improving the mixing process, the mix design, the surface quality and the structural design. Moreover, durability, potential new applications and finally the recycling and the life cycle analysis were addressed.

This paper presents the results obtained in the task concerning recycling. The concept of removable structures, allowing the recycling of entire structural elements, was out of the scope of this study, and the paper focuses on the material aspect. It shows that CERACEM can be crushed and separated into good quality sand on one hand and fibers on the other. Then, the paper describes a method for characterizing the sand in order to include it in a rational concrete mix design method. Finally recycling of crushed CERACEM in a self compacting concrete or in a new batch of CERACEM is evaluated.

2. Choice of a crushing method

Around 300 kg of CERACEM were cast in different types of samples (20x10x5 cm or 20x5x5 cm bars or 10x10x10 cm cubes) and kept in laboratory more than 28 days before being crushed with different methods. The mechanical properties of the samples where thus assumed to be representative of those which could be obtained at long term, when recycling question raises.

Two kinds of laboratory crushers where available at LCPC (see Fig. 1 and Fig. 2) for preliminary experiments, dealing with some kilograms of CERACEM. They shown that crushing with the jaw crusher was not efficient: samples tend to slip or to block the jaws, probably because the available gap between the jaws was not large enough compared to the samples thickness. We then obtained 'sea urchins'-type coarse aggregates with poor forms and with most of fibers remaining embedded in cement paste. The incorporation of such particles in concrete was not relevant, as they might lead to a poor workability. On the contrary, crushing with the impactor was quite easy and we obtained a mix of sand and fibers clearly separated. The jaws crusher was then excluded.

Fig. 1 Jaw crusher: the material is crushed between a fixed jaw and a mobile one.

Fig. 2 Impactor: the material is crushed by the impact of steel pieces in rotation around the horizontal axis.

In a second step and to facilitate the job in the laboratory, we proceeded a pre-crushing of 270 kg of CERACEM samples, with an industrial giratory crusher (see Fig. 3) adjusted to provide the finest grading curve (0-30 mm). The main part of the product was then submitted to a secondary crushing with the impactor available at LCPC. We finally obtained (see Fig. 4) a 0/3 mm sand with limited fine content (7 %) on one hand, and fibers with limited volume of residual paste (32.5 % in weight), on the other hand. The fibers were easily extracted with a magnet.

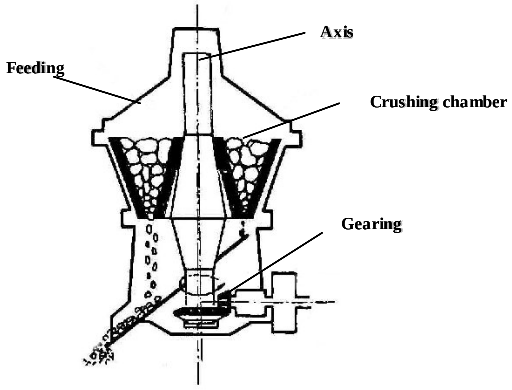

Fig. 3 Giratory crusher: the bottom of the axis is entrained around a circle by a gear; the top of the axis is fixed.

The remaining part (some kilograms) was crushed with a small giratory crusher available at the Regional Laboratory of Angers. Giratory crusher is the most widely spread type of crusher because it allows a high reduction ratio and a high production flow. Figure 5 shows that the grading curve of the final sand obtained with the impactor is almost the same as with the giratory crusher. This suggests that the process adopted for the study may be representative of a common career installation.

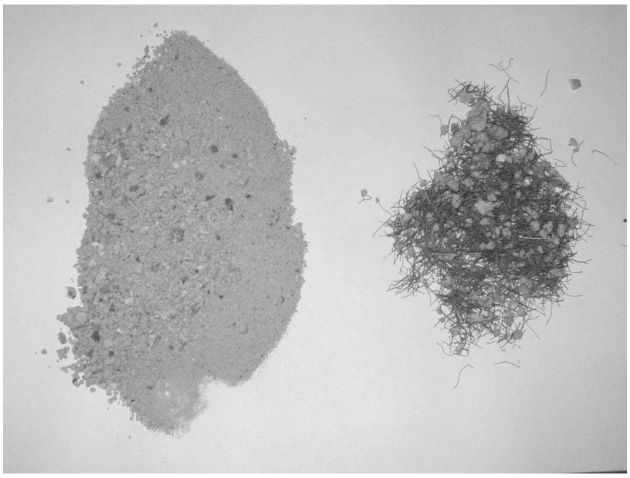

Fig. 4 0/3 mm sand and fibers obtained from CERACEM crushing

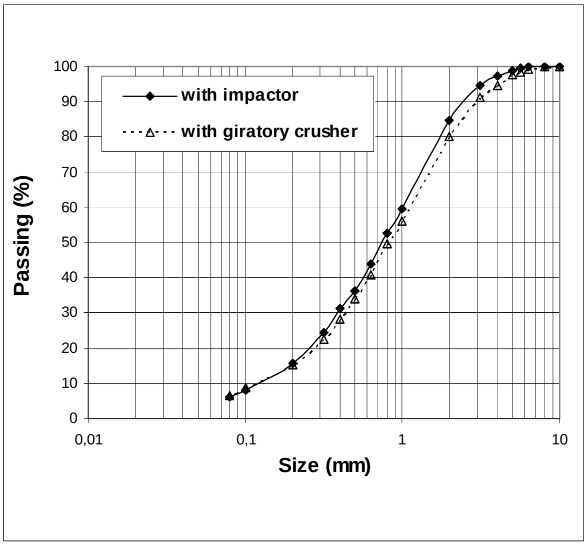

Fig. 5 Grading curve of sand obtained from CERACEM with two types of secondary crushing.

In conclusion, crushing of CERACEM and extraction of fibres appear to be easily feasible at industrial scale.

3. Evaluation of recycled sand properties

This part of the paper presents the characterization of the sand obtained from CERACEM crushing, as a constituent of concrete, which is a natural potential outlet for it.

As a basic information, the real specific gravity and the water absorption were evaluated according to NF EN 1097-6. There are equal to 2670 kg/m3 and 3.5% respectively. The water absorption is moderate compared to classical values obtained with sand recycled from normal strength concrete. The use of this sand in concrete should then not raise particular problem to maintain the workability of the fresh concrete nor need pre-saturation. This is due to the low water to cement ratio and the high volume of silica fume contained in the CERACEM.

As far as the concrete strength is concerned, this sand may act as a classical aggregate, but also as a binder. In fact, CERACEM has very low water content and a low permeability. Thus, an important part of the cement content will no be hydrated during the structure life. It is likely that a part of this unhydrated cement becomes available in the 7% of fine particles (less than 80µm), obtained after CERACEM crushing.

The characterization of this sand will then be made considering these two roles, on the basis of concrete mixture design concepts developed at LCPC. These concepts are summarized in [2] and presented hereafter.

It has been shown that the compressive strength of a concrete R_c can be calculated from the compressive strength of its matrix R_m with Eq. 1.

$$R_c = \frac{pR_m}{1+qR_m} \qquad (1)$$

Where p and q are aggregate properties:

- p describes the bond between aggregate and cement paste;
- p/q describes the 'ceiling' effect (limitation of concrete strength due to the aggregate strength). q=0 when the aggregate is hard.

Moreover the tensile splitting strength Rt_b depends on the compressive strength according the Eq. 2

$$R_{tb} = k_t . R_c^{0.57} \qquad (2)$$

where k_t is a characteristic of the aggregate.

The matrix compressive strength R_m can be calculated with Eq. 3 where A is the air content, W_{eff} the free water content and Rc_{28} the cement strength (according to EN 196-1). C_{eq} is the equivalent cement content, in terms of compressive strength. It includes the Portland cement content plus the reactive mineral addition, if any (fly ash, silica fume, limestone, filler…). The MPT is the maximum paste thickness. This term depends on the concrete composition and the packing density of the constituents.

$$R_m = 13.4 R_{c28} \left(\frac{1}{1+3.15\left(\frac{W_{eff}+0.5A}{C_{eq}}\right)} \right)^{2.85} MPT^{-0.13} \qquad (3)$$

For the calculations, we have first determined the virtual packing density (as defined in [2]) of each monosized class of the recycled sand. A 0.585 value was obtained which is classically observed for crushed rough fine grains. Then we have used BetonlabPro [3] software in which these concrete mixture design concepts are implemented.

The fine particles (< 80 µm) of the 0/3 mm sand are expected to release un-hydrated cement, thus we will assume that C_{eq} can, in that case, be defined by Eq. 4, where F is the content of fines coming from the recycled sand, and k a constant describing the chemical activity of these fines:

$$Ceq = C + kF = C(1 + kF / C) \qquad (4)$$

The value of k was determined by comparing the compressive strength measured on 4x4x16 cm samples at 7 and 28 days of two standard mortars (according to EN 196-1). Standard mortars are made with a hard siliceous normalized sand and with a water to binder ratio of 0.5. The first mortar was produced with a CEM I 52.5 N cement from Saint Pierre La Cour. In the second mortar, 25% in weight of the cement was replaced by fines (< 80 µm) sieved from the 0/3 mm sand. Considering that for the two mortars we have q=0 (the normalized sand is hard), the same values of p, Rc_{28} and MPT, k can be easily deduced from Eq. 3 and Eq. 4. Table 1 summarizes the results obtained.

Table 1 Results on normalized mortars

	7 days	28 days
Plain Mortar strength (MPa)	44.4	57.3
Mortar with fines strength (MPa)	31.1	43.1
k	0.28	0.413

These results confirm the chemical activity of the fines of the sand: 100 kg of sand contain 7 kg of fines which have the same role as 2.9 kg of cement.

In order to determine, the p, q and k_t values of the 0/3 mm recycled sand, we have designed mortars made up with this sand, with variable water to cement ratio. For each batch (10 liters), the temperature and the specific gravity (for air calculation) of the mortar were measured. Moreover, four Ø11x22 cm cylinders were cast (3 for compressive strength, 1 for tensile splitting strength). The batches volume was limited due to the small amount of recycled sand available for the research. The theoretical matrix compressive strength R_m of each mortar was calculated with BétonlabPro 2. Thus, having several pairs (R_m;R_c) and (R_{tb};R_c), it was possible to fit p, q and k_t with the mean square error method according to Eq. 1 and Eq. 2.

Cement content varied between 400 and 1000 kg/m^3 to give a wide range of water to cement ratio, and Chrysofluid GT superplasticizer was used to maintain an acceptable workability. The table 2 summarizes the mortars recipes and the results obtained.

No airmeter was available at the beginning of this study, except for the mix C480. The air content was then calculated from the mortars experimental specific gravity. The two air contents obtained for mix C480 present a significant difference. The analysis of the theoretical calculation underlined its sensitivity to water absorption of the recycled sand (and thus, its specific gravity). Nevertheless, the previous values were confirmed by new measurements and the difference remained unexplained.

Table 2 Composition and performances of mortars made of recycled sand 0/3 mm.

Mix (In kg)	C400	C480	C550	C650	C800	C1000
Recycled sand 0/3	1535	1486	1406	1321	1140	914
CEM I 52.5 N St Pierre la Cour	400	480	550	650	800	1000
Chrysofluid GT	0	0	0	6.5	13	16.5
Added water	265	267.8	265	264	271	298
Efficient water	211.3	215.8	215.8	222.3	240.2	277.6
De-aerated theo. volume (m^3)	0.913	0.925	0.917	0.924	0.923	0.940
Theoretical specific gravity (kg/m3)	2409	2416	2422	2425	2410	2372
Experim. specific gravity (kg/m3)	2221	2228	2247	2257	2260	2227
Calculated air (%)	7.8	7.8	7.2	6.9	6.2	6.1
Air (Mortar airmeter) (%)		3.1				
Slump (cm)	9.0	6.0	5.0	12.5	12.5	6.0
R_c at 28 days (MPa)	39.0	51.0	56.7	64.6	88.6	86.6
Rt_b at 28 days (MPa)	4.4	5.2*	5.2	4.5	5.6	5.5
MPt (mm)	0.219	0.264	0.307	0.378	0.422	0.645
Rm at 28 days (MPa) with calculated air	51.4	65.0	80.2	96.6	117.3	124.6
Rm at 28 days (MPa) with 3% of air	61.8	77.3	92.6	109.3	128.2	134.1

* measured on 3 samples

When calculated air values are used in R_m calculation, the curve fitting gives p=0.731 and q=0.0004 for the recycled sand. When a conventional air content of 3% is chosen, the fitted values are p=0.646 and q=0. These last values give a safer estimation of the compressive strength (ie a lower value for a given mix), and are thus adopted here. The p value is moderate compared to what could be expected considering the cementitious nature of the sand. The high p/q value can be explained by the high strength of the matrix and the calcined bauxite in the CERACEM.

Relationship between R_c and R_{tb} is of poor quality. This is probably due to the fact that only one cylinder was used to evaluate R_{tb}. Curve fitting gives a mean value of k_t=0.461. This value is in the top of the classical range observed on natural aggregates. Moreover, it is certainly a safe value as the model under-evaluates the value for mix C480, for which 3 cylinders were tested.

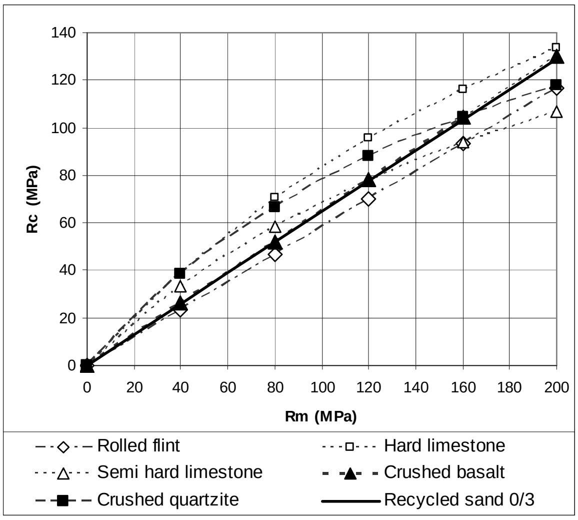

Fig. 6 R_c-R_m relationship for different aggregates

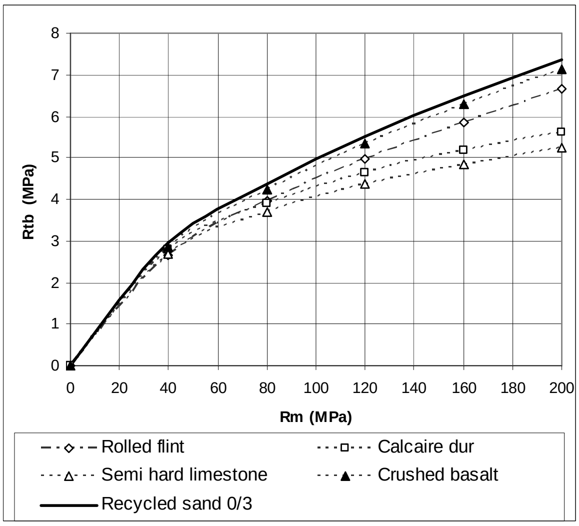

Fig. 7 Rt_b-R_m relationship for different aggregates

In conclusion, Fig. 6 and Fig. 7 show that the recycled sand 0/3mm have rather good mechanical properties compared to classical aggregates evaluated in [2], particularly if a high tensile strength is required.

4. Recycling of sand in high quality concrete

This chapter presents two examples of concrete using the 0/3mm sand recycled from CERACEM.

In a first time, a self compacting was made with a gneiss and a river sand with known properties (p=0.95, q=0.004 and k_t=0.44). Then, the river sand was replaced by an equivalent volume of recycled sand 0/3mm. BétonlabPro was used to adjust the water to obtain the same workability. The data are summarized in Table 3.

The experimental strength of SSC2 confirmed the theoretical values (R_c=37.9 and R_{tb}=3.7 MPa) calculated with the mechanical parameters of the recycled sand previously fitted. Because it is crushed and has larger water absorption, the recycled sand increases the water demand of the concrete. This effect was slightly underestimated here. In order to reach the same slump flow as SCC1, a maximum of 10 more liters water should be added in SCC2. This will lead to theoretical values of 35 and 3.5 MPa for R_c and R_{tb} respectively.

Table 3 Recycling sand in self compacting concrete

Mix (in kg)	SCC1	SCC2
Gneiss Pontreaux 6.3/10	840	840
Silico-calcareaous river sand Pilier 0/4	760	/
Recycled sand 0/3	/	790
CEM I 52.5 St Pierre La Cour	300	300
Limestone filler Bétocarb P2 Erbray	200	200
Chrysofluid GT superplasticizer	4.5	4.5
Added water	211	233
Slump flow (cm)	50	39
Yield stress* (Pa)	318	391
Plastic viscosity* (Pa.s)	51	59
Rc at 28 days (MPa)	34.7	38.1
Rtb at 28 days (MPa)	3.2	3.7

*measured with BTRHEOM [4]

In a second time, the calcined bauxite sand of a CERACEM recipe was replaced by the recycled sand. Results are shown in table 4. It can be seen that the slump flow was not affected and that decrease of compressive strength at 28 days was limited to 10%. This is an encouraging result for a high added value recycling when considering the important cost of calcined bauxite.

Table 4 Recycling sand 0/3 mm in CERACEM

Mix (in kg)	I1	I2
Bauxite sand	789	/
Recycled sand 0/3	/	789
Slump flow (cm)	54	52
R_c at 2 days (MPa)*	126.5	114.7
R_c at 28 days (MPa)*	211.4	189.9

*on 10x10x10 cm cubes

5. Recycling of fibers in CERACEM

Finally, recycled fibers were used to replace the fibers in CERACEM. In table 5, the weight of recycled fibers accounts for the 32.5% in weight of remaining paste after crushing.

The recycled fibers have no influence on the compressive strength, nor on slump flow. This last point can probably be explained even if recycled fibers are warped during crushing, by the high volume of paste. The increase of flexural strength at 28 days should be considered with care because tests have been realized on small 4x4x16 cm samples and perpendicularly to the cast flow.

Thus, the fibers orientation may not be relevant compared to a real structure. Flexural tests on larger samples, with post-pic analysis should be made to confirm these preliminary results.

Table 5. Recycling fibers in CERACEM

Mix (in kg)	I1	I2
New fibers	195	/
Recycled fibers	/	301
Slump flow (cm)	54	54
R_c at 2 days (MPa)*	126.5	128.5
R_c at 28 days (MPa)*	211.4	212,5
R_{fm} at 2 days (MPa)**	35	24.7
R_{fm} at 28 days (MPa)**	29.7	34.6

*on 10x10x10 cm cubes, **on 4x4x16 cm bars

6. Conclusions

This study has shown that CERACEM can be crushed in a 0/3 mm sand and fibers, which can be easily extracted with a magnet. At industrial scale, one should probably pay a special attention to crusher wear, because the product is quite abrasive.

A mechanical characterization of the recycled sand has been proposed, to include it in high added value concrete, thanks to a rational mix design method. This sand behaves like a hard sand and its fines (<80µ) have a moderate binder effect. Despite it is crushed, it can be used to replace a river sand in a self compacting concrete with no change in slump flow nor in strength. When used as replacement of calcined bauxite sand in CERACEM, workability is not disturbed and loss of compressive strength is limited to 10%.

Preliminary results show that fibers could be recycled in CERACEM with few consequences on properties. More validation is needed concerning the flexural behaviour.

In conclusion, this study makes it possible to consider serenely the use of this kind of material in all its life cycle.

7. Acknowledgement

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