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Quality improvement of mixed and ceramic recycled aggregates by biodeposition of calcium carbonate

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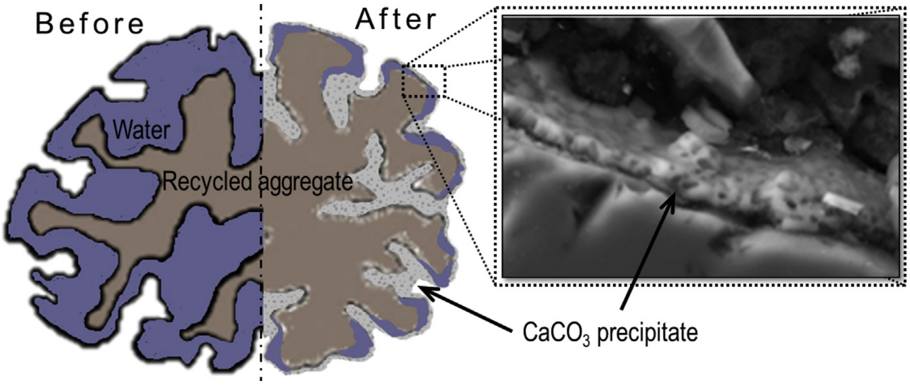
HIGHLIGHTS

- The biodeposition of $CaCO_3$ on RMA was proposed to reduce their water absorption.
- Commercial recycled mixed aggregates obtained from recycling plants were tested.
- $CaCO_3$ effect on water absorption, weight and consolidation of RMA was analysed.
- Characteristic appearance of precipitate from *B. sphaericus* was observed by SEM.
- Biodeposition had positive influence on RMA waterproofing.

GRAPHICAL ABSTRACT



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ABSTRACT

This research focuses on improving the quality of mixed and ceramic recycled aggregates by microbially induced carbonate precipitation (*Bacillus sphaericus*). The precipitation contributed to a weight increase and unleashed a waterproofing response. The roughness of the ceramic particles created a more uniform layer compared to natural or concrete particles. For the concrete fraction, which had a higher macroporosity, the consolidation effect was more pronounced. High ceramic content aggregates profited from a greater biodeposition, leading to a remaining amount of precipitates after sonication which was still greater than in cementitious materials. Pore-filling effect was detected by SEM, supporting the waterproofing result.

1. Introduction

Population growth and urbanization have accelerated consumption of concrete and construction and demolition waste generation, therefore the transformation of this product flow into raw materials used in the manufacture of new concrete is extensively researched in several countries during the last decades. Many studies [1–12] focusing on replacement of natural aggregates by recycled aggregates (RA), have shown the feasibility of such practices. However, several works reported that the high water absorption capacity of recycled aggregates due to their high

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porosity severely limits its acceptance in the construction market [10,13–15].

Several techniques have been studied to solve this problem: use of water-reducing admixtures [16,17], pre-saturation of recycled aggregates [10,18], chemical treatment [19,20], two-stage mixing approach [21,22]. This paper suggests the biodeposition of calcium carbonate on the mixed and ceramic recycled aggregates as a new technique to reduce the water absorption drawback.

Recently, bacterially induced carbonate precipitation has been proposed as an environmentally friendly technique to improve the durability of cementitious materials due to its protective effect based on consolidating or waterproofing properties. It has been applied as a consolidating surface treatment or as an effective way to seal cracks and fissures [23–39]. Several studies have been using ureolytic bacteria, because these bacteria are able to induce the precipitation of calcium carbonate by the production of the urease enzyme, which catalyzes the hydrolysis of urea to CO_2 and ammonia, resulting an increase of the pH and carbonate concentration in the bacterial environment [40–43].

The *Bacillus* group has been considered as one of the most suitable kinds of microorganism to reach a biologically induced mechanism of calcium carbonate precipitation [44,45], because they are found abundantly in natural environments, they can be easily cultivated and they show a remarkable potential to form large amounts of calcite in a relatively short time. The type of mineral produced is largely dependent on the environmental conditions [46] and no specialized cell structure or specific molecular mechanism is thought to be involved [47]. *Bacillus pasteurii* [24,29,48–52], *Bacillus lentus* [52,53], *Bacillus sphaericus* [25,26,29,37,53,54], *Bacillus cereus* [30], *Bacillus subtilis* [55,56], *Bacillus megaterium* [57], *Bacillus pseudofirmus* [58], etc. have been proven potentially useful for biodeposition of calcium carbonate in construction materials.

Microbially induced carbonate precipitation has been considered first for the protection of ornamental stones and limestone monuments. In situ applications were performed [40,42,54,56,59], leading to a further optimization and industrialization of the technique, based on the collaboration between the French company Calcite Bioconcept, the Laboratory for Research of Historic Monuments and the University of Nantes [30]. Subsequently, biodeposition was investigated as a surface treatment for cementitious materials [25,26,33,34,53]. The promising results of this technique encouraged our research group to evaluate the effect of biodeposition on mixed and ceramic recycled aggregates destined to be used in concrete production as replacement of natural aggregate. The aim was especially to solve the important problem of high water absorption values associated commonly with this type of materials. *B. sphaericus* was the microorganism chosen for this application.

Only a limited amount of previous studies exist about the improvement of the properties of recycled aggregates using biodeposition [49,50] and they are focused on recycled concrete aggregates, which come from 100% old concrete. Furthermore, these manuscripts only analyse recycled aggregates that were entirely obtained from concrete that was specifically prepared for laboratory biodeposition tests, no previous experiments have been performed on commercial recycled aggregates obtained from recycling plants.

The major novelty of our work lays exactly in these aspects. The 3 different samples of recycled aggregates used for this work are commercial products. They are obtained from three European recycling plants (two of them located in Spain and another one in Belgium), with different contents of concrete, unbound natural aggregates and ceramic. Attention was paid to the effects of their variable composition especially regarding the ceramic fraction (with contents higher than 33% in all the samples), since RA contains not only old concrete, and the ceramic fraction usually plays an essential role in this type of recycled material [1–3,9,12,60].

2. Materials and methods

2.1. Mixed and ceramic recycled aggregates

Mixed and ceramic recycled mixed aggregates were obtained by crushing of construction and demolition waste (CDW) in three CDW recycling plants, two from Spain (TEC-REC sample: Tecnología y Reciclado S.L., Madrid, and BIERZO sample: Bierzo Recicla S.L., Leon) and one from Belgium (ANTWERP sample: Antwerp Recycling Company, Antwerp). Coarse aggregates 4–20 mm were used in the research. The properties of RA were determined according to the EN 12620+A1 [61] standard and are summarized in Table 1.

The composition of RA samples used in this study was obtained according to the European standard EN 933-11 [62] and is shown in Table 2. According to the Spanish Association Managers of Construction and Demolition Waste [63], TEC-REC and ANTWERP samples were considered mixed recycled aggregates, because their ceramic content was higher than 30% and lower than 70%. The BIERZO sample was defined as ceramic recycled aggregate, since its ceramic content was greater than 70%. Most of the ceramic particles in the BIERZO sample came from roof tile and brick wastes. The ceramic content of TEC-REC and ANTWERP samples had a more heterogeneous origin (bricks, roof tiles, sanitary ware, tiles…).

These RA samples were chosen mainly due to their composition, and especially their ceramic content, considering that TEC-REC and ANTWERP samples show a typical composition of the construction and demolition waste from Mediterranean countries, where ceramic materials, such as roof tiles and hollow bricks in façades and partition walls, are one of the mainstays in terms of construction materials [3]. The BIERZO sample has been chosen for this study since its high ceramic content could help to understand the different effect of bacterially induced carbonate precipitation on RA depending on the presence and amount of ceramic fraction.

The attached mortar content of the three RA samples has been determined (Table 3), since generally this material plays a key role in the water absorption of the recycled aggregates. The method used was designed based on the techniques followed by Tam et al. [60], in their study on removal of cement mortar remains from recycled aggregates. In this case, the RA samples were soaked in hydrochloric acid (HCl) with concentration of 0.1 mol (this concentration was chosen in order to remove the old cement mortar, but not decrease the aggregates quality or remove other cement based materials, which were integrated into the aggregate) at around 20 °C for 24 h. Subsequently the samples were rinsed with distilled water to remove the acidic solvent. Taking into account the dry weight before and after the soaking treatment, the attached mortar content is calculated.

Taking into account published research findings [64], which said that porosity has a pronounced effect on the immobilization of microbial cells, a mercury intrusion porosimetry test (MIP) was applied on ceramic and cement-based particles from recycled aggregates. The tests were conducted using a Micromeritics AutoPore IV 9500 porosimeter, which operates in the pressure range 0.0034–227.5270 MPa over a pore diameter range of 0.006–175 µm. These results of pore size distribution are discussed in conjunction with the consolidating effect of the biodeposition treatment.

2.2. Bacterial strain and cultivation conditions

B. sphaericus LMG 222 57 (Belgian Coordinated Collection of Microorganisms, Ghent) was used for this research. Based on the studies of Dick et al. [53], this strain is able to precipitate calcium carbonate ($CaCO_3$) on its cell constituents and in its micro-environment by decomposition of urea ($CO(NH_2)_2$) into carbonate (CO_3^{2-}) and ammonium (NH_4^+). Later, the carbonate promotes the microbial deposition of $CaCO_3$ in a calcium rich environment.

Liquid culture media used to grow *B. sphaericus* consisted of autoclaved yeast extract and filter sterilized urea solution. The final concentrations of yeast extract and urea were 20 g/l and the pH of the medium was 7. Cultures were obtained after two times subsequent culturing (using 1% inoculums) from a −80 °C stock culture.

Table 1
Properties of RA samples.

	TEC-REC	ANTWERP	BIERZO
Maximum particle size (mm)	16.00	16.00	16.00
Minimum particle size (mm)	4.00	4.00	4.00
Granulometric modulus	7.67	7.75	7.96
Fines content (%)	0.04	0.87	0.72
Apparent density (Mg/m^3)	2.53	2.51	2.65
Oven-dry density (Mg/m^3)	2.08	2.06	2.29
Saturated surface dry density (Mg/m^3)	2.26	2.24	2.43
Flakiness index (%)	14.75	19.10	24.67
Los Angeles coefficient (%)	40.99	39.00	33.23

Table 2
Composition of RA samples.

Component (%)	TEC-REC	ANTWERP	BIERZO
Ru: Unbound natural aggregates	17.5	22.5	0.0
Rb: Ceramic materials	33.6	38.4	97.9
Rc: Concrete and mortar	44.1	37.1	2.1
Ra: Asphalt	0.4	1.7	0.0
Rg: Glass	0.8	0.0	0.0
X: Others (Gypsum)	3.6	0.3	0.0

Table 3
Attached mortar content of RA samples.

Sample	Attached mortar content (%)
TEC-REC	3.49
ANTWERP	3.07
BIERZO	2.08

Then they were incubated at 28 °C on a shaker at 100 rpm for 24 h. The final concentration of bacteria cells in the *B. sphaericus* culture was about 10^8 cells/ml and the pH reached the value around 9.3.

2.3. Biodeposition treatment of recycled aggregates

Biodeposition treatment was performed in an air conditioned room (20 °C, 60% RH) under static and non-sterile conditions (open to the air). In the first step, dry recycled aggregates were immersed for 24 h in one day old *B. sphaericus* grown culture. After this incubation period, aggregates were removed from the culture solution. In the second step, aggregates were immersed for 4 days in a deposition medium containing 12 g/l of urea, 47 g/l of $Ca(NO_3)_2{\cdot}4H_2O$ and 5 g/l of yeast extract. After this immersion time, the treated aggregates were gently washed and drained to remove calcium carbonate precipitate which had a weaker bonding with the aggregate surface.

2.4. Effect of biodeposition treatment on recycled aggregates

2.4.1. Weight variation

The weight of biotreated aggregates should increase after the calcium carbonate deposition, as it could be expected. To test this fact, 6 subsamples were taken from each RA studied sample (3 subsamples with a particle size of 4–12.5 mm, further referred to as S group, and the other 3 samples with a particle size 12.5–20 mm, called L group). Dry weight of RA subsamples was recorded (oven-dried at 78 °C for 48 h) before and after biodeposition treatment. The weight change, could serve as estimation for the amount of calcium carbonate that was precipitated.

2.4.2. Water absorption

To evaluate the waterproofing effect of the biodeposition treatment, water absorption tests on the recycled aggregates were performed with treated and untreated samples, which were divided by dimension in two groups (S group and L group, as described earlier), to determine also the influence of sample size on the performance of the biodeposition treatment. This test was carried out with the pycnometer method according to the European Standard EN 1097-6 [65], but with modified temperature, since temperatures higher than 78–90 °C could remove interlayer water from some existing components such as C-S-H gels [66] and distort the results. Therefore, although the established temperature of drying in this standard was 105 ± 5 °C, in this case 78 °C was chosen and the drying time period was extended from 24 h to 48 h.

2.4.3. Resistance to sonication

Ultrasonication helps to estimate the adhesion force and the consolidation efficacy of the newly formed calcium precipitate [54]. Biotreated and untreated aggregates were subjected to six cycles of sonication. During each cycle, the sample was immersed in distilled water in a 35-kHz ultrasonic bath (Bandelin Sonorex, Bandelin Electronic GmbH & Co.) and after 5 min the aggregates were taken out from the bath and were dried for 48 h in an oven at 78 °C. The weight loss after ultrasonic attack was then determined by weighing the aggregates again. Therefore, the resistance to sonication was represented by the difference between dry weight in the initial state (aggregate before sonication attack) and dry weight after each sonication cycle.

2.4.4. Characterization of the calcium carbonate biodeposition crystal by SEM analysis

By Scanning Electron Microscopy (SEM), the microstructure and the distribution of the calcium carbonate deposition on the mixed and ceramic recycled aggregates were analysed. Chemical composition of the precipitate was evaluated by Energy Dispersive X-ray (EDX) analysis. Both analyses were performed by using a Hitachi S-4810 microscope. This equipment was also used to test the superficial morphology of RA particles.

3. Results and discussion

3.1. Weight variation

The calcium carbonate precipitation, induced by the bacterial treatment, can be seen as a white layer on the RA (Fig. 1). As shown the Fig. 2, the biodeposition treatment increased the weight of all RA tested samples, and this weight gain depends on several factors. First, the greater percentage of weight increase was detected in the samples from the S group, 16–46% higher than for the L group. This was probably caused by the higher surface/volume ratio of the S group samples, in comparison with the samples of the L group, and taking into account that biodeposition is considered a surface treatment by several authors [25,50,67]. This statement was confirmed in the present paper by SEM analysis (see further). Secondly, the weight increase was growing with the increase of ceramic content in the RA sample. This may be related to the roughness of the RA particles, considering that the ceramic aggregate surface has a greater roughness than unbound natural aggregates. Therefore, the biodeposition is easier on the surface of ceramic and cement-based particles. In addition, ceramic aggregates roughness is lower than that shown by old concrete particles (this fact has been qualitatively checked by SEM analysis, as shown in Fig. 3). The surface of these concrete particles seems too irregular to allow the deposition of calcium carbonate in larger $CaCO_3$ layers, whereas the less irregular ceramic surface allows the generation of a more continuous calcium carbonate layer (Fig. 1). These results are in concordance with the information obtained from the sonication test of the current research.

All test samples showed higher weight gain than the material discussed in the published research of Qiu et al. [50], which displayed a weight increase of 1.03% in the 100% concrete recycled aggregates (5–20 mm particle size) when microbial carbonate precipitation was carried out with bacteria concentration of 10^8 cells/ml, at 35 °C and pH 9.5 and with a solution containing 16.8 g/l of calcium. Their lower values of weight increase may be related to the lack of ceramic content in the tested recycled aggregates.

It is important to highlight the observation of some authors [68–70], who state the profound effect of calcium concentration and method of calcium and urea addition on the biodeposition treatment. Previous studies of the authors of this paper [36,37,71,72] have reported that the chosen parameters for biodeposition treatment in the current research are suitable to achieve an optimal microbially induced carbonate precipitation on construction materials.

3.2. Water absorption

Based on the results of water absorption of the RA before and after biodeposition (Fig. 4), it can be assumed that this technique reduces the water permeability of all tested samples, although only to a limited extent (3% of reduction for S samples of ANTWERP, with a greater decrease for the larger aggregates (18% for L samples of TEC-REC and 10% for L samples of BIERZO). The difference in the reduction of water absorption between both size classes is 46% for TEC-REC samples, 41% for ANTWERP samples and 16% for BIERZO samples. This behavior is probably associated with the higher content of cement-based particles in the TEC-REC and ANTWERP samples, considering that larger particles of recycled concrete or mortar usually show wider and longer cracks compared with smaller cement-based particles, resulting in a larger quantity of calcium

Fig. 1. Samples appearance after biodeposition treatment.

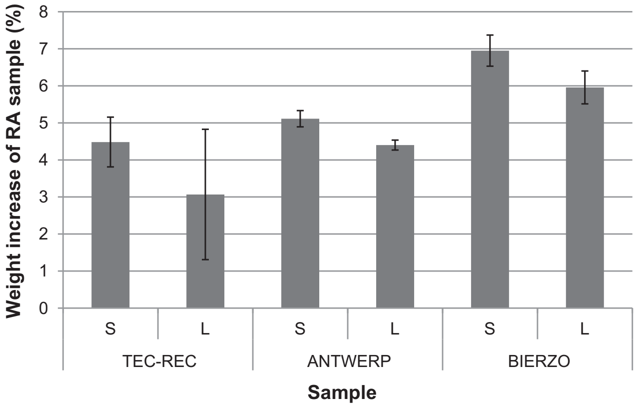

Fig. 2. Weight increase of RA samples after biodeposition.

precipitate being attached in these areas leading to the registration of a more pronounced waterproofing effect.

The reduction in water absorption could be also dependent on the composition of recycled mixed aggregates. The test results pointed to a lower water absorption reduction when the unbound natural aggregates content in the samples was greater (in the ANTWERP sample with the highest content of unbound natural aggregates according to Table 2, the reduction was 2.7% for the S group and 3.8% for the L group). However, samples with higher content of cement-based particles (TEC-REC sample) showed a greater reduction of water absorption (11.7% for the S group and 17.9% for the L group). The higher attached mortar content of the TEC-REC sample, according to the data shown in Table 3, in turn coincided with a higher reduction of water absorption after biotreatment.

The cause of this behavior could be the roughness and the porosity, especially macroporosity, of the different constituents present in recycled aggregate samples, since the roughness and the porosity of cement-based particles is higher than that of unbound natural aggregates [4,6,7,10,11]. Declet et al. [73] stated that the surface roughness can affect the adhesion of the calcium carbonate precipitate onto the aggregate surface, therefore it is expected to be more powerful on ceramic and cement-based particles. Also the higher porosity and roughness of ceramic and cement-based particles than these properties in the unbound natural aggregates affects the production of precipitate because more calcium carbonate can be deposited on the more rough and porous surfaces, where the less irregular surface of ceramic particles allows the generation of a more continuous calcium carbonate layer. The greater macroporosity of cement-based particles in comparison with ceramic ones, as shown in the MIP analysis (Fig. 5), justifies the higher waterproofing effect on samples with more concrete and mortar particles, since greater $CaCO_3$ is deposited inside the superficial macropores, in comparison with the more continuous biofilm that is formed over the surface of ceramic particles, which offers a lower pore-filling effect.

Authors as Grabiec et al. [49] and Qiu et al. [50] claimed that the biodeposition process, using in their cases the microorganism *B. pasteurii*, led to reduction in the water absorption of recycled aggregate produced by crushing 100% old concrete. They tested different bacteria concentrations and recycled aggregate qualities. Grabiec et al. [49] observed a water absorption decrease of 30–35% for aggregates of particle size 6/8 mm, and 50% drop in water absorption for particle size 12/16 mm, when a bacteria

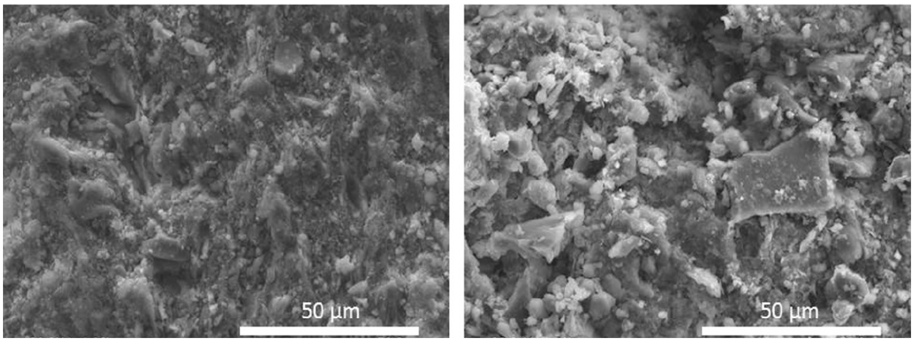

Fig. 3. Surface SEM images of ceramic (left) and concrete (right) recycled aggregates.

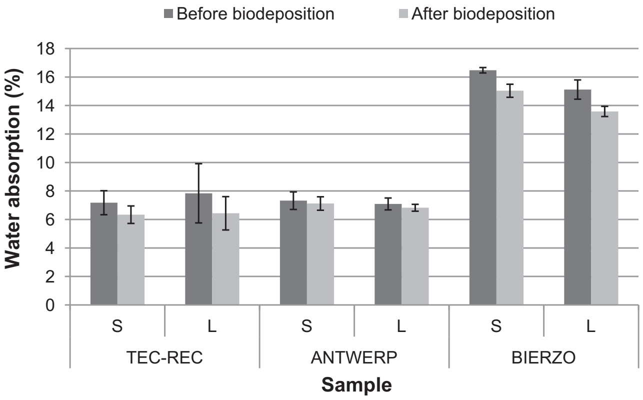

Fig. 4. Water absorption of recycled mixed aggregates before and after biodeposition.

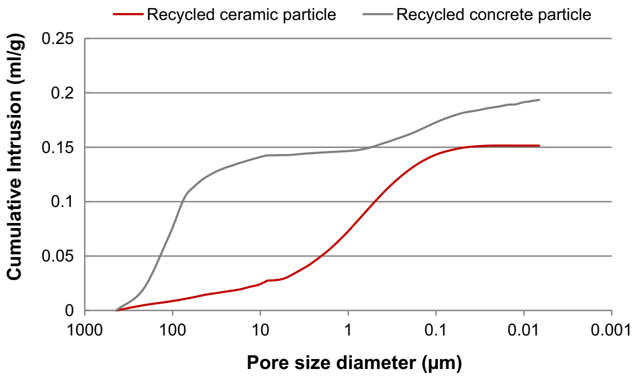

Fig. 5. Pore size distribution of recycled ceramic particle and recycled concrete particle.

concentration of 10^7–10^8 cells/ml was applied at 30 °C temperature. Qiu et al. [50] tested the effect of biodeposition on recycled concrete aggregates of particle size 5–20 mm, showing that a treatment with bacteria concentration of 10^6 cells/ml, at 25 °C, pH 8.2 and 5.6 g/l of calcium content, decreased the water absorption of recycled aggregates with 8%. When the bacteria concentration was 10^8 cells/ml, and application conditions were 35 °C, pH 9.5 and 16.8 g/l of calcium content, the water absorption was reduced by 8–16%. The greater effect of water absorption decrease published by these authors when the bacteria concentration was similar to the one used in the present research (10^8 cells/ml) may be explained by the higher content of cement-based particles present in their recycled aggregate samples (100% concrete).

3.3. Resistance to sonication

RA or different composition exhibits differences in resistance against ultrasonic attack of the samples. As shown in Fig. 6, the sample with higher content of cement-based particles (TEC-REC) displays that biotreated aggregates register 44% less weight loss upon sonication than untreated aggregates in case of L size and 6% for the S size. This result can be compared with the findings of De Muynck et al. [74], which support that concrete prisms treated with bacteria in culture liquid and biodeposition medium exhibited greater resistance to sonication than untreated prisms. This consolidating effect can be associated to the stronger bond that calcium precipitate provides to the cementing layer between the surfaces of the concrete or mortar aggregate. In the same way as for the water absorption results, this positive effect is more obvious for the bigger particles because they have wider and longer cracks and a larger quantity of calcium carbonate can be deposited on those surface cracks.

When the ceramic content increases in the sample (as for the BIERZO RA), the resistance to sonication increases for both treated and untreated aggregates. However, for these RA the biotreated aggregates exhibit greater weight loss than untreated aggregates, 74% higher in case of S size and 98% for the L size. Nevertheless, since more $CaCO_3$ has been deposited on the ceramic aggregates in the first place (Fig. 2), the remaining amount of carbonate deposition would be still much larger than for the RA with lower ceramic fraction (Fig. 6).

Porosity testing of ceramic and cement-based particles from recycled aggregates supports the stronger pore-filling effect by calcium precipitate on recycled concrete aggregates, since as can be seen in the Fig. 5, particles from old concrete show greater

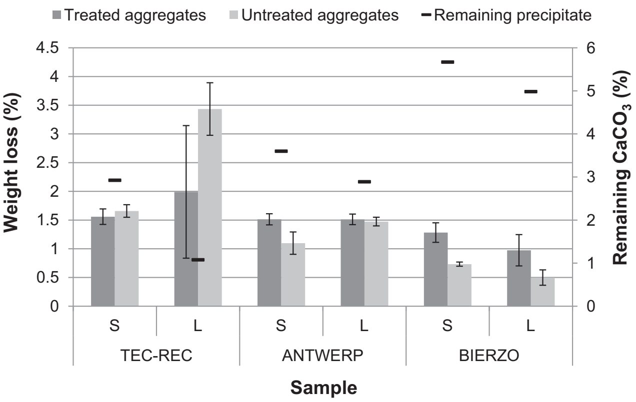

Fig. 6. Weight loss of treated and untreated RA samples after six cycles of sonication, and remaining amount of $CaCO_3$ of treated samples.

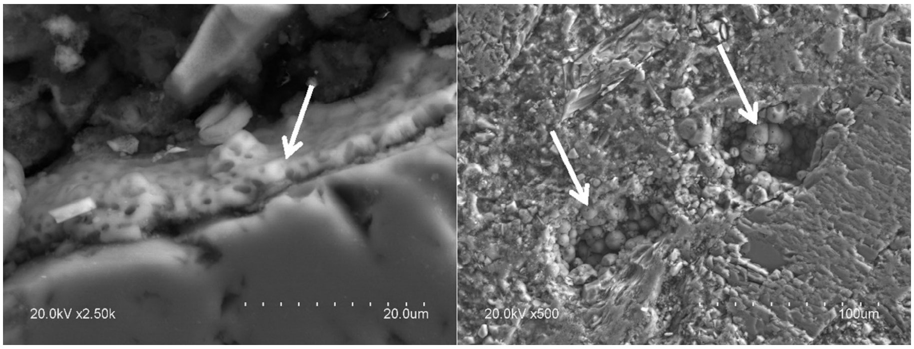

Fig. 7. $CaCO_3$ precipitate over the aggregate surface (left). $CaCO_3$ precipitate in aggregate pores (right).

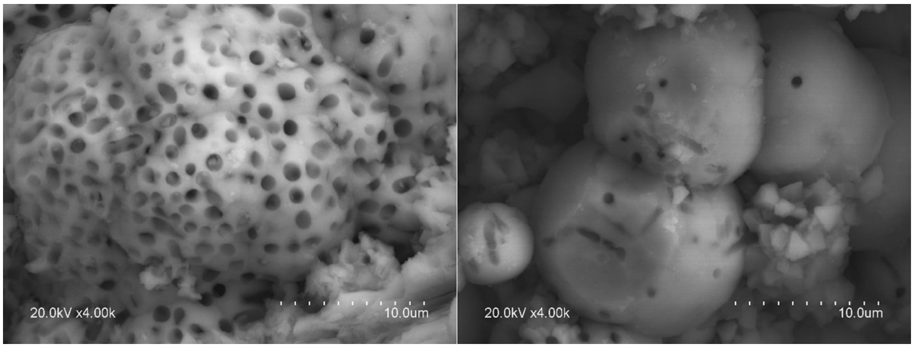

Fig. 8. $CaCO_3$ precipitate with high bacterial activity (left). $CaCO_3$ precipitate with low bacterial activity (right).

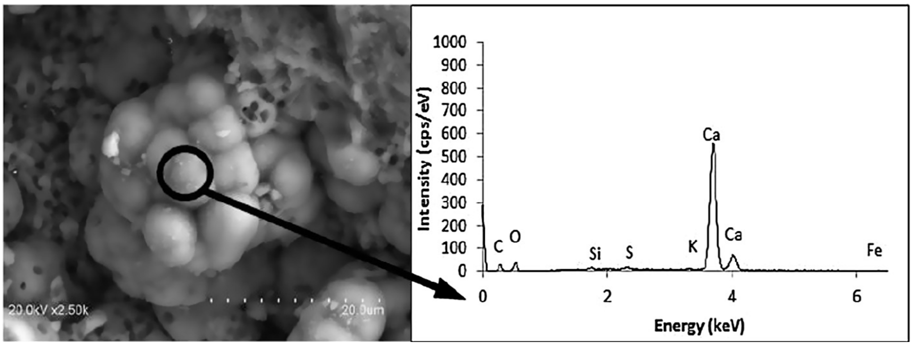

Fig. 9. SEM image, EDX spectra and element composition of $CaCO_3$ precipitate on biotreated RA.

porosity, with especially a greater amount of pores with diameter larger than 1 μm. On the other hand, the pore size distribution of ceramic particles from RA displays a lower presence of macropores, which results in a limited deposition of calcium carbonate inside the pores, although a more continuous carbonate layer is formed and the adhesion to the particle surface of intermediate roughness is better than for recycled concrete aggregates.

3.4. Characterization of the calcium carbonate biodeposition crystals by SEM analysis

SEM analysis (Fig. 7/Left) allows seeing the calcium carbonate deposition over the surface of the aggregate with a uniform and low thickness, in concordance with the results published by Kim et al. [29], who tested biodeposition of *B. sphaericus* and *B. pasteurii* on normal and lightweight concrete samples. Although, in their case, the appearance of $CaCO_3$ precipitate showed a more irregular surface of the crystals, in comparison with the more regular $CaCO_3$ crystals displayed in this paper, on the areas where there were not too many imprints of bacterial cells (Fig. 8).

The calcium carbonate stratum on this kind of RA is easy to recognize because the microbial deposition of *B. sphaericus* has a characteristic appearance, it looks like a white agglomeration of globular structures, which show the imprints of bacterial cells involved in carbonate precipitation, more or less prevalent according to the bacterial activity in each area (Fig. 8). The biodeposition of *B. pasteurii* shown in the study of Qiu et al. [50] was composed of crystals of spherical shape, but the crystals had a smooth surface without the empty spaces that were noticed in the current *B. sphaericus* deposition. In addition, the spherical structures from *B. pasteurii* were distributed with less compactness than the crystals from *B. sphaericus* seen in this study. Grabiec et al. [49] referred to the presence of crystals of calcium carbonate from *B. pasteurii* over the surface of recycled concrete aggregates, but in their case, the $CaCO_3$ crystals showed more irregular shapes in comparison with the deposition evaluated in the present research. This aspect of variability between different papers may be explained by the nutrients used during the cultivation and biotreatment conditions, since De Muynck et al. [25] confirmed that the type of medium composition had a profound impact on calcium carbonate crystal morphology.

Fig. 7 (Right) makes it possible to see the partial pore-filling effect of the biodeposition treatment, since globular calcium carbonate precipitate has been detected on the internal pore surface of a recycled ceramic aggregate, improving impermeability of the treated aggregate. When the calcium carbonate layer over the aggregate surface and the pore-filling effect are taken into account, a waterproofing result is expected, which is concordant with the reduction of the water absorption values for biotreated aggregates.

The pore-filling effect of the treatment with this kind of bacteria may be compared to the incorporation of these or other types of bacteria into porous aggregates to induce self-healing of cracks in concrete. However, in the current treatment vegetative bacterial cells are used to obtain an immediate precipitation of calcium carbonate by subsequent submersion of the aggregates in the bacterial culture and a nutrient solution. Hence, the calcium carbonate precipitation is formed on the aggregates before they are added into the concrete mix. In case self-healing is aimed at, the bacteria should be introduced in dormant stage, as bacterial spores, into the porous aggregates. They should remain dormant until the aggregate is fractured by a propagating crack. Only at that stage they will make contact with nutrients and oxygen, they will germinate and induce bioprecipitation that will fill the crack, as has been illustrated by the research groups of Jonkers (TU Delft, The Netherlands) and De Belie (UGent, Belgium) [75,76], among others.

EDX results summarized in Fig. 9 confirm that the globular shapes are likely to be calcium carbonate precipitate because they have as main component calcium, followed by oxygen and carbon.

4. Conclusions

Bacterial precipitation acts as superficial treatment of the recycled aggregates, covering the external part of the aggregate and filling some superficial pores. Treatment with a *B. sphaericus* culture with about 10^8 cells/ml provides an easy method to control the precipitation of calcium carbonate on recycled mixed aggregate under suitable conditions of distribution and quantity.

This biological technique increased the weight of RA, more noticeable when the particle size was smaller and the ceramic content of aggregate samples was higher, due to the relation surface/volume and the roughness of the aggregate, and considering that this technique of microbially induced deposition imparts mainly a superficial effect.

The produced calcium carbonate deposition created a limited waterproofing effect, which allowed to decrease the water absorption of the RA. This will enhance the concrete workability without the need to increase the water content. This is in turn beneficial for the concrete permeability and the reduction of the penetration of aggressive substances that can accelerate the degradation of concrete in its future applications. These waterproofing crystals had greater effect when the content of cement-based materials in the RA sample was higher.

The consolidating effect of $CaCO_3$ on recycled aggregates seems to be more profound on RA with higher content of concrete and mortar particles since the precipitated layer reduces the mass loss under ultrasonic attack. The opposite effect is seen on RA with high ceramic content. Nevertheless, since more $CaCO_3$ was deposited on the ceramic particles in the first place, the remaining amount of precipitates would still be higher than in the case of cementitious materials. The reason could be the higher macroporosity in the case of cement-based particles allowing the calcium carbonate crystals to deposit rather in the pores than on the surface and creating a consolidating effect. On the other hand, the biodeposition of calcium carbonate on the ceramic aggregates is rather on the surface and a small part of this deposition seems to be removed by the sonication.

This study showed by SEM analysis that induced calcium carbonate precipitation using *B. sphaericus* on RA presented a peculiar appearance which was characterized by spherical shapes with imprints of bacterial cells involved in carbonate precipitation being more or less prevalent according to the bacterial activity.

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