Durability of mortars with leftover recycled sand

Manh Tan Le, Christelle Tribout, Gilles Escadeillas

Durability of mortars with leftover recycled sand

Manh Tan LE [a]*, Christelle TRIBOUT [a], Gilles ESCADEILLAS [a]

[a] Université de Toulouse, UPS, INSA; LMDC (Laboratoire Matériaux et Durabilité des Constructions), 135, Avenue de Rangueil; F-31 077 Toulouse Cedex 04, France

* Corresponding author. Tel +33665087813; E-mail address: mtle@insa-toulouse.fr

1. Introduction

Concrete is the most widely used material in construction. However, it has a negative impact on the environment due to the consumption of non-renewable resources (rocks for cement and aggregates, oil to produce the energy needed to manufacture it), production of greenhouse gases during cement production (about 1 ton of CO_2 per ton of clinker) and waste during its manufacture. For environmental and also economic reasons, it is becoming urgent to reduce the environmental impacts of concretes by reducing or optimizing wastes at the manufacturing stage. Such is the aim of this research.

Most concretes used on construction sites are made with ready mixed concrete manufactured in a concrete batching plant. A manufacturer produces about 40,000 m^3 of fresh concrete annually [1]. These concretes are transported from the plant to the construction site by mixer truck. If too much concrete is ordered, the leftover concrete is returned to the factory and goes to waste. The fresh concrete that becomes waste in Europe is estimated at 1-4% of the total amount of concrete processed, depending on the location or region [2]. Within the EU, 234 million m^3 of ready-mix concrete was produced in 2013. With a return rate of 3%, the amount of leftover ready-mix totaled 7 million m^3/year, with a value of 466.2 million euros [3]. This means that the residual concrete of each ready-mix plant is 1,600 m^3 per year, or around 4,000 tons of concrete. The cost of storing and processing such amounts is also huge. Therefore, it is necessary to find sustainable recovery solutions for this concrete.

Currently, the profession uses two solutions for residual concrete. The first is to wash the concrete returns, to separate the aggregates and loaded water. Aggregates can be reused for road building

and the loaded water is used for the next production of concrete. The second solution is to dump the returns in skips, leave this residual concrete to cure for a few days and then crush it (Figure 1). In this study, the residual concrete is treated by the second solution.

Although large aggregates (gravel) can be reused without difficulty [4], the same cannot be said for fine aggregates (sand). Evangelista et al. [5] show that recycled sand (RS) has characteristics and behavior that are very different from those of natural sand. Because of the way it is produced, the shape of RS is irregular, apparently with high roughness and surface area. Moreover, its mineralogical composition is very rich in calcium or siliceous oxide and cement. Obviously, the layer of hydrate absorbs water. Zhao et al. [6, 7] show that the quantity of linked hydrate in the RS is different for each fraction and, consequently, the water absorption coefficient of the RS is also different. Some research has focused on modeling to find a method for determining the water absorption coefficient of each fraction [6, 8]. The newly developed and traditional methods (NF EN 1097-6) give very similar results for the fraction larger than or equal to 0.8 mm. However, for the fraction smaller than 0.8 mm, the methods give very different values. The workability of mortar is also strongly influenced by the moisture condition of the RS. Remond et al. [9] show that the time necessary to obtain moisture equilibrium in the pre-saturation state is above 7 days.

When the RS is substituted in the mortar, the strength of the mortar can drop by as much as 60% of the initial value for mortar without RS [10]. Zhao et al. [6] show an important influence of the finest fraction (less than 0.63 mm) of the RS since it engenders the most penalizing effect on the mechanical properties of mortars.

Although there are still problems, the performance of the concrete may be acceptable for some ways of valorization. The mechanical performance is low and presents uncertainty but use is possible in some cases. For sustainable use, it is also necessary to study the durability of mortars in which RS is incorporated.

The work presented here mainly studied RS durability. Many indicators of durability were considered (air permeability, chloride ion migration, capillarity, carbonation and porosity accessible to water) according to the mortar composition. The results were compared with those for reference mortars made with natural sand. In order to take account of the fact that outside storage of this young concrete leads to its carbonation, two series of mortars were formulated by replacing natural sand (NS) with either non-carbonated recycled sand (RS) or carbonated recycled

sand (CRS). We know that natural carbonation is a very slow process. Recycled aggregates, especially fine parts, incorporate portlandite and hydrated silicates that can be carbonated faster than concrete in structures. A French national project named FastCarb [11] is dealing with the study of the accelerated carbonation. Started in 2018, its aim is to store CO_2 in "recycled concrete aggregates" in an accelerated manner, to improve the quality of these aggregates by blocking the porosity and, ultimately, to reduce the CO_2 impact of concrete in structures.

2. Materials and methods

2.1 Materials

2.1.1 Sands

The leftover concrete was formulated with siliceous aggregates and CEM I or II as is usually done in the region of Toulouse, France. This remaining concrete had been dumped and left to harden.

After crushing in industrial conditions**,** the recycled aggregates were stored in closed bags to prevent supplementary carbonation. These aggregates were sieved with a 4 mm mesh in order to keep only the sand fraction, which was dried at 80°C to constant mass.

Three sands were used:

- a non-carbonated **R**ecycled **S**and (RS). For some parts of this study, the RS was divided into 3 fractions: Fine (f) - 0/0.25 mm, Medium (m) - 0.25/1 mm and Coarse (c) - 1/4 mm;
- a **C**arbonated **R**ecycled **S**and (CRS) obtained by placing the RS in an accelerated carbonation chamber with 50% CO_2 and 60% RH for 1 week. CRS was studied only on the total range of 0/4 mm;
- a **N**atural **S**and (NS), rounded, with the petrographic nature of silica sand, grading 0/4 mm. As for RS in some parts of this study, the NS was also divided into 3 fractions Fine (f), Medium (m) and Coarse (c).

The particle size distributions of NS and RS are shown in Fig 2. The NS curve is typical of the natural river sands of the Toulouse region of France. The RS and CRS curves are typical of crushed sands and particularly of sand from crushed mortar [9]. CRS is simple RS that has been carbonated, which changes its chemical composition but not its shape. Thus, particle size distributions of RS and CRS were similar and only the RS curve is presented.

Fig 3 gives the water absorption coefficient (WA) of the studied sands, determined with the standard method 1097-6 [12]. RS has the largest value with 12.5% WA, followed by CRS with 8.1%, and NS with 1.2%. The presence of old cement paste in RS induces an increase of about 10% of WA, compared to NS. The WA of CRS decreases with respect to RS due to calcium carbonate precipitation, which appears during the carbonation of portlandite and C-S-H. This new component increases the volume of the solid and reduces porosity and WA [13].

Fig 3 also shows the WA results for different grades. WA is higher when the grain size is small, for both NS and RS. The WA in fine fraction RS_f is about 9 times higher than that of NS_f and the same proportions are found for the medium fractions, RS_m and NS_m. For the two coarsest fractions, RS_c and NS_c, WA is about 12 times higher in RS_c. This high value of WA is in accordance with the results obtained by Zhao et al. [6, 7, 10]. Pore structure and the amount of bound cement paste can explain this high value of WA in RS in comparison with NS. In the RS, the bound cement paste leads to increased porosity and induces water absorption. It can also be noted that there are some difficulties in determining the WA value of fine fraction [6]. This fraction contains smaller grains or cement with a large water absorption capacity, so there is a greater risk of some interstitial water being present between the grains. That could explain the higher uncertainty associated with RS_f.

Fig 4 shows the real density and the absolute density of the three sands: NS, RS and CRS. The real density test was also performed with the 1097-6 standard method [12]. The absolute density results were compiled by hydrostatic weighing, according to standard NF EN 1097-7 [14], of a sample crushed above 80 µm and placed in a vacuum. The absolute density is maximal with the NS (2.70 g/cm^3) and lower in RS or CRS. The real density was lower (2.62, 2.01 and 2.20 g/cm^3 for NS, RS and CRS respectively), particularly for RS and CRS. The difference between real density and absolute density for RS and CRS comes from the porosity of the old cement paste present in RS and CRS sands. The more the older cement paste is present, the greater the volume of porosity is. This increase of porosity induces a decrease of the real density. The RS has more old cement paste, more pores and lower real density. In the case of CRS, the carbonation induces a filling of the pores and consequently the real density of CRS is higher than that of the corresponding RS.

Fig 4 also gives the density of each fraction of the NS and RS. When the standard deviation is taken into account, densities of the NS are the same for all fractions because of its homogeneous composition, whereas there are large variations between the fractions of the RS, which become even greater as the fractions become finer. A large standard deviation is observed in the RS_f

fraction in comparison with other fractions. All differences can only come from the cementitious matrix present in the RS, which constitutes a large proportion of the fine fraction, as has already been shown with the SEM images.

Both WA and density can be used to classify the aggregates according to Silva et al. [15] which propose a generic prediction model with these parameters, regardless of their size, type and origin: CII for RS and BIII for CRS (Fig 5).

2.1.2 Cement

The cement used was ordinary Portland cement CEM I 52.5 R as specified in European Standard EN 197-1 [16]. This cement, produced by Lafarge, La Malle (France), has a density of 3.15 g/cm^3 and Blaine fineness of 4300 cm^2/g. Its chemical and mineralogical composition is given in Table 1.

2.1.3 Mortars

2.1.3.1 Formulation

Two series of mortars were studied: the RS and CRS series. RS and CRS were made by replacing NS by RS at 4 rates (0, 33, 66 and 100%).

The formulations of the three series of mortars were based on four principles:

- NS was replaced by the same volume of RS or CRS (650 l/m^3);
- The same amount of effective water was used (222 l);
- The quantity of cement (CEM I 52.5 R) used throughout was fixed at 333 kg/m^3;
- An air volume of 22 l/m^3 was taken into account for all formulations.

The formulations are presented in Table 2.

The mortars were cast according to standard EN 196-1 [17]. The dry sands were pre-saturated 24 hours before casting with a quantity of water corresponding to their WA, placed in sealed bags and then stored in an air-conditioned room at 20 ± 2 °C. As the sand had been pre-saturated, the amount of water added in the mixer corresponded to the effective water.

Two kinds of geometric shapes were used according to the test standards: cylinders (diameter (ϕ) 11 cm, height (H) 22 cm) for durability tests, and prisms (4x4x16 cm), for strength and carbonation tests. After casting, the samples were covered and placed in the humidity chamber at 20 °C and more than 90% RH, demolded one day after pouring and then stored in water at 20 °C until the date of the test.

2.2 Methods

2.2.1 Workability

To measure the consistency of mortars, a workability test was performed according to standard NF P 18-452 [18]. The test was performed immediately after mixing (between 1 and 3 minutes after).

2.2.2 Apparent specific mass

The density of the fresh mortar was measured according to standard NF EN 12350-6 [19].

2.2.3 Strength

Compressive strength testing [17] was performed on all specimens with a constant stress rate (2.4 kN/s) controlled by the mortar press in the laboratory. The compressive strength test was conducted at 2, 7 and 28 days. At each date, 2 specimens were tested in flexion and 4 half specimens in compression.

2.2.4 Durability tests

At 21 days, two cylindrical samples of each composition were sawn into five parts: three with a thickness of 50 ± 1 mm and two of 20 ± 1 mm. A 10 mm section was excluded at each end. Samples were then put back into humid conditions [NF EN 12390-2 [20]] until the test, which took place at 28 days.

2.2.4.1 Porosity accessible to water and Density

For each composition, four ϕ110xH20 mm specimens were saturated under vacuum for 24 hours and dried at 105°C to constant mass. This test is defined in standard NF EN 18-459 [21].

2.2.4.2 Chloride ion migration

The test was performed according to the NT BUILD 492 method [22]. The catholyte solution was 10% NaCl by mass in tap water and the anolyte solution was 0.3 mol/l NaOH in distilled water. The temperature of the sample and solutions was maintained at 20 °C during the test. Three ϕ110xH50 mm specimens were tested, under a voltage of 10 V for 24 hours.

2.2.4.3 Air permeability

After 28 days in humid conditions, three ϕ110xH50 mm specimens were placed at 105°C until the date of the air permeability test. The test was performed according to XP P18-463 [23] with a CEMBUREAU apparatus. The specimens were placed in a constant gas pressure gradient after 28

days at 80°C and in the dry state. The permeability was determined by measuring the gas flow through them.

2.2.4.4 Capillarity

This test was performed on the samples that had been used for the air permeability test. In accordance with standard EN 772-11 [24], samples were immersed in water to a maximum height of 3 mm, which was obtained by using shims. At each time, the specimens were removed from the container, wiped with a paper towel, weighed, and then replaced in the container. The capillarity was measured at 0.25, 0.5, 1 and 2 hours.

2.2.4.5 Carbonation

The carbonation test was performed according to standard NF XP P18-458 [25]. After 28 days in water, two 4x4x16 cm specimens were placed at 40 °C for a week and put into a chamber with 4% CO_2 and 65% HR. A 2 cm sample was sawn at each date: 3, 7, 14 and 28 days. The carbonated concrete thickness was measured after wetting the samples and spraying phenolphthalein solution on the fracture surfaces of the samples considered. Phenolphthalein solution reveals the interface between the safe (pH > 9) and the carbonated zone (pH < 9) by color difference.

3. Results and discussion

3.1 Characterization of the sands

The amount of cement paste in the different fractions was observed by SEM. Figure 6 presents SEM images with EDS analyses for fractions RS_f and RS_c, which were respectively the finest and the coarsest. The siliceous mapping shows the place of siliceous aggregates. The calcium mapping, linked to the paste content, shows that more cement paste is present in RS_f. This observation is in accordance with the findings of Evangelista et al. [5]. For the RS_c fraction, the coarse aggregates are surrounded by only a thin layer of calcium. So, when the grain size is smaller, the amount of paste linked is greater, which also explains the tendency of the water absorption coefficient presented before.

Cement content was determined by soluble and insoluble methods [26]. Both methods led to similar results: 29-30% for RS_f; 21-22% for RS_m and 16-17% for RS_c, the highest content being found for the RS_f fraction, as expected.

These results were also confirmed by thermogravimetric results (Table 3). The sample was put in an argon atmosphere and subjected to a rise of temperature 10°C/min. The C-S-H mass loss was 6.2 %; 4.4% and 3.3 % for RS_f, RS_m and RS_c fractions, respectively. Portlandite was less present in the RS fraction, in a range of 0.6-1% of the total. The calcium carbonate rate was high, with 8.6%; 4.9% and 4.3% for RS_f, RS_m and RS_c fractions, respectively.

Thus, the main differences in chemical and physical properties between RS and NS were determined. The RS is surrounded by a layer of hydrates, mainly compounds with C-S-H, calcium carbonate and portlandite. This layer increases the porosity of the RS, thus increasing its water absorption coefficient. The distribution of the old cement paste in the RS is non-homogeneous since it depends on the grain size. Fine parts like RS_f contain more cement paste.

The RS and CRS can strongly influence the mortar properties because of their structural and chemical differences compared to NS. The next part of the study explains how these modifications can influence the mortar properties and durability.

3.2 Characterization of the mortars

3.2.1 Workability

The workability of RS and CRS series is shown in Fig 7. Workability increases with the percentage of RS whatever the kind of mixture, a fact that could be explained by the presence of an excess of effective water due to the difficulty of determining the true amount of absorbed water [6]. The reduction of the time could also be explained by the fact that RS is lighter than NS (see Fig 4) and leads to an easier mortar flow. In addition, the old cement paste layer bound to the aggregates in RS makes this sand smoother than NS. Some of the absorbed water was able to migrate into the mortar during the vibration period [27].

3.2.2 Apparent specific mass

Figure 8 shows the fresh density of the RS and CRS mortars with all substitution rates. It can be seen that the density of mortars decreases with the rate of replacement by RS or CRS.

If these experimental densities are compared with the theoretical densities calculated from the formulations (Table 2), the experimental values are the same for RS replacement if we take the dispersion into account. A difference for CRS mixtures (+25 l) can be observed, which could be explained by more air content.

3.2.3 Compressive strength

Figure 9 presents the results of the compressive strength test at 2, 7 and 28 days for the RS and CRS series.

In all cases, the mortar RS0 shows the best performance and strength decrease with the rate of replacement of sand. The more NS is replaced, the greater the resistance drop since the resistance of the old cement paste layer around the aggregates of RS is weaker than that of NS aggregates alone.

For the RS series, the maximal decrease for a total replacement is 28%, 22% and 26% respectively at 2, 7 and 28 days. These results were also found by Zhao et al. [6], who reported that mortar made with 100% replacement with RS showed a similar reduction rate to that of the reference mortar RS0. At 2 and 28 days, the performance of RS33 showed results very close to the reference (decrease of 8% and 3% respectively).

For the CRS series, the performance was higher than for the RS series. At 28 days, replacing 100% of NS by CRS induced a decrease of only 10%.

3.3 Durability

All durability results in the hardened state of RS and CRS mortars with different substitution rates are presented in Table 4.

3.3.1 Density and Porosity

The apparent density decreases with the replacement of NS by RS or CRS. Considering the dispersions, this could be explained by the fact that RS or CRS are lighter than NS.

For the RS and CRS series, the porosity accessible to water increases with the replacement rate. The presence of old paste around RS and CRS explains this tendency.

3.3.2 Chloride ion diffusion

The chloride ion migration coefficient for RS and CRS series is about 10^{-11} m^2/s, with good repeatability for all mixtures.

Two phenomena can lead to an increase in the diffusion coefficient: an increase of porosity or a drop in the chloride fixation capacity. For these mixtures, the two events are in competition. On the one hand, the more NS is replaced, the more the porosity increases, due to the presence of a

greater old paste content. On the other hand, when NS is replaced by RS or CRS, the quantity of old paste is increased to fix chloride (with formation of chloroaluminates). In the case of this study, the two effects cancel each other out.

3.3.3 Air permeability

The values of air permeability at 28 days and at the dried state for RS and CRS series increase in the same manner from 50 to 350. 10^{-18} m^2 (repeatability is good for all mixtures). These results agree with porosity results (see 3.3.1) and the literature [25, 26].

3.3.4 Capillarity

The capillarity results show a classical square root progression versus time. The values of the slopes, representing the speed of capillarity, are only presented at 7 days in the table for the RS and CRS series (the 28 days results were similar).

The capillarity coefficient increases with the rate of RS or CRS substitution. The capillarity of the RS series is about twice that of the CRS series.

3.3.5 Accelerated Carbonation

As for the capillarity results, a near-linear evolution with the square root of time is observed. For the same reason as for capillarity, the results are presented as a speed of carbonation in Table 4. The results for RS and CRS mixtures are lower than the reference one. In this case also, two phenomena are in competition. On the one hand, the carbonation speed increases with the porosity. On the other hand, the carbonation speed decreases with the quantity of available carbonable products. This is the case when we replace NS by RS or CRS, due to the presence of old paste. In this study, the influence of carbonable products is greater than the influence of porosity. Also, this explanation can be valid to explain the slight difference between RS and CRS: the lower porosity of CRS compensates for the initial carbonation of the portlandite of these aggregates.

3.3.6 Performance approach

In order to highlight the effect of recycled sand in substitution of natural sand, durability indicators (I) were calculated as the ratios between the mortars under study (RS, CRS) and the reference mortar RS0. All the indexes were chosen to express the durability of the mixtures: an index higher than 1 [30] indicated that the studied performance was better than the reference one and consequently the durability was improved thanks to the presence of recycled sand.

These indicators were calculated using the following equations:

$$I_S = Strength\ index = \frac{Strength\ with\ RS/CRS/FRS}{Strength\ of\ RS0}$$

$$I_{Cl} = Chloride\ ion\ migration\ index = \frac{Log(Chloride\ migration\ coeff\ \text{of}\ RS0)}{Log(Chloride\ migration\ coeff\ with\ RS/CRS/FRS)}$$

$$I_{Poro} = Water\ porosity\ index = \frac{Porosity\ of\ RS0}{Porosity\ with\ RS/CRS/FRS}$$

$$I_{Cap} = Capillarity\ index = \frac{Capillarity\ coefficient\ of\ RS0}{Capillarity\ coeff\ with\ RS/CRS/FRS}$$

$$I_{Perm} = gas\ permeability\ index = \frac{Log(Gas\ permeability\ at\ dried\ state\ of\ RS0)}{Log(Gas\ permeability\ at\ dried\ state\ with\ RS/CRS/FRS)}$$

$$I_{Carbo} = Carbonation\ index\ at\ 28\ days = \frac{Carbonation\ depth\ at\ 28\ days\ of\ RS0}{Carbonation\ depth\ at\ 28\ days\ with\ RS/CRS/FRS}$$

Figs. 10 and 11 present the results of durability indices for the RS and CRS series, respectively. Each axis represents an indicator, as shown above. A bold black line represents the index equal to 1, meaning that the performance of the mixture with recycled sands is equivalent to that of the reference with natural sand (RS0).

Generally, for both kinds of mixtures, the durability range is very close to that of the RS0 mixture. However, a marked increase in durability can be noted for the chloride ion migration index, I_{cl}, of the CRS series.

The substitution of 66% or 100% or RS of CRS impacts the index values slowly.

It can also be underlined that CRS mixtures show performances equal to or even better than those of RS mixtures (better compressive strength indices, migration indices and carbonation indices).

3.4 Discussion

RS differ from NS mainly in that they are composed of two fractions of different natures: natural aggregates and the old cement paste attached to them. The physical properties of recycled aggregates are different from those of natural aggregates. In SEM images, the RS often appears angular and rough, which, according to Evangelista and Brito [31], leads to greater internal friction.

The link between decrease of density and strength can help to predict results for other formulations. Fig. 12 presents the relation between the strength of hardened mortar and the decrease of density when NS is replaced by RS and CRS. The linear relationship between decrease of density and compressive strength is observed for both series, with good correlations in the case of CRS and acceptable ones for RS. This linear relation between density and strength in the case of recycled sand can also be found in the work of Tahar et al. [32].

The more NS is replaced by RS, the lower is the density and also the compressive strength. The CRS series has the lowest slope, about 4 or 5 times lower than the RS series. This series loses less strength than the others when NS is replaced. These results agree with the aggregate ranking proposed by Silva et al. [15] since RS (CII) ranks lower than CRS (BIII). This could be explained by the improvement of the quality of CRS aggregates with carbonation. The role of interfacial transition zone (ITZ) can be used to explain the compressive strength. In fact, by reducing the water absorption and the porosity, especially by the formation of carbo-aluminates, we provide a stronger ITZ so the compressive strengths are improved [36-38].

Figure 13 presents different models of the three sands, NS, RS and CRS. The NS is presented as rounded particles, the RS is rough and is presented as one or more NS particles within a layer of old cement paste, and the CRS is the same as RS but the old cement paste is carbonated and is shown in darker gray.

The angular shape and the bound old cement paste layer are the main causes of the variation in the characteristics of the recycled aggregates: decrease in density and increase in water absorption. Numerous studies have confirmed the results for these characteristic [36]–[40]. Carbonation does not modify the granulometry of the sand but, by absorbing CO_2, the CRS becomes about 10% denser than RS (Fig 8) and its water absorption coefficient decreases from 12.5% to 8.1%**.**

Thus, the presence of old cement paste in the recycled aggregates modifies their chemical characteristics relative to those of the natural aggregates. The cement content of the sand depends on the crushing cycle of the concrete and is directly related to the size of the aggregate [38]. Using two different methods, we observed the highest cement content for fraction RS_f and the lowest for fraction RS_c. Moreover, the characteristic of this layer depends directly on the origin of the recycled concrete [41].

335 Table 5 presents the variation of characteristics and durability for different sands (with total
336 replacement of NS by RS or CRS). They are organized in three groups: group (1) shows the
337 variation of characteristics between the fresh and hardened states (except for water absorption,
338 which is the only criterion measured on the sands), and groups (2) and (3) show the variation of
339 the mortar durability in the hard state. Group 2, with the porosity test, air permeability test and
340 capillarity test, shows that durability is lowered, while group 3, with the carbonation test and
341 chloride ion migration test, shows that durability is improved.

342 In group 1, although the water absorption is strong and reminds us that the sands were pre-
343 saturated, the workability characteristic is good.

344 The results of group 2 are strongly influenced by the porosity of the sand. That is why the
345 differences between results with RS and CRS are small. The high porosity creates more space in
346 the structure of the mortar and less connection, thus decreasing the strength. However, Zhao et
347 al. demonstrate that porosity is not the only factor influencing the compressive strength of mortar
348 [42]. Capillary absorptions are significantly increased in the case of recycled aggregate mortars,
349 due to a greater quantity of connected capillary pores [31], [43]. This high porosity is also a
350 disadvantage for the air permeability. The more pores there are, the more easily the air can
351 penetrate into the mortar.

352 In the mortar, 2/3 of the total volume is occupied by sand and 1/3 by cement paste. When 100%
353 of natural sand is replaced by recycled sand, we can see an increase of mortar porosity (+14.9%)
354 equivalent to the increase of granular porosity (+ 14.3%). For replacement of carbonated recycled
355 sand, the difference between the increase of mortar porosity (+ 13.5%) and that of granular
356 porosity (+9.6%) is more visible. A difference in air content, not measured in this study, could
357 explain this result.

358 The results of group 3 are influenced not only by the porosity but also by the chemical
359 composition of the sand. In this case, the important factor is the carbonation of old cement
360 pastes. The carbonation of the recycled sand creates a volume of by-products that can block pores
361 and decrease the penetration of CO_2. With the chloride ion migration test, the aluminates and
362 portlandite in the mortar capture the Cl^- ions in solution to form chloroaluminates and calcium
363 chloride, reducing the penetration of Cl^-. Although improved resistance to chloride migration is
364 observed with CRS, the use of RS does not have the same effect. The replacement of NS by RS

365 favors the propagation of chlorides. These phenomena are also found in the studies by Kou and
366 Poon [31], and De Brito and Alves [34]. Abbas et al. [44] find diffusion coefficients of the same
367 order of magnitude as those of traditional concretes.

368 ## 4. Conclusions

369 In this paper, we looked for a way to add value to recycled sand from leftover concrete. We
370 studied the influence of the partial or total substitution of natural sand (NS) by non-carbonated
371 (RS) or carbonated recycled sand (CRS) in mortars following a performance approach. In the light
372 of the tests results, the following conclusions can be drawn:

373 1. RS contain many hydrates and calcium carbonate in their structure. These hydrates lead to
374 an increase in pore ratio and a decrease in density. They also lead to weaker material.
375 2. The cement content of this RS varied from 17 to 30% by mass according to the granular
376 fractions, the highest value being observed in the fine fraction.
377 3. The characterization of recycled carbonated sand CRS showed that its porosity was lower
378 than that of RS (32.9% instead of 34.3%).
379 4. The strength results were only slightly affected by substitution of NS by CRS (-5% for total
380 replacement) whereas substitution of NS by RS was more unfavorable (-26% for total
381 replacement).
382 5. The substitution of RS or CRS increases the porosity of mortar.
383 6. In dry conditions, the permeability of both RS100 and CRS100 tripled compared with that
384 of RS0. Carbonation of RS had no great influence on the transport of air and there was no
385 change between the RS and CRS series.
386 7. CRS presented favorable resistance to the migration of chloride, with a reduction of 66%
387 for total replacement, whereas total substitution of NS by RS was unfavorable, with an
388 increase of 36%.
389 8. A better tendency was observed for the carbonation result. The carbonation speed was
390 reduced by about 25% when NS was replaced by RS or CRS.
391 9. The use of CRS could be very interesting. In order to generalize the conclusions, it would be
392 necessary to study other recycled sands.

5. Acknowledgements

The authors wish to express their gratitude to the Granulab Company for providing the recycled sand used and for their financial support of this research.

6. References

[1] "Recyclage," *Solutions de traitement des rebuts de béton frais*. [Online]. Available: http://bennerecyclagebeton.unblog.fr/environnement/.

[2] L. de B. P. Vieira and A. D. de Figueiredo, "Evaluation of concrete recycling system efficiency for ready-mix concrete plants", *Waste Manag.*, vol. 56, pp. 337–351, Oct. 2016.

[3] "Ready mix concrete reclaimer and recycler, restbeton auswaschanlagen - Bibko GmbH." [Online]. Available: http://www.bibko.com/en/.

[4] M. Etxeberria, E. Vázquez, A. Marí, and M. Barra, "Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete", *Cem. Concr. Res.*, vol. 37, no. 5, pp. 735–742, May 2007.

[5] L. Evangelista, M. Guedes, J. de Brito, A. C. Ferro, and M. F. Pereira, "Physical, chemical and mineralogical properties of fine recycled aggregates made from concrete waste", *Constr. Build. Mater.*, vol. 86, pp. 178–188, Jul. 2015.

[6] Z. Zhao, S. Rémond, D. Damidot, and L. Courard, "Une nouvelle méthode de caractérisation des granulats recyclés industriels: application aux mortiers", *2e édition de la Conférence Internationale Francophone: Nouveaux Matériaux et Durabilité*, Douai, France, Nov. 2015 (Academic paper (PDF) accessible by ResearchGate).

[7] Z. Zhao, S. Rémond, D. Damidot, and W. Xu, "Teneur en pâte de ciment et coefficient d'absorption d'eau des sables recyclés", *15e édition des Journées Scientifiques du Regroupement Francophone pour la Recherche et la Formation sur le Béton*, Douai, France, July 2014 (Academic paper (PDF) accessible by ResearchGate*)*.

[8] V. W. Y. Tam, X. F. Gao, C. M. Tam, and C. H. Chan, "New approach in measuring water absorption of recycled aggregates", *Constr. Build. Mater.*, vol. 22, no. 3, pp. 364–369, Mar. 2008.

[9] T. Le, S. Rémond, G. Le Saout, and E. Garcia-Diaz, "Fresh behavior of mortar based on recycled sand – Influence of moisture condition", *Constr. Build. Mater.*, vol. 106, pp. 35–42, Mar. 2016.

[10] Z. Zhao, S. Remond, D. Damidot, and W. Xu, "Influence of fine recycled concrete aggregates on the properties of mortars", *Constr. Build. Mater.*, vol. 81, pp. 179–186, April 2015.

[11] *FastCarb,* "Accueil", [Online]. Available: https://fastcarb.fr/.

[12] NF EN 1097-6, "Tests for mechanical and physical properties of aggregates — Part 6: Determination of particle density and water absorption", Jan. 2014.

[13] J. Zhang, C. Shi, Y. Li, X. Pan, C.-S. Poon, and Z. Xie, "Influence of carbonated recycled concrete aggregate on properties of cement mortar", *Constr. Build. Mater.*, vol. 98, pp. 1–7, Nov. 2015.

[14] NF EN 1097-7, "Tests for mechanical and physical properties of aggregates — Part 7: Determination of the particle density of filler — Pycnometer method", Jun. 2008.

[15] R. V. Silva, J. de Brito, and R. K. Dhir, “Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production”, *Constr. Build. Mater.*, vol. 65, pp. 201–217, Aug. 2014.

[16] NF EN 197-1, "Cement - Part 1: composition, specifications and conformity criteria for common cements", Apr 2012.

[17] NF EN 196-1, "Methods of testing cement - Part 1: determination of strength", Sep. 2016.

[18] NF P18-452, "Concretes - Measuring the flow time of concretes and mortars using a workabilitymeter", Feb. 2017.

[19] NF EN 12350-6, "Testing fresh concrete - Part 6: density", Apr. 2012.

[20] NF EN 12390-2, "Testing hardened concrete - Part 2: making and curing specimens for strength tests", Apr. 2012.

[21] NF P18-459, "Concrete - Testing hardened concrete - Testing porosity and density", Mar. 2010.

[22] NT BUILD 492, "Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments", Nordtest.info, Nov. 1999.

[23] XP P18-463, "Concrete - Testing gas permeability on hardened concrete", Nov. 2011.

[24] NF EN 772-11, "Methods of test for masonry units - Part 11: Determination of water absorption of aggregate concrete, autoclaved aerated concrete, manufactured stone and natural stone masonry units due to capillary action and the initial rate of water absorption of clay masonry units", Aug. 2011.

[25] XP P18-458, "Tests for hardened concrete - Accelerated carbonation test - Measurement of the thickness of carbonated concrete", Nov. 2008.

[26] H. Hornain and G. Arliguie, *GranDuBé: grandeurs associées à la durabilité des bétons*. Chapter II.1, p305, Presses des Ponts, 2007.

[27] L. Bello, E. Garcia-Diaz, and P. Rougeau, “An original test method to assess water absorption/desorption of lightweight aggregates in presence of cement paste”, *Constr. Build. Mater.*, vol. 154, pp. 752–762, Nov. 2017.

[28] R. Putra Jaya, B. H. Bakar, M. A. Megat Johari, and M. H. Ibrahim, “Strength and permeability properties of concrete containing rice husk ash with different grinding time”, *Open Eng.*, vol. 1, pp. 103–112, Mar. 2011.

[29] S. Rasiah, J. Kaabi, A. Mohammad, and Singh, “Permeability And Drying Of Pervious Concrete Pavers”, Conference: ISEC-7, Honanulu, Hawaii, Jun. 2013.

[30] R. San Nicolas, *Approche performantielle des bétons avec métakaolins obtenus par calcination flash*. Toulouse 3 thesis, 2011.

[31] L. Evangelista and J. de Brito, “Durability performance of concrete made with fine recycled concrete aggregates”, *Cem. Concr. Compos.*, vol. 32, no. 1, pp. 9–14, Jan. 2010.

[32] Z. Tahar, T.-T. Ngo, E. H. Kadri, A. Bouvet, F. Debieb, and S. Aggoun, “Effect of cement and admixture on the utilization of recycled aggregates in concrete”, *Constr. Build. Mater.*, vol. 149, pp. 91–102, Sep. 2017.

[33] V. W. Y. Tam, X. F. Gao, and C. M. Tam, “Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach”, *Cem. Concr. Res.*, vol. 35, no. 6, pp. 1195–1203, Jun. 2005.

[34] W. Li, J. Xiao, Z. Sun, S. Kawashima, and S. P. Shah, “Interfacial transition zones in recycled aggregate concrete with different mixing approaches”, *Constr. Build. Mater.*, vol. 35, pp. 1045–1055, Oct. 2012.

[35] M. B. Leite and P. J. M. Monteiro, “Microstructural analysis of recycled concrete using X-ray microtomography”, *Cem. Concr. Res.*, vol. 81, pp. 38–48, Mar. 2016.

[36] S. C. Angulo, P. M. Carrijo, A. D. Figueiredo, A. P. Chaves, and V. M. John, “On the classification of mixed construction and demolition waste aggregate by porosity and its impact on the mechanical performance of concrete”, *Mater. Struct.*, vol. 43, no. 4, pp. 519–528, May 2010.

[37] L. Evangelista and J. de Brito, “Criteria for the Use of Fine Recycled Concrete Aggregates in Concrete Production", Conference on the Use of Recycled Materials in Building and Structures, RILEM, Barcelona, Spain, Nov. 2004, (Academic paper (PDF) accessible by ResearchGate).

[38] M. S. de Juan and P. A. Gutiérrez, “Study on the influence of attached mortar content on the properties of recycled concrete aggregate”, *Constr. Build. Mater.*, vol. 23, no. 2, pp. 872–877, Feb. 2009.

[39] A. Katz, “Properties of concrete made with recycled aggregate from partially hydrated old concrete”, *Cem. Concr. Res.*, vol. 33, no. 5, pp. 703–711, May 2003.

[40] S.-C. Kou and C.-S. Poon, “Properties of concrete prepared with PVA-impregnated recycled concrete aggregates”, *Cem. Concr. Compos.*, vol. 32, no. 8, pp. 649–654, Sep. 2010.

[41] A. K. Padmini, K. Ramamurthy, and M. S. Mathews, “Influence of parent concrete on the properties of recycled aggregate concrete”, *Constr. Build. Mater.*, vol. 23, no. 2, pp. 829–836, Feb. 2009.

[42] H. Zhao, Q. Xiao, D. Huang, and S. Zhang, “Influence of Pore Structure on Compressive Strength of Cement Mortar”, *Sci. World J.*, vol. 2014, p. e247058, Mar. 2014.

[43] J. de Brito and F. Alves, “Concrete with recycled aggregates: the Portuguese experimental research”, *Mater. Struct.*, vol. 43, no. 1, pp. 35–51, Dec. 2010.

[44] A. Abbas *et al.*, “Quantification of the residual mortar content in recycled concrete aggregates by image analysis”, *Mater. Charact.*, vol. 60, no. 7, pp. 716–728, Jul. 2009.

Durability of mortars with leftover recycled sand

Manh Tan LE [a, *], Christelle TRIBOUT [a], Gilles ESCADEILLAS [a]

[a] Université de Toulouse, UPS, INSA; LMDC (Laboratoire Matériaux et Durabilité des Constructions), 135, Avenue de Rangueil; F-31 077 Toulouse Cedex 04, France

[*] Corresponding author. Tel +33665087813; E-mail address: mtle@insa-toulouse.fr.

Figure 1: Return of concrete from construction site 2

Figure 2: Particle size distributions (NS: Natural Sand; RS: Recycled Sand) 2

Figure 3: WA of different sands and their fractions by NF P 1097-6 method 3

Figure 4: Density of different sands and their fractions 3

Figure 5: Aggregate classification based on the relationship between water absorption and oven dried density (Silva et Al).....3

Figure 6: SEM observation (Top: RS_f Fraction 0 / 0.25 mm and bottom: RS_c Fraction 1 / 4 mm) 4

Figure 7: Workability of the RS and CRS series 4

Figure 8: Density of the RS and CRS series in fresh state.....5

Figure 9: Compressive strength of the RS and CRS series.....5

Figure 10: Durability index for the RS mortars 6

Figure 11: Durability index for the CRS mortars 6

Figure 12: Relation between compressive strength and decrease of density of hardened mortars ..6

Figure 13: Schematic representation of sands (Black: natural sand; light grey: old cement paste; grey shaded: carbonated old cement paste; white: new cement paste) 6

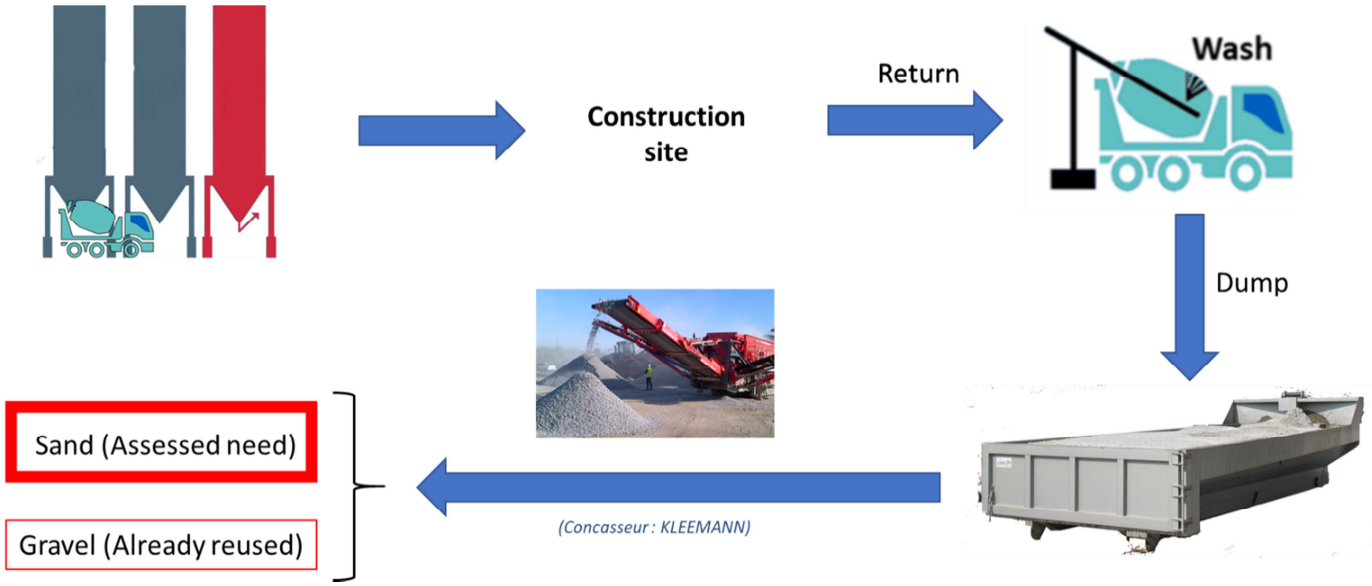


Figure 1: Return of concrete from construction site

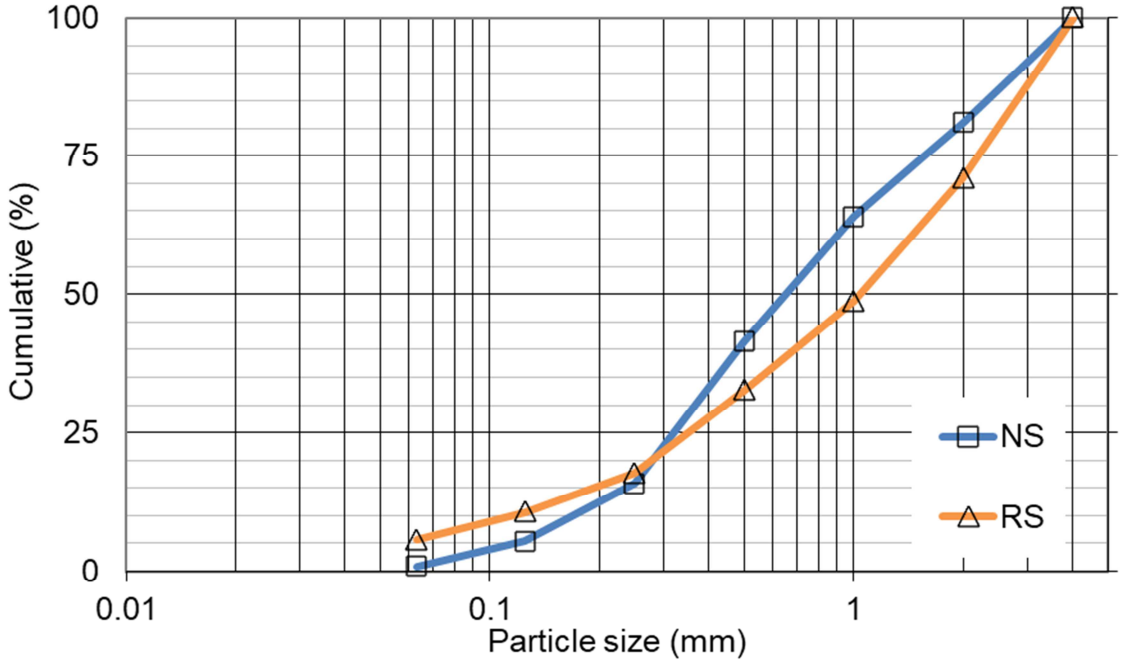


Figure 2: Particle size distributions (NS: Natural Sand; RS: Recycled Sand)

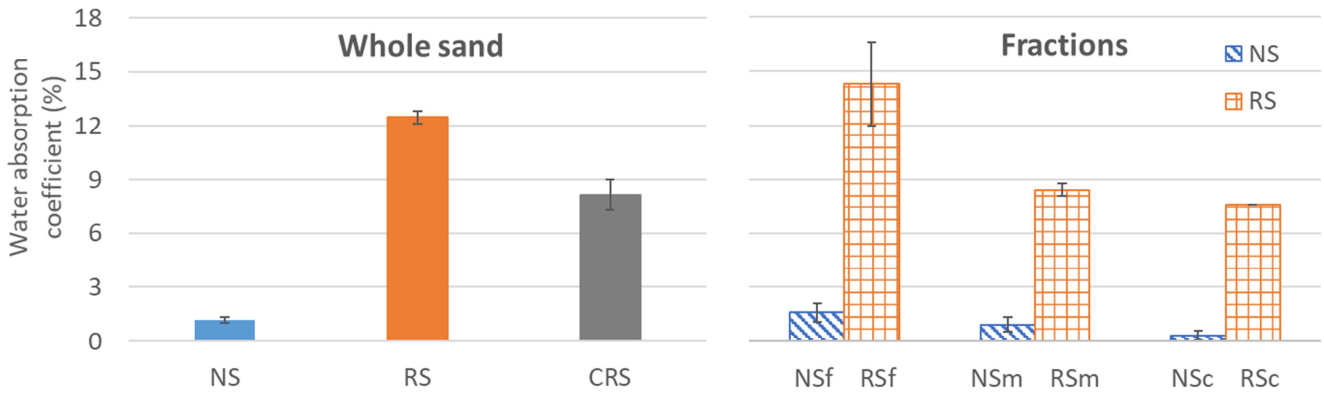


Figure 3: WA of different sands and their fractions by NF P 1097-6 method

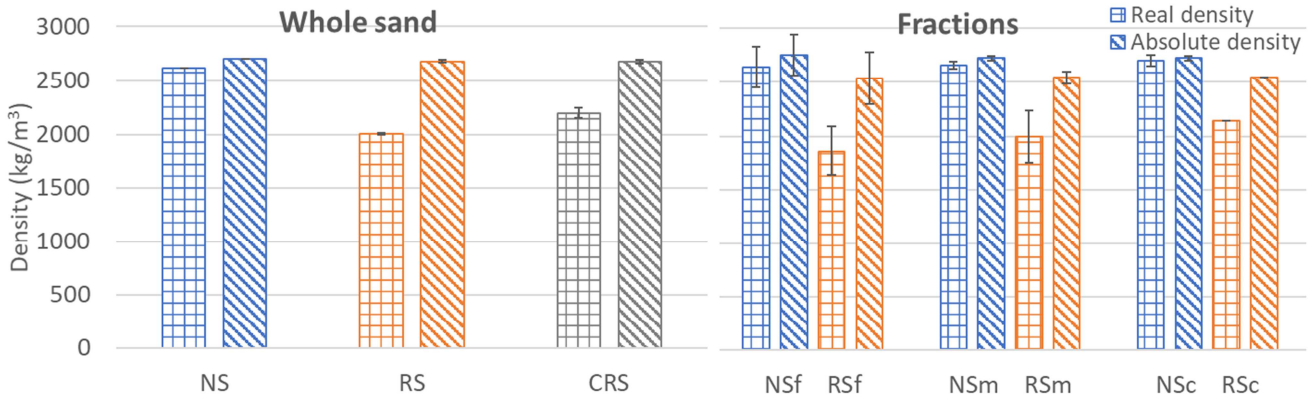


Figure 4: Density of different sands and their fractions

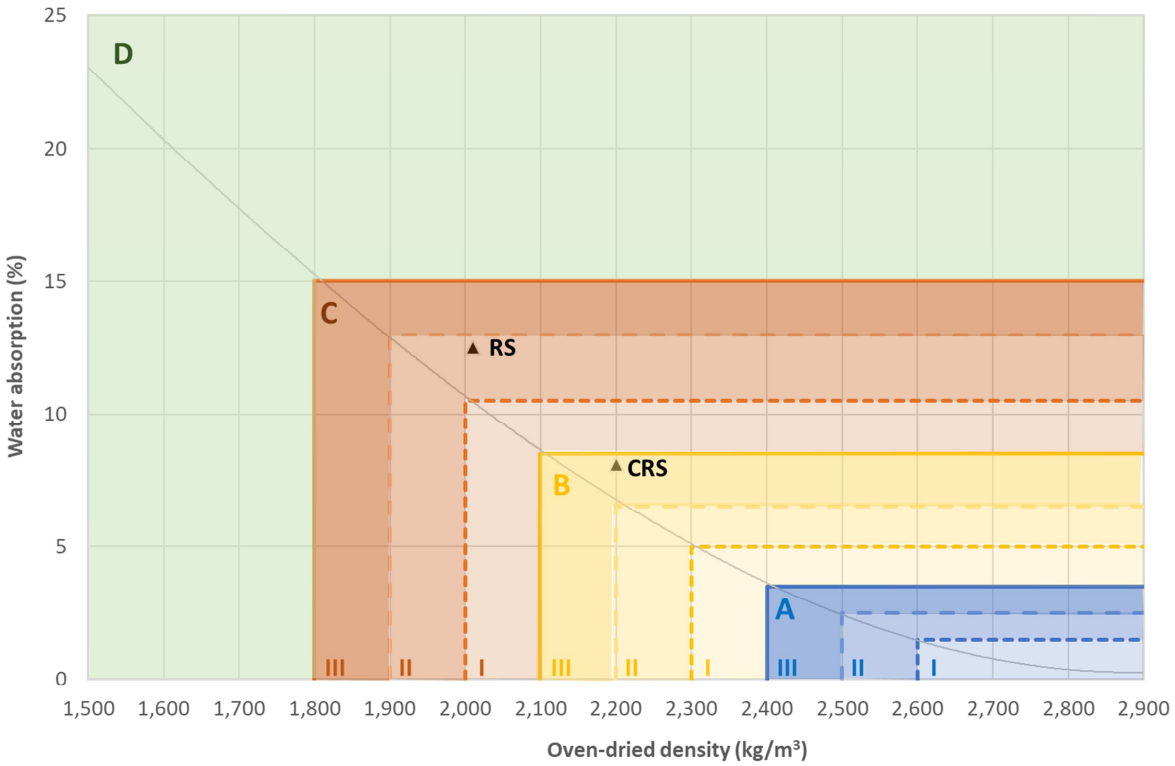
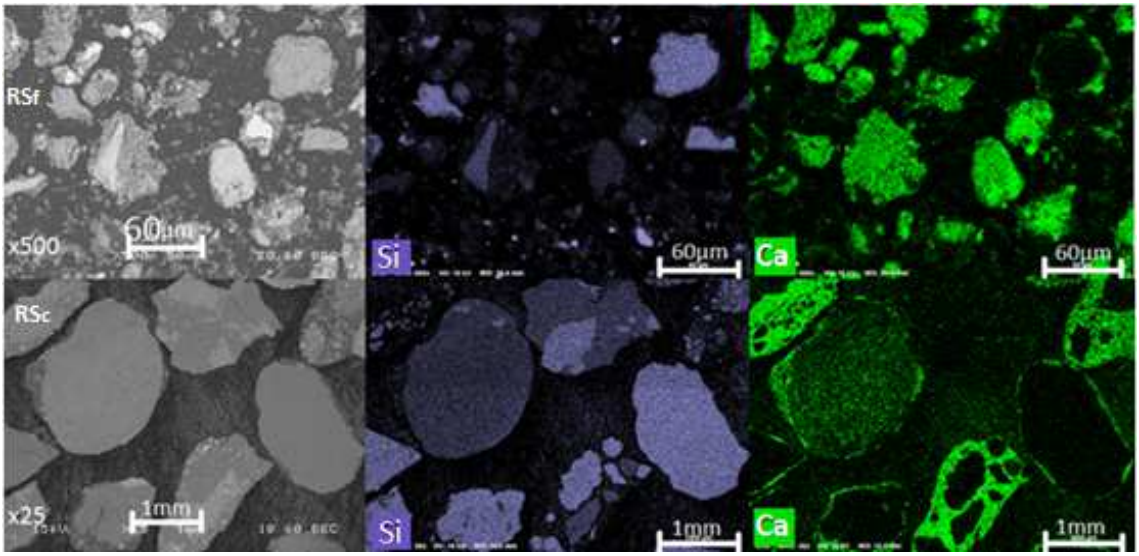


Figure 5: RS and CRS classification according to the aggregate codification proposed by Silva et al. [15]



Original Image in BSE mode *Siliceous mapping* *Calcium mapping*

Figure 6: SEM observation (Top: RS_f Fraction 0 / 0.25 mm and bottom: RS_c Fraction 1 / 4 mm)

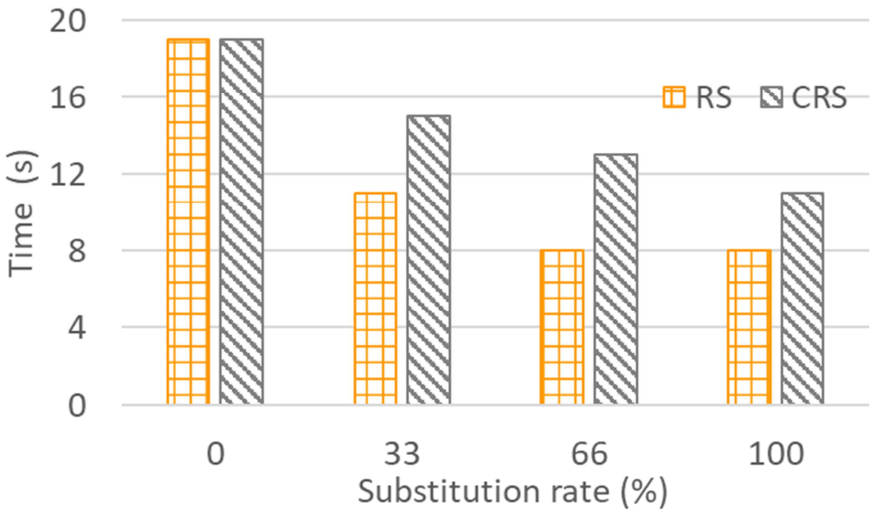


Figure 7: Workability of the RS and CRS series

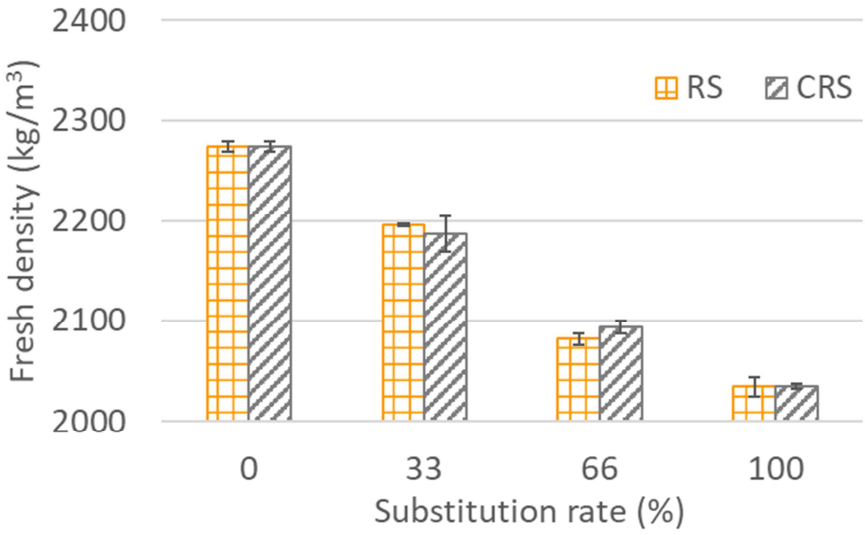


Figure 8: Density of the RS and CRS series in fresh state

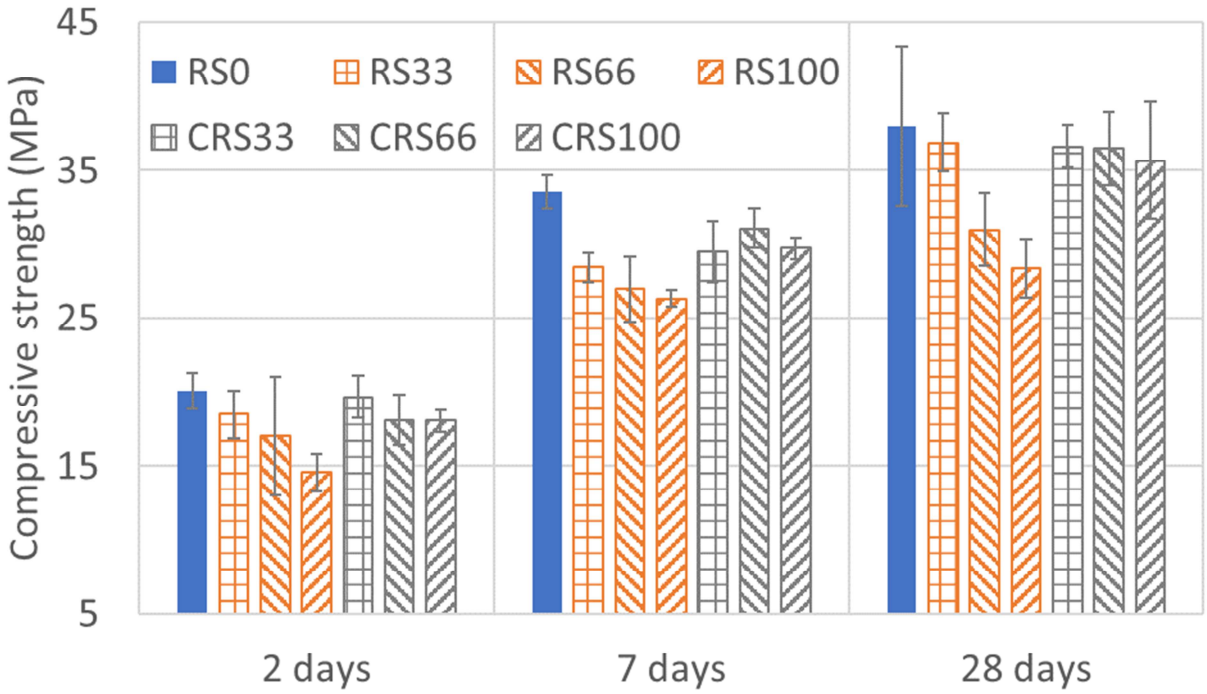


Figure 9: Compressive strength of the RS and CRS series

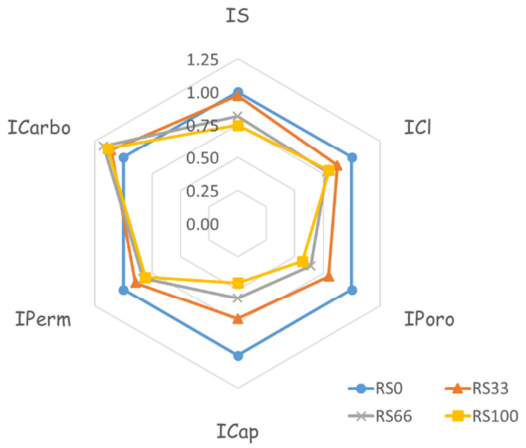


Figure 10: Durability index for the RS mortars

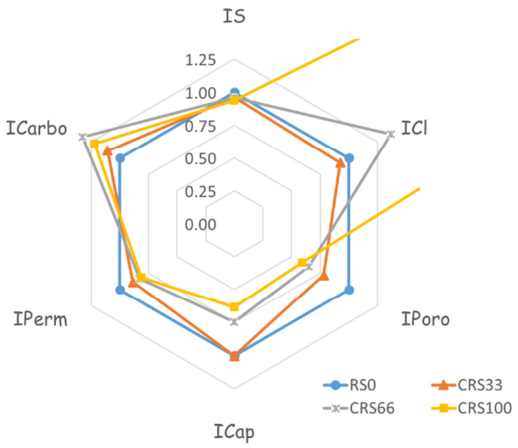


Figure 11: Durability index for the CRS mortars

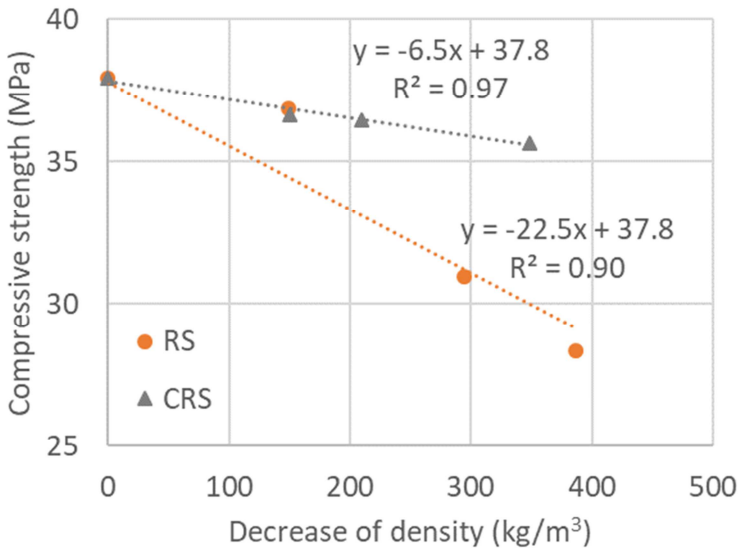


Figure 12: Relation between compressive strength and decrease of density of hardened mortars

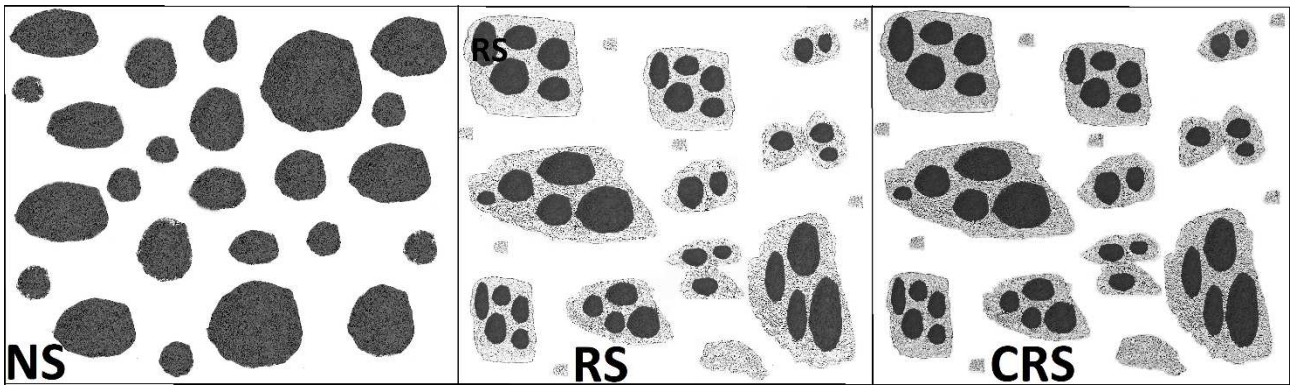


Figure 13: Schematic representation of sands (Black: natural sand; light grey: old cement paste; grey shaded: carbonated old cement paste; white: new cement paste)

Durability of mortars with leftover recycled sand

Manh Tan LE [a, *], Christelle TRIBOUT [a], Gilles ESCADEILLAS [a]

[a] Université de Toulouse, UPS, INSA; LMDC (Laboratoire Matériaux et Durabilité des Constructions), 135, Avenue de Rangueil; F-31 077 Toulouse Cedex 04, France

[*] Corresponding author. Tel +33665087813; E-mail address: mtle@insa-toulouse.fr.

Oxides	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	LOI
% mass	63.99	19.89	5.64	2.47	1.77	3.13	0.4	0.07	1.73

Bogue composition	C_3S	C_2S	C_3A	C_4AF
% mass	53.7	17.9	9.5	6.9

Table 1: Chemical and mineralogical compositions of ordinary Portland cement

Composition	**Sand ratio (%)**		**Mass (kg)**		**Water for saturation**	**Cement (C)**	**Effective Water (W)**	**C/W**	**Theoretical density**
	NS	**RS**	**NS**	**RS**	**(kg)**	**(kg)**	**(kg)**		**(kg/m^3)**
RS0	100	0	1703.0	0	19.8	333	222	0.67	2277.8
RS33	66	33	1135.3	435.5	67.5	333	222	0.67	2193.4
RS66	33	66	567.7	871.0	115.3	333	222	0.67	2109.0
RS100	0	100	0	1306.5	163.1	333	222	0.67	2024.6

	NS	**CRS**	**NS**	**CRS**	**(kg)**	**(kg)**	**(kg)**		**(kg/m^3)**
CRS33	66	33	1135.3	476.7	51.9	333	222	0.67	2218.9
CRS66	33	66	567.7	953.3	84.0	333	222	0.67	2160.0
CRS100	0	100	0	1430.0	116.1	333	222	0.67	2101.1

Table 2: Compositions of RS and CRS mortar series

	Loss of mass %		
Decomposition range (°C)	80-350	450-550	550-1000
Composition	C-S-H, Aft	Portlandite	Calcium carbonate
RS_f	6.2	0.9	8.6
RS_m	4.4	0.6	4.9
RS_c	3.3	1.0	4.3

Table 3: Mass loss based on TG results for the different fractions of RS (%)

	MORTAR :	Reference	With RS substitution			With CRS substitution		
Durability	Unit	RS0	RS33	RS66	RS100	CRS33	CRS66	CRS100
Apparent density	kg/m^3	2038.7	1889.3	1744.3	1652.3	1888.1	1773.9	1690.0
		7.1	*7.1*	*12.2*	*3.9*	*25.5*	*9.0*	*13.3*
Porosity	%	19.4	24.4	30.3	34.3	24.9	29.9	32.9
		0.1	*0.3*	*0.3*	*0.6*	*0.2*	*0.2*	*0.1*
Coefficient of chloride diffusion	E-11 m^2/s	3.3	4.0	4.7	4.5	3.7	2.4	1.1
		0.22	*0.15*	*0.11*	*0.35*	*0.09*	*0.21*	*0.06*
Permeability at 28 days	E-16 m^2	66.7	104.0	155.0	229.0	182.0	241.0	284.0
		15.2	*6.0*	*8.9*	*15.1*	*17.7*	*10.1*	*44.0*
Permeability at dry state	E-16 m^2	113.0	198.0	298.0	343.0	208.0	302.0	338.0
		9.4	*25.8*	*16.6*	*18.2*	*25.9*	*1.1*	*47.3*
Capillarity speed	kg/m^2/min$^{1/2}$	0.3	0.4	0.5	0.6	0.3	0.4	0.4
		0.0074	*0.0368*	*0.0069*	*0.0186*	*0.0316*	*0.0121*	*0.0117*
Carbonation speed	mm/jour$^{1/2}$	3.3	2.7	2.7	2.8	2.8	2.5	2.8
		0.1	*0.2*	*0.1*	*0.1*	*0.2*	*0.1*	*0.2*

Standard deviation

Table 4: Durability of RS and CRS mortar series

	Criteria in comparison with NS		RS	CRS
Basic characteristics	Fresh density (3.2.2)		-	-
	Workability (3.2.1)		++++	+++
	Water Absorption (2.1.1)	**(1)**	----	---
	Hardened density (3.3.1)		--	--
Durability	Strength (3.2.3)		--	-
	Porosity (3.3.1)	**(2)**	---	--
	Air permeability (3.3.3)		-	-
	Capillarity (3.3.4)		---	--
	Carbonation (3.3.5)	**(3)**	+	++
	Chloride ion migration (3.3.2)		-	++++

Table 5: Variation of the measured parameters for RS and CRS mixtures: what effect? ('+' positive effect; '-' negative effect; 'X' slight; 'XX' average: 'XXX' significant; 'XXXX' strong).