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Effect of adhered mortar of recycled concrete aggregates on long-term concrete properties

S. Manzi[1], C. Mazzotti[1] and M.C. Bignozzi[1]

[1] *Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, University of Bologna, Italy*
viale Risorgimento 2, 40136 Bologna, Italy
stefania.manzi4@unibo.it, claudio.mazzotti@unibo.it, maria.bignozzi@unibo.it

ABSTRACT

The scope of the paper is to study and compare the properties of concrete made of coarse recycled concrete aggregates with the properties of conventional concrete made of natural ones. In particular, the effects of recycled concrete aggregates on long-term behaviour of concrete (shrinkage and creep) are reported highlighting the correlations between cement paste porosity and mechanical properties. Moreover, the adhered mortar of the recycled concrete aggregates is determined and its influence on the final concrete properties is investigated as its content and porosity can greatly influence the final properties of the new concrete. The obtained results are promising in view of a current use of construction and demolition waste (C&DW) for new sustainable structural concrete.

Keywords. C&DW; recycled concrete aggregates, adhered mortar, mechanical properties, long-term properties

INTRODUCTION

Aggregates are the major components of concrete and have a great effect on the engineering properties of the final concrete (Neville, 1996). Natural resources are greatly affected by their extensive use due to the increasing demand of concrete buildings. The less natural aggregates are used in concrete production, the lower the impact the concrete industry has on the environment. The increasing charges for landfill, as well as the shortage of natural resources for aggregates production are encouraging the sustainable use of waste from construction sites as a source of new aggregates. Indeed, the use of C&DW for the production of new concrete has become popular in the last years (Marinković, 2010; Rao, 2007). This is also due to the introduction in the European standards and Eurocodes of the possibility to use recycled concrete aggregates, if preliminary suitable characterizations are made.

Concrete with recycled aggregates have been studied extensively in terms of environmental impact (Marinković, 2010; Meyer, 2009), mix-design (Etxeberria, 2007) and short-term mechanical performances (Rahal, 2007; Tabsh, 2009), but there is a lack of data on long-term properties. In this paper, the effects of coarse recycled concrete aggregates on both short and long-term mechanical and physical properties of new structural concrete are investigated. Moreover, an integrated approach involving mechanical characterizations and porosimetric analysis is carried out. Only few researches have been carried out in this direction on concrete containing recycled aggregates (Domingo-Cabo, 2009; Fathifazl, 2011), while several studies focused on the relation between cement matrix pore size distribution and shrinkage/creep in traditional concrete structures.

In this study, concrete waste coming from the demolition of a concrete building in Punta Perotti (Bari, Italy) was crushed to obtain coarse recycled aggregates with grain size distributions suitable to produce high quality concrete for structural applications. Indeed, aggregates play a primary role in determining workability, strength, dimensional stability and durability of concrete. Exploiting previous researches in this field (Manzi, 2011; Manzi 2013), concrete mixes with 100 % coarse recycled concrete aggregates were designed and characterized at the fresh and hardened state by physical and mechanical tests to investigate their short- and long-term behaviour. The experimental results are discussed and correlated with the porosity data, to highlight their effects on the macroscopic behaviour of new concrete mixes. A control concrete mix, prepared with natural aggregates and both the same cement amount and D_{max} is reported for comparison. Finally, the adhered mortar of the used recycled concrete aggregates was determined and its influence on the final concrete properties was investigated, showing that its quantity and porosity can greatly influence the final properties of the new concrete (Etxeberria, 2007).

EXPERIMENTAL PART

Materials. Cement type CEM II-A/LL 42.5 R, according to UNI EN 196-1, was used as binder. An acrylic based superplasticizer was used for all the concrete mixes.

Sand (0 - 6 mm), fine gravel (6 - 16 mm) and gravel (16 - 25 mm) (Cave Pederzoli, Bologna, Italy) were used as natural aggregates. A cumulative grain size distribution (sand: 48 vol%, fine gravel: 25 vol% and gravel: 27 vol%) was prepared setting the maximum diameter equal to 25 mm and according to Fuller distribution.

Concrete waste coming from the demolition of a never finished concrete construction in Punta Perotti (Bari, Italy, 2006) was used as recycled aggregates. Punta Perotti building demolition constitutes a significant C&DW case study because in the building no interior partitions, technological systems, etc. were present. After demolition, a large part of the concrete waste was disposed to landfill and a part was collected by the University of Bologna for scientific purposes. Compressive tests made on concrete cores of the original building showed medium-high compressive strength ($f_{cm} \approx 36$ MPa), thus making the relevant demolition waste very attractive for the production of new structural concrete. The demolished concrete underwent on-site crushing in different stages. A first crushing treatment, used to separate concrete from steel, was made with clamp mechanical excavators and jackhammers immediately after the building demolition. Then, C&DW was treated on site with a mobile crusher (secondary crushing treatment) and jaw crusher (maximum sieve open: 9 cm) to obtain a nearly homogeneous material. Furthermore, a crushing treatment was made with a laboratory jaw crusher (maximum sieve open: 25 mm) to obtain chunks with size and grain size distribution similar to the coarse natural aggregates (fraction 16 – 25 mm).

Water absorption and saturated surface-dried density of both natural and recycled aggregates were determined according to UNI EN 1097-6 and are reported in Table 1. The coarse recycled aggregates exhibit sharp contours and are similar in appearance to the coarse natural crushed aggregates, however their texture is rougher due to the adhered mortar, with higher water absorption and lower density than natural aggregates as also reported elsewhere (Domingo-Cabo, 2009). The recycled aggregates have mainly a calcareous ($CaCO_3$) nature (determined by Philips 1840 powder diffractometer with Cu anode), whereas natural aggregates are prevalently based on crystalline silica.

Table 1. Physical properties of natural and recycled aggregates

	Sand (0-6 mm)	Fine gravel (6 - 16 mm)	Gravel (16 - 25 mm)	Recycled aggregate (16 - 25 mm)
Water absorption (%)	2.2	1.4	1.2	7.0
Saturated surface-dried density (Mg/m^3)	2.7	2.6	2.6	2.3

Samples preparation. The studied concrete mixes are reported in Table 2. Cement content (350 kg/m^3) and D_{max} (25 mm) were constant for all the formulations. Reference mix, named C0, was prepared with 100 % natural aggregates and water/cement ratio w/c = 0.48. In order to investigate the effects of 100 % coarse aggregate substitution on the concrete properties, two different concrete mixes were studied. A first concrete mix, named C1, was prepared replacing all the natural gravel (27 vol% on the total volume of aggregates) with the coarse recycled aggregates and with workability similar to the reference mix. Therefore a slightly higher w/c ratio (0.52) than the reference concrete was necessary. A further concrete mix, named C2, was prepared with the same content of coarse recycled aggregates of C1 but with the same w/c ratio of C0. The mixes were prepared in a laboratory concrete mixer (190 L) according to the following procedure: first, aggregates (gravel, fine gravel and sand) were added and mixed for about 5 minutes. Then, cement, water (75%) and superplasticizer along with the remaining water were added and mixed for further 3 minutes. For all the investigated mixes, superplasticizer was dosed to ensure a slump between 10-20 cm (S3 or S4). C2 required a slightly higher amount of superplasticizer than the other mixes.

Table 2. Concrete mix-design

	C0	C1	C2
Cement (kg/m^3)	350	350	350
Water (kg/m^3)	168	182	168
Water/cement ratio	0.48	0.52	0.48
Natural aggregates[(a)] (kg/m^3)	1800	1331	1331
Recycled aggregates[(a)] (kg/m^3)	0	419	419
Superplasticizer[(b)] (%)	1.0	0.8	1.2
Slump (cm)	19	23	10

[(a)] saturated surface-dried (ssd) conditions; [(b)] mass% on cement amount

Samples characterization. Slump test was performed to measure concrete workability, according to UNI EN 12350-2. For each formulation at least 10 cylindrical concrete samples (diameter: 12 cm, height: 24 cm) as well as 2 cubic samples (15x15x15 cm) were prepared and cured for 28 days at room temperature (≈ 22°C) and relative humidity (R.H.) > 95%, for physical and mechanical tests. Water absorption (w_a) test at atmospheric pressure was performed on 2 cubic concrete samples, according to UNI 7699. Concrete compressive strength (f_{cm}) was determined using a universal testing machine (4000 kN), according to UNI EN 12390-3; four concrete cylindrical samples were tested for each mix at 28 days from casting. Secant elastic modulus (E), according to UNI 6556, was also measured by compression tests on cylindrical samples always at 28 days; two samples for every mix were considered. Moreover, the long-term behaviour of the recycled aggregates concretes was investigated by creep and shrinkage tests. Two cylinders for each mix were subjected to creep test (Figure 1), according to ASTM C512/C512M-10 and two cylinders were subjected to shrinkage test starting after two days from casting. All the tests were performed in a climate chamber at 20 ± 1 °C and 60 % R.H. for nearly two years with specimens in drying conditions. The longitudinal strain variation with time of each cylinder was measured by using electrical strain gauges connected to a digital acquisition system (Mazzotti, 2012). For creep tests, a compression stress of about 30 % of the strength at the time of loading (i.e. within stress limit of linear viscoelasticity) was applied at 28 days from casting. Pore size distribution was investigated by mercury intrusion porosimeter (MIP, Carlo Erba 2000), equipped with a macropore unit (Fisons 120) on samples constituted by the adhered mortar detached from recycled aggregates and samples of the new cement matrix. Porosimeter samples, about 1 cm^3, were cut by a diamond saw, dried under vacuum and kept under P_2O_5 in a vacuum dry box till testing.

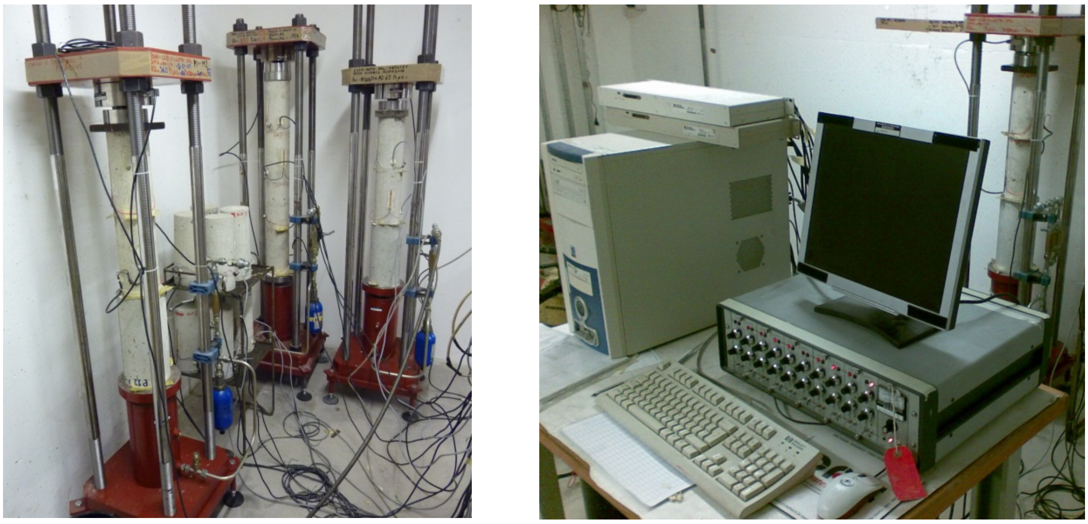

Figure 1. Creep test on the concrete mixes

RESULTS AND DISCUSSION

Slump tests results are reported in Table 2. Due to the higher *w/c* ratio used in C1 mix, C0 and C1 exhibit a similar slump (≈ 20 cm). On the contrary, C2 shows a considerable reduction of workability compared to C0 despite the larger content of superplasticizer used in the mix (the upper limit suggested by the producer was met). Indeed, the shape and morphology of the recycled aggregates, mainly covered by hardened cement mortar or paste, have a strong effect on the fresh concrete properties (Etxeberria, 2007) and the expected workability can be reached more easily by increasing the water content in the mix than by adding a large amount of admixtures, even though the mechanical consequences are very different.

At the hardened state, C0 (with natural aggregates) and C2 (with 100% coarse recycled aggregates and the same *w/c* ratio as C0) show comparable w_a values: 6.1% and 6.2%, respectively. This result is index of good quality concrete mixes, also in terms of durability features. An increase in w_a was detected for C1 (w_a =7.6 %) due to the higher *w/c* ratio used in the mix rather than to the presence of the recycled aggregates. The mechanical properties (f_{cm} and E) of the investigated concrete samples after 28 days of curing are reported in Figure 2. C1 shows a slightly higher compressive strength (about 44 MPa) than the reference concrete C0 (about 41 MPa), even if a higher *w/c* ratio was used, and C2 shows the highest compressive strength (about 52 MPa) among the investigated formulations (about 25% higher than C0). The compressive test results highlight that when recycled concrete aggregates are of good quality and properly assorted, they can lead to concrete with comparable and even higher mechanical strength of that produced with natural aggregates only, even when a high water/cement ratio is adopted. Elastic modulus results confirm previous results: C0 and C2 show similar E values (≈ 30 GPa), whereas C1 exhibits the lowest value (27 GPa) according to its highest porosity (expressed as water absorption measurement). Indeed, the short-term mechanical properties so far determined suggest that both the recycled concrete mixes are suitable for structural applications.

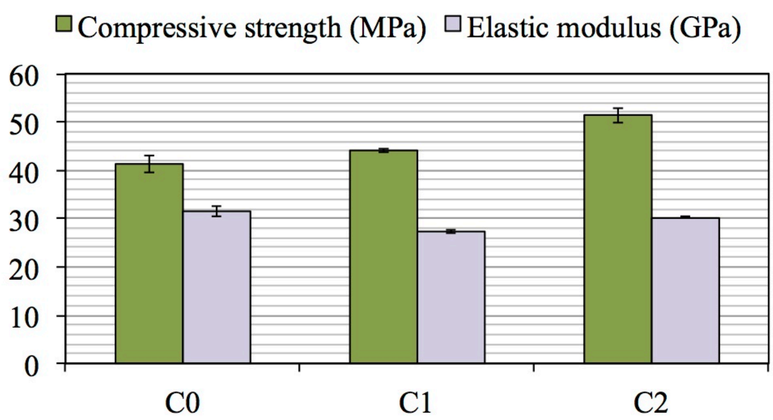

Figure 2. Mechanical properties of the concrete mixes

Long-term behaviour of three mixes considered were monitored for nearly two years; in particular, shrinkage strains (autogenous and drying contributions) and specific creep (creep strain per unit of applied stress, basic and drying contributions together) are shown in Figure 3 and 4, respectively. From a qualitative point of view all the shrinkage curves are similar, showing a rapid shrinkage strain increase in the first three months. Then the slope of the curves decreases with time, becoming almost flat after ten months. C0 shows the smallest strains among the investigated concretes, in accordance with literature data (Rao, 2007). Concrete with coarse recycled aggregates usually leads to larger values of shrinkage because the recycled aggregates have a lower modulus of elasticity than the natural ones and offer less restraint to the potential shrinkage of the cement paste. However, unexpectedly, mixes C1 and C2 exhibit the same shrinkage strain trend, despite the different *w/c* ratio used in the two mixes.

As for the specific creep curves, the following observation can be drawn: (*i*) the slope of all the curves (reference included) is still appreciable after nearly two years, meaning that the creep phenomenon is still quite active and not only related to the presence of recycled aggregates; (*ii*) C2 shows the lowest creep values among the studied concrete mixes; (*iii*) contrary to shrinkage results, the creep values of the recycled concrete C1 and C2 are clearly influenced by the *w/c* ratio (and corresponding mechanical properties). Indeed, the total replacement of the coarse natural aggregates with recycled ones can lead to positive effects on creep if comparable *w/c* ratio is used. Such performance on long-term properties for C2, in fact, agrees with the highest compressive strength and low water absorption previously reported. C2 appears to be a very dense concrete where localized stresses and micro-cracks are minimized at the interface between aggregate and matrix. On the contrary, C1 with a higher *w/c* ratio shows the highest creep values, in accordance with the highest water absorption.

In order to better characterize the recycled aggregates, the content of adhered mortar was determined. A thermal treatment consisting in cycles of soaking in water and heating was made on the recycled aggregates to detach the adhered mortar (de Juan, 2009). In particular, the following steps were followed: *i*) water saturation of the adhered mortar by water immersion for 2 h at room temperature; *ii*) high temperature treatment at 500 °C for 2 h; *iii*) fast cooling in cold water. The heating process produces vapour in the saturated mortar and consequent internal overpressure, while the sudden cooling causes stress and cracks in the adhered mortar, which can be then easily removed by hand pressure. Finally, the adhered mortar content was calculated according to equation (1):

$$\%\,\text{adhered mortar} = \frac{m_i - m_f}{m_i} \cdot 100 \qquad (1)$$

where m_i and m_f are the initial and final masses of the sample, respectively.

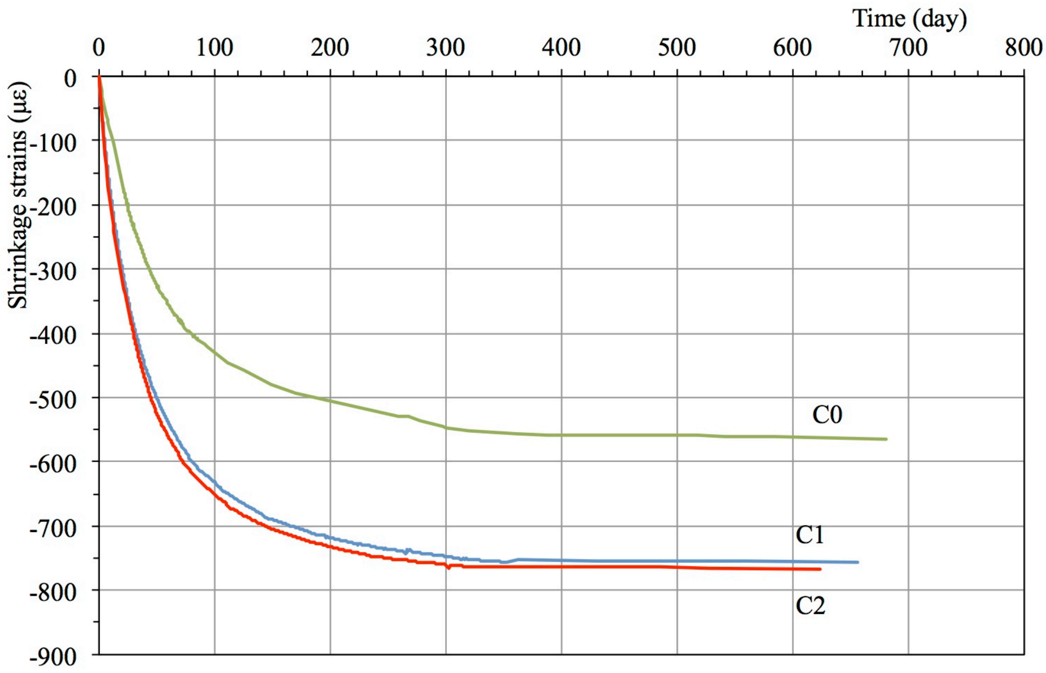

Figure 3. Shrinkage strains for the concrete mixes

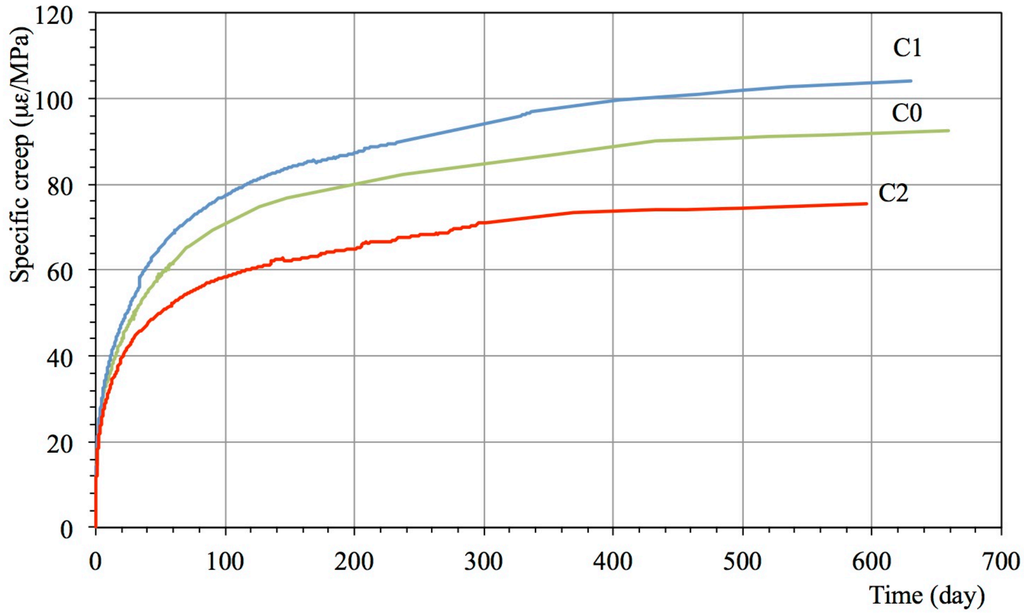

Figure 4. Specific creep for the concrete mixes

In order to verify the results repeatability, the adhered mortar content was determined by applying the described procedure on 2 and 15 coarse recycled aggregates. The following percentages (average values) of adhered mortar were obtained: 70 % and 74 %, respectively. The test showed a good repeatability of results between application to only few aggregates (2) or to a larger number (15). The amount of the adhered mortar determined is higher than that one reported by de Juan (2009), however in this work a very good level of separation between aggregates and cement mortar has been reached.

Figure 5 shows the cumulative pore size distributions, determined by MIP, of the adhered mortar of the recycled aggregates and three cement mortar samples coming from C0, C1 and C2. The last three samples are representative of the new cement matrix located among coarse aggregates in the investigated concretes. Cement mortar samples coming from C1 and C2 concretes are less porous than both the cement mortar coming from reference concrete C0 and the adhered mortar of recycled aggregates. When coarse recycled aggregates are used for the preparation of new concrete mixes, the fresh cement mortar adheres on the adhered mortar of the aggregates filling their porosity and creating a new cement matrix more compact of the previous one and of that formed when only natural aggregates are used. Indeed, the "old" mortar adhered to the recycled aggregates and the "new" one coming from the investigated concrete created a very good connection layer between natural and recycled aggregates. The porosity reduction shown by C2 and C1 compared to C0 is particularly evident for pore sizes lower than 0.1 μm, which are those characteristic of cement paste hydration. The lowest porosity determined for C2 between the two recycled concrete mixes is ascribed to lower *w/c* ratio used.

Finally, porosity data for C2 are in good agreement with the good concrete performances observed during the mechanical and creep tests, confirming that microstructural properties are the basis of the macroscopic behaviour of concrete structures.

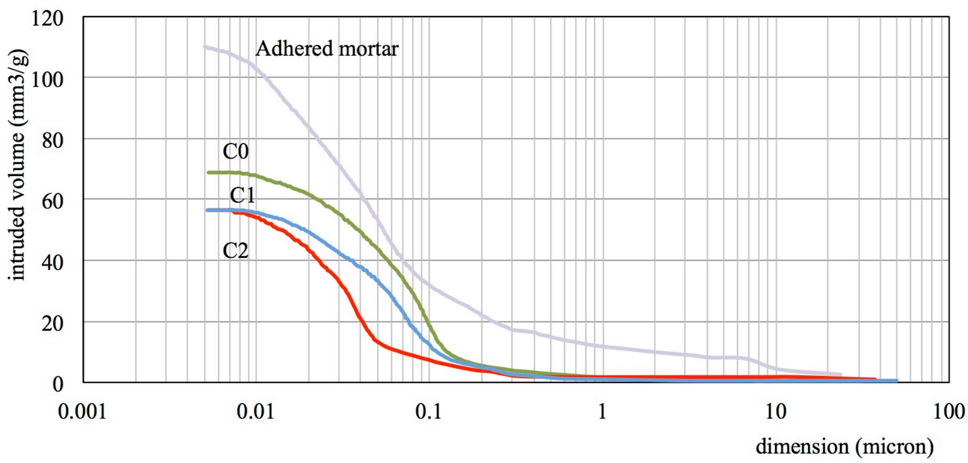

Figure 5. Pore size distribution

CONCLUSIONS

In this study the properties of concrete made with coarse recycled concrete aggregates were compared with those of conventional concrete. Based on the results of the investigation, the following conclusions are obtained:

- the concrete workability is strongly affected by the shape and texture of the coarse recycled aggregates surface;
- at the hardened state, the physical (w_a) and mechanical (f_{cm} and E) properties of concrete with recycled aggregates are comparable to those of conventional concrete, or even better if the same *w/c* ratio is considered. In particular, C2 shows a compressive strength increase of about 25 % compared to C0, thus highlighting that recycled aggregates, if properly assorted, can be successfully used in the production of concrete suitable for structural applications;
- shrinkage strain is negatively influenced by the use of recycled concrete aggregates, regardless the water/cement ratio used. On the contrary, creep results appear less sensitive to *w/c* ratio and the best behaviour was determined for C2, where recycled aggregates are used;
- porosity measurements have highlighted how the cement matrix of the recycled concrete mixes is favourably influenced by the presence of the adhered mortar on the recycled aggregates surface. Indeed the “new” cement mortar creates on the adhered mortar very compact layers, which bind together natural and recycled aggregates.

These results, which are part of a more extensive research currently running on C&DW, are extremely promising in view of a current use of recycled concrete aggregates for structural concrete with sustainable features.

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