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# Durability of Mortars Packaged with Production Waste of Autoclaved Aerated Concrete

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**Abstract.** *The building sector is responsible for the introduction of about 40% of the waste in the environment (60 Mtons per year in Italy), with serious consequences for our future. Therefore, the statistics of the last few years have induced many researchers and many companies to investigate more sustainable products and technologies. Among these strategies, the re-use of waste materials has been widely encouraged. Many solutions have been proposed in the field of mortars for which the use of waste products such as ceramic materials, polystyrene, clay, concrete, has been tried out. The results have often been encouraging, especially for masonry mortars. Nevertheless, very few attempts have been made to place this type of products on the market. Moreover, the "younger" building materials such as Autoclaved Aerated Concrete have not been fully investigated in their potential use as recycled aggregates. The goal of this research was to evaluate the characteristics of mortars packaged with different percentages of production waste of Autoclaved Aerated Concrete components as aggregates, in order to assess the possible use of these conglomerates as masonry mortars or as plasters. The first campaign included tests for determining mechanical resistance, density, capillary water absorption, adherence to substrate, resistance to carbonation. The tested mortars had satisfactory mechanical characteristics and generally exhibited a good capacity to withstand the actions of atmospheric agents. Finally, the results highlighted the direct connection between Autoclaved Aerated Concrete percentage and mechanical and durability properties.*

**Keywords:** *Building Materials Production Waste, Carbonation, Lightweight Aggregates, Recycled Conglomerates, Sustainability.*

## 1 Introduction

The reuse of building waste materials in sustainable concretes or mortars has raised over the last years due to the environmental impact of building constructions. Building materials production waste is preferred rather than Construction and Demolition one due to its controlled chemical composition. The replacement of ordinary aggregates with production waste ones generally affects the mechanical performances of concretes or mortars owing to the low density of recycled aggregates (de Brito *et al.,* 2005; Ćosić *et al.*, 2015).

Nepomuceno, Isidoro and Catarino (2018) suggested a 30% threshold value of volume-replacement percentage of natural coarse aggregate with recycled ceramic in case of structural concrete. Actually, an increase of porosity and of average pore diameter is observed when the recycled aggregates are used (Anastasiou *et al.,*2018; Dang *et al.*, 2019). The accretion of macropores and the reduction of micropores increases the resistance to external sulphate attack as a consequence of the lower capillary pores transport phenomena (Coppola *et al.*, 2018). Moreover, the porosity improves the thermal insulation performances of mortars (Khan, 2002; Mendes *et al.*, 2019).

Despite the raising interest on recycled lightweight aggregates, it is presently unclear whether the high porous structure of the recycled conglomerates affects their durability due to the microstructural changes induced by the aggregates. In particular, the relation between recycled mortars morphology and their carbonation resistance has not been fully investigated.

In order to analyze the effects of the use of a production waste lightweight material on the physical, the mechanical and the resistance to carbonation properties of conglomerates, five groups of mortars packaged with an increasing percentage by mass of Autoclaved Aerated Concrete (AAC) recycled aggregates were tested and compared. The changes in density, porosity, water adsorption, mechanical strengths and carbonation depths were measured.

The results of this study may be used to define the threshold of AAC aggregate percentage with the respect to the application of conglomerate as masonry mortars or as renderings and plasters.

# 2 Materials and Methods

## 2.1 Materials

The tested mortars were packaged with natural hydraulic lime (NHL 5 according to UNI EN 459-1:2010 standard) supplied by TSCcalce.

A natural siliceous sand and a recycled Autoclaved Aerated Concrete were used as aggregates. The natural sand was provided by Bacchi s.p.a and its apparent density, stated by the manufacturer, was 1460 kg/m$^3$. The recycled aggregate was supplied by Bacchi s.p.a, resulted from the production waste of Autoclaved Aerated Concrete (AAC) wall components. The particles size distribution of the recycled aggregate was measured through the dry sieving method according to UNI EN 933-1: 2012 and it is shown in Figure 1.

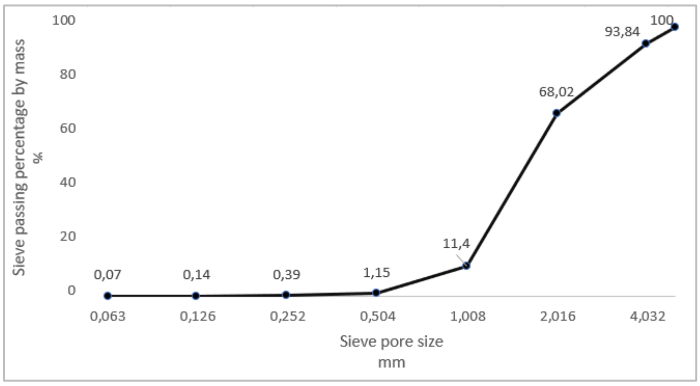

**Figure 1**. Particle size distribution of Autoclaved Aerated Concrete recycled aggregates according to the sieving test method.

The particle density and the water adsorption of AAC aggregates were analyzed according to UNI EN 1097-6:2013 pycnometer method for aggregate particles passing 4 mm test sieve and retained on the 0,063 mm test sieve. The outcomes are shown in Table 1.

**Table 1**. Particle density and water adsorption of Autoclaved Aerated Comcrete recycled aggregates.

| M1 (g) | M2 (g) | M3 (g) | M4 (g) | $\rho_{rd}$ (kg/m$^3$) | $\rho_{ssd}$ (kg/m$^3$) | $\rho_a$ (kg/m$^3$) | W (%) |
|---|---|---|---|---|---|---|---|
| 77,93 | 477,73 | 452,29 | 45,11 | 860 | 1480 | 2290 | 72,76 |

M1, saturated and surface dried mass in air; M2, mass of pycnometer containing the saturated aggregate sample and the water; M3, mass of pycnometer filled with water only; $\rho_{rd}$, oven dried particle density; $\rho_{ssd}$, saturated and surface dried particle density; $\rho_a$, apparent particle density; W, water adsorption.

The chemical composition of the recycled aggregates was determined by a ThermoGravimetric Analysis (TGA) using a Netzsch- STA 409 PC Luxx apparatus. The mass losses of an AAC aggregate sample of 20 mg were monitored over time as the sample was heated in a controlled atmosphere. The temperature ranged from 23° to 1200° with a 10°/min heating rate. The mineralogical composition of AAC aggregates was analyzed by X-ray Diffraction (XRD) technique using a Philips X'pert PRO multipurpose powder diffractometer with X-ray wavelength of 1,54 Å. The outcomes were compared with the standard patterns of the International Centre for Diffraction Data database. The main mineralogical phases were Silicon Oxide, Calcium Carbonate, Calcium Hydroxide Hydrated Silicates and Calcium Sulfate Hydrated. A distilled water was used as kneading water.

Five groups of mortars with five specimens in each group were analyzed. All the tested specimens were packaged using the hydraulic lime and a binder-aggregate ratio of 1:3 by mass. The first group – noted 1 - was taken as reference and it was composed of mortars with 100% natural aggregate percentage. In the other four groups – noted 2,3,4,5 - the natural sand was gradually replaced with an increasing percentage by mass of recycled aggregate from 12,5% to 50%. The water – binder ratio of 2,3,4,5 was adjusted due to AAC aggregate water adsorption. Table 2 shows the compositions of the tested mortars.

**Table 2**. Compositions of tested mortars.

| | HL (g) | SS (g) | AAC (g) | W (g) | W/B | RA (%) |
|---|---|---|---|---|---|---|
| 1 | 450 | 1350 | 0 | 225 | 0,50 | 0 |
| 2 | 450 | 1181,25 | 168,75 | 337,5 | 0,75 | 12,5 |
| 3 | 450 | 1012,50 | 337,50 | 450 | 1,00 | 25 |
| 4 | 450 | 843,75 | 506,25 | 562,5 | 1,25 | 37,5 |
| 5 | 450 | 675 | 675 | 675 | 1,50 | 50 |

HL, hydraulic lime; SS, siliceous sand; AAC, Autoclaved Aerated Concrete recycled aggregates; W, kneading water; W/B, water/binder ratio; RA, AAC percentage by mass on the total aggregates.

## 2.2 Methods

### *2.2.1 Mixing procedure of mortars and testing program of physical, mechanical and resistance to carbonation properties*

Physical, mechanical and resistance to carbonation tests were performed on prismatic specimens according to UNI EN 196-1:1996 specifications. The natural sand and the recycled aggregates were dry premixed before they were blended with the hydraulic lime and the kneading water. The specimens were molded in prismatic casts (40x40x160 mm) and cured in a climatic chamber (MSL Humichamber EC 125) under controlled conditions according to UNI EN 1015-11:2007. Three specimens of each group were tested for density, porosity, water adsorption, compressive and flexural strength, two specimens of each group were tested for resistance to carbonation.

### *2.2.2 Apparent and bulk dry densities, open porosity and water adsorption*

The tests were conducted according to UNI EN 1936:2007 specifications. The prismatic specimens were dried in an oven at 70±5° temperature until a constant mass was recorded.

As the mass was stabilized, the three specimens of each group were weighted and their dry mass M1 was recorded. Then the dry specimens were stored for 24h under vacuum in a vessel in which the pression was gradually lowered to 15±5 mmHg. After this period a volume of water was introduced in the vessel so that the specimens were immersed for at least 5 mm. The specimens were kept under vacuum and immersed in water for 24h with the same pression of 15±5 mmHg. Finally, the pression was returned to the atmospheric value and the specimens were left immersed for other 24h. After the 72h storage the immersed specimens were weighted and the M2 value was recorded. The mortars were then wiped with a cloth and the mass of the saturated specimens, noted M3, was measured.

The apparent ($\rho_a$) and the bulk ($\rho_r$) densities, the open porosity ($p$) and the water adsorption ($W$) were finally calculated using the UNI EN 1936:2007 equations.

## 2.3 Mechanical Properties

The compressive and the flexural resistance tests were performed according to UNI EN 1015-11:2007 procedure using the Alpha Technologies Tensometer 2020 machine. The compressive load cells were of three types: groups 3,4,5 were tested with 5kN, group 2 with 10kN and group 1 with 15kN. The flexural load cells were 5kN for groups 4,5 and 10kN for groups 1,2,3.

### *2.3.1 Adherence on substrates test*

The adhesive strength of mortars on substrates was measured according to UNI EN 1015-12:2016 procedures. Three different substrates - brick, tuff and lapil-cement - were tested and their fracture patterns were compared.

### *2.3.2 Resistance to carbonation*

The resistance to carbonation test and the analysis of the results were conducted according to UNI EN 13295:2005 indications. The carbonation depth was measured according to UNI EN 14630:2003 procedures. The measurement was repeated only two times - on 15th and on 30th day- because all the specimens were fully carbonated after thirty days.

# 3 Results

## 3.1 Apparent and Bulk Dry Densities, Open Porosity and Water Adsorption

The apparent and the bulk dry densities, the open porosity and the water adsorption of the tested mortars are shown in Table 3. The mean values for the three specimens of each group are reported. The reference mortar -1- exhibited an apparent density 66% higher than the group 5.

The open porosity and the water adsorption of group 5 were respectively twice and three times as high as group 1.

**Table 3**. Apparent and bulk dry densities, open porosity and water adsorption. Mean values of the three specimens of each group are reported.

| | $\rho_a$ (g/cm$^3$) | $\rho_r$ (g/cm$^3$) | $p$ (%) | $W$ (%) |
|---|---|---|---|---|
| 1 | 1,75 | 2,24 | 22 | 12,58 |
| 2 | 1,51 | 2,13 | 29 | 19,35 |
| 3 | 1,27 | 1,95 | 35 | 27,12 |
| 4 | 1,20 | 1,91 | 37 | 31,07 |
| 5 | 1,05 | 1,87 | 44 | 41,53 |

$\rho_a$, apparent dry density; $\rho_r$, bulk dry density; p, open porosity; W, water adsorption

### 3.2 Mechanical Properties

The mean values of flexural and compressive strength are reported in Table 4. The flexural resistance of group 4 was tested only on two specimens due to the breakage of one sample during the curing period. The group 5 exhibited a flexural and a compressive resistance fifteen and ten times, respectively, as low as mortars of group 1.

**Table 4**. Flexural and compressive strength. Mean values of the three specimens of each group* are reported.

| | $\sigma_f$ (MPa) | $\sigma_c$ (MPa) |
|---|---|---|
| 1 | 2,62 | 6,93 |
| 2 | 1,54 | 4,53 |
| 3 | 0,67 | 1,49 |
| 4 | 0,13 | 0,90 |
| 5 | 0,17 | 0,57 |

* Except for flexural resistance of group 4 (mean values of two specimens); $\sigma_f$ , flexural resistance; $\sigma_c$, compressive resistance.

The compressive strength values were compared to UNI EN 998-2:2016 and to UNI EN 998-1:2016 specifications with respect to the classes of masonry and rendering or plastering mortars, respectively. The classification of the tested mortars is reported in Table 5.

### 3.3 Adherence on Substrates Test

The adhesive strength of mortars on each of the tested substrates is shown in Table 6. Mean values of recorded resistance are reported along with UNI EN 1015-12:2016 fracture pattern classification. The A, B, C pattern types referred to an adhesion fracture at the interface between mortar and substrate, to a cohesion fracture in the mortar itself and to a cohesion fracture in the substrate material, respectively.

**Table 5**. Classification of the tested mortars according to UNI EN 998-1,2:2016.

| | UNI EN 998-2 | UNI EN 998-1 | |
|---|---|---|---|
| | Table 1 | Table 1 | Table 2 |
| 1 | M5 | CS III/ IV | GP-LW-CR-OC |
| 2 | M2,5 | CS II/ III | GP-LW-CR-OC-R-T |
| 3 | M1 | CS I | GP-LW-CR-OC-T |
| 4 | / | CS I | GP-LW-CR-OC-T |
| 5 | / | CS I | GP-LW-CR-OC-T |

/ not classified; GP general purpose; LW lightweight rendering/plastering; CR coloured rendering mortar; OC one coat rendering mortar for external use; R renovation mortar; T thermal insulation mortar

**Table 6**. Adhesive strength on substrates. Mean values of resistance and fracture pattern type are reported.

| | Brick | | Tuff | | Lapil-cement | |
|---|---|---|---|---|---|---|
| | $f_u$ (MPa) | FP | $f_u$ (MPa) | FP | $f_u$(MPa) | FP |
| 1 | 0,24 | A | 0,29 | B/C | 0,56 | A |
| 2 | 0,34 | A | 0,34 | B/C | 0,26 | B |
| 3 | 0,30 | B | 0,04 | B/C | 0,14 | B |
| 4 | 0,16 | B | 0,05 | A | 0,12 | B |
| 5 | / | / | / | / | 0,09 | B |

$f_u$, adhesive strength; FP, fracture pattern; / it was not possible to measure the strength

### 3.4 Resistance to Carbonation

The results of the resistance to carbonation test are shown in Figure 2. On the 15th day the group five was carbonated twice as high as the reference mortar whereas all the specimens were fully carbonated on the 30th day.

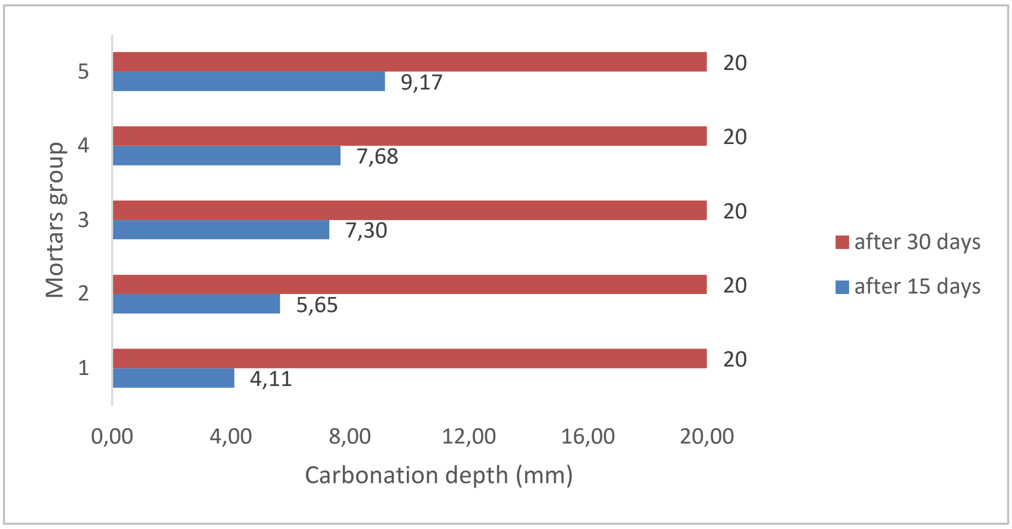

**Figure 2.** Resistance to carbonation test. Carbonation depth on 15th and 30th day are reported.

## 4 Discussions and Conclusions

The aim of the research was to investigate the influence of Autoclaved Aerated Concrete waste production aggregates on the mechanical and the durability properties of mortars, with specific respect to the resistance to carbonation. Results indicate that the replacement of the ordinary siliceous sand with AAC aggregate impacts on the hard-state properties of mortars.

The density and the mechanical properties – compressive and flexural strengths – and the adhesive strength to substrates decreased as the recycled aggregate percentage grew. Concerning the adhesive strength to substrate, the adherence to tuff rapidly lowered as the sand was replaced with AAC. Moreover, the open porosity and the water adsorption increased as AAC replaced the natural sand. Actually, the mortars with a higher percentage of AAC needed more kneading water due to the AAC adsorptive properties. Finally, the highest AAC mortar exhibited a short-term low resistance to carbonation, whereas the same value of carbonation depth was observed on 30th day measurement for all the specimens.

Similar trends were reported by Blanco *et al.* (2000) who recorded a strong correlation between the use of lightweight aggregates and the physical and the mechanical properties of concretes. Moreover, the discussed results are consistent with Zhao *et al.* (2015) who measured the reduction of flexural and compressive strength of concretes due to the use of recycled aggregates. Tewar *et al.* (2017) also investigated the substitution of natural sand with AAC waste production aggregates and they reported the growing of kneading water mass and the lowering of compressive strength as AAC percentage was kept higher. Finally, the higher porosity of recycled-aggregates conglomerates was found responsible for a higher CO2 uptake, similar to Evangelista *et al.,*(2010); de Oliveira Andrade *et al.,*(2018).

However, the tested mortars were packaged with only one type of binder and one particle sizes distribution of aggregates, mainly ranged between 2 and 4 mm. Therefore, further studies are necessary to find if the type of binder and the packing of aggregates can modify the discussed results. The resistance to carbonation test needs to be repeated with a shorter time interval between the measures in order to better evaluate the evolution of the phenomenon. Finally, a mechanical test on the carbonated specimens has to be executed to investigate the effects of CO2 diffusion on the compressive and the flexural strength of the mortars.

In conclusions, the substitution of natural sand with AAC aggregates seems to be useful to package both masonry and rendering or plastering mortars. Moreover, the increased porosity and the reduced density of higher AAC percentage mortars suggest their potential thermal insulating properties. Conversely, a threshold for AAC percentage is necessary for masonry mortars packaged with hydraulic lime due to the reduction of mechanical performances and resistance to carbonation.

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