

Part B

Manuscript Draft

Manuscript Number:

Title: Investigation on the use of foamed plastic waste as natural aggregates replacement in lightweight mortar

Article Type: Full length article

Keywords: A. Foams; B. Adhesion; D. Recycling; D. Mechanical testing; Lightweight aggregates

Corresponding Author: Dr. Bartolomeo Coppola,

Corresponding Author's Institution: University of Salerno

First Author: Bartolomeo Coppola

Order of Authors: Bartolomeo Coppola; Luc Courard; Frédéric Michel; Loredana Incarnato; Luciano Di Maio

Abstract: The large growth of plastic consumption and consequently of plastic waste, requires new forms of recycling, avoiding landfill disposal. Polymeric aggregates obtained from recycled materials are often used for the production of lightweight mortars whose properties are widely reported in the literature. In this work, new kind of polymeric aggregates with a particular set of properties are used as sand substitutes in lightweight mortars. Particularly, starting from end of waste materials, a process of extrusion - melt foaming was applied to produce polymeric particles characterized by high porosity and surface roughness. The process also allowed to tailor the particles size in order to accurately substitute natural sand particle size distribution in the mortar samples. Natural quartz sand was replaced by artificial aggregates at two volume fractions (10 and 25%) both in saturated and unsaturated conditions. Moreover, two different w/c ratios were investigated (0.45 and 0.50). The higher porosity and rough surface of foamed aggregates resulted in a good adhesion with the cement paste. SEM investigations revealed the presence of interlocking positions onto aggregates surface and an ITZ very similar to that between natural aggregates and cement paste. At increasing sand replacement a reduction of mortar consistency was observed and, as expected, also a mechanical properties decrease. However, for all the investigated lightweight mixtures, compressive strength values are higher than the minimum compressive strength required for structural concrete (17.25 MPa). The use of artificial plastic aggregates, obtained by foam extrusion process, provides some advantages: reduction of natural sand consumption, use of plastic waste otherwise not used, decrease of structures dead-weight and improved aggregates/cement paste ITZ.

Suggested Reviewers: Andrzej Garbacz
DEPARTMENT OF BUILDING MATERIALS ENGINEERING, WARSAW UNIVERSITY OF
TECHNOLOGY
a.garbacz@il.pw.edu.pl

Valeria Corinaldesi

Università Politecnica delle Marche
v.corinaldesi@univpm.it

Opposed Reviewers:

Bartolomeo Coppola
Department of Industrial Engineering
University of Salerno, Italy

10/03/2016

Dear Editor,

We wish to submit a manuscript entitled "*Investigation on the use of foamed plastic waste as natural aggregates replacement in lightweight mortar*" for consideration by *Composites Part B: Engineering*.

We confirm that this work is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere.

In this paper, we report on the production and use of lightweight aggregates obtained from recycled plastic waste. In particular, plastic aggregates were produced by foam extrusion process of a polyolefin blend. This is significant because it allows the use of post-consumer plastic waste which are generally not used due to their low mechanical properties. Moreover, the foam extrusion process leads to the production of aggregates with a porous and rough surface, resulting in a good bond with the cement paste. Many authors, in fact, reported about the low bond between plastics and cement paste which causes several issues. Thus, a simple process of foam extrusion could be an easy way to use post-consumer plastic waste for the production of sustainable cement composites. The novelty of this work lies on the production of engineered aggregates (characterized by high porosity and surface roughness) and the investigation of the interfacial transition zone (ITZ) between manufactured aggregates and the cement paste studying the influence of w/c ratio, aggregates surface, porosity and saturation. Moreover, the large growth of plastic consumption and consequently of plastic waste, requires new forms of recycling, avoiding landfill disposal. The aim of this work was to analyze the use of foamed plastic waste as aggregates to produce a lighter and sustainable mortar. To this extent, this paper should be of great interest among readers of this journal and for the scientific community in general.

Thank you for your consideration of this manuscript.

Sincerely,

Bartolomeo Coppola.

Investigation on the use of foamed plastic waste as natural aggregates replacement in lightweight mortar

Bartolomeo Coppola ^{a,*}, Luc Courard ^b, Frédéric Michel ^b, Loredana Incarnato ^a, Luciano Di Maio ^a

^a University of Salerno, Department of Industrial Engineering, Via Giovanni Paolo II n. 132, 84084 Fisciano (SA), Italy

^b University of Liège, ArGEnCo Department, Quartier Polytech 1, Allée de la découverte 9, B-4000 Liège, Belgium

* Corresponding author.

E-mail addresses: bcoppola@unisa.it (B. Coppola), luc.courard@ulg.ac.be (L. Courard), frederic.michel@ulg.ac.be (F. Michel), lincarnato@unisa.it (L. Incarnato), ldimaio@unisa.it (L. Di Maio).

Abstract:

The large growth of plastic consumption and consequently of plastic waste, requires new forms of recycling, avoiding landfill disposal. Polymeric aggregates obtained from recycled materials are often used for the production of lightweight mortars whose properties are widely reported in the literature. In this work, new kind of polymeric aggregates with a particular set of properties are used as sand substitutes in lightweight mortars. Particularly, starting from end of waste materials, a process of extrusion - melt foaming was applied to produce polymeric particles characterized by high porosity and surface roughness. The process also allowed to tailor the particles size in order to accurately substitute natural sand particle size distribution in the mortar samples. Natural quartz sand was replaced by artificial aggregates at two volume fractions (10 and 25%) both in saturated and unsaturated conditions. Moreover, two different *w/c* ratios were investigated (0.45 and 0.50). The higher porosity and rough surface of foamed aggregates resulted in a good adhesion with the cement paste. SEM investigations revealed the presence of interlocking positions onto aggregates surface and an ITZ very similar to that between natural aggregates and cement paste. At increasing sand replacement a reduction of mortar consistency was observed and, as expected, also a mechanical properties decrease. However, for all the investigated lightweight mixtures, compressive strength values are higher than the minimum compressive strength required for structural concrete (17.25 MPa). The use of artificial plastic aggregates, obtained by foam extrusion process, provides some advantages: reduction of natural sand consumption, use of plastic waste otherwise not used, decrease of structures dead-weight and improved aggregates/cement paste ITZ.

Keywords:

A. Foams; B. Adhesion; D. Recycling; D. Mechanical testing; Lightweight aggregates.

1. Introduction

1 The use of plastics in our life seems to be essential due to their versatility and unique properties like lightweight,
2 durability, low cost and ease to process. Plastics world production reached the three hundred megatonne in 2013 [1],
3 establishing itself as the most common material of the 21th century. However, linked to plastic production and disposal
4 there are considerable environmental problems. One of the disadvantages resides on the speed with which these
5 materials immediately became waste. Moreover, in Europe, only the 69% is recycled and recovered (in part to produce
6 energy) while the 31% of plastic waste goes to landfill [1]. Recycling is the only key to reduce environmental issues
7 caused by waste disposal and use of non-renewable resources. Plastic waste sorting allows the recovery of large
8 volumes of polymeric fractions but while rigid plastics are easy to separate and recycle, more difficulties are found for
9 flexible films which represent a great part of plastic waste. Moreover, the presence of different plastic types, which are
10 not easy to separate and often are also immiscible at micro-scale produces materials with very poor properties [2,3,5].

11 In view of that and considering the desire to reduce the use of natural resources in the construction industry, with
12 particularly attention to land consumption for concrete aggregates, more and more researchers are investigating the
13 possibility of using waste plastic materials as aggregate replacement in mortar or concrete. Considering the great part of
14 mortar or concrete volume occupied by aggregates (about 70%) [4] is clear the great influence that also low volume
15 fraction substitutions could have on the composite properties.

16 Using plastic aggregates is possible to produce lighter and sustainable concrete with promising properties in terms of
17 fracture mechanism (toughness increase) [6,7], thermal conductivity [8 - 11, 10] and water vapor permeability
18 [8,12,13]. On the other side, rheology [14 - 17] and mechanical properties [6, 13 -16,] are negatively affected by the
19 presence of plastic aggregates. More recently some authors investigated the residual properties of concrete containing
20 plastic aggregates after high temperatures or fire exposure [18,20]. Sokołowska et al. [19] studied the influence of
21 crushed HDPP wastes also into Concrete-Polymer Composites (C-PC).

22 Generally plastic aggregates have various shapes (pellets, flakes, fibrous etc.) and particle size distribution which
23 usually differs from sand or aggregates used as reference sample [9 - 13 ,15,16, 21]. Artificial aggregates
24 manufacturing, starting from recycled plastic waste materials, confers the possibility to prepare a well-defined particle
25 size distribution, fitting standard or practically requirements. Another important aspect is represented by aggregates
26 segregation and composite compaction [14, 22,23]. Marzouk et al. [23], for example, shown that for increasing
27 replacement up to 50%, compactness is good while increasing more than this value, a cavernous structure is achieved.
28 Thus, the importance to have a precise particle size distribution lies not only on the possibility to easily compare results
29 from different authors but also to achieve a good composite.

1
2 One of the main drawbacks in the use of plastic aggregates is the low wettability of artificial aggregates, due to their
3 hydrophobicity, and thus the poor ITZ with the cementitious matrix [6,16, 24,25]. Moreover, as stated elsewhere, the
4 presence of free water around plastic aggregates causes a more porous ITZ but also the reduction of hydration products
5 at ITZ. Moreover, ITZ microstructure have a great influence on diffusive transport into cementitious matrix and a
6 denser ITZ corresponds to a higher barrier to water and gases [30]. To overcome this drawback, some authors
7 investigated the possibility to cover artificial aggregates by ground granulated blast furnace slag (GBFS) [25] or by sand
8 [26].
9

10
11
12 Several authors studied the use of plastic foams as aggregate replacement [22,27,28], revealing some issues: i.e.
13 aggregates proportioning, deformability, water absorption and buoyancy. On the contrary, by using foams a better
14 adhesion can be achieved thanks to foams porous surface that enables the penetration of both water and cement paste
15 [9,20,22,27 - 29].
16
17

18
19 As previously stated, polyethylene terephthalate (PET), high density polyethylene (HDPE) and other rigid plastics are
20 easily separated during recycling process and most of the works in literature are carried out considering such materials
21 for aggregate production [11, 10, 15, 16, 26, 31, 32]. On the contrary, the fraction represented by flexible items (mainly
22 films for packaging) i.e. low density polyethylene (LDPE), polypropylene (PP) and their blends, is difficult to recycle
23 and was not already investigated by researchers for aggregates production.
24
25

26
27 In this work “end of waste materials”, obtained by the separation and mechanical recycling of post-consumer packaging
28 films of small size were used to produce lightweight aggregates for sand substitution in mortars. Due to the low
29 properties of such kind of polymeric blends, their use is so far rare. In order to obtain a suitable material for the
30 production of cementitious composites, the extrusion-foaming process was used in order to obtain particles of specific
31 size (and particle size distribution fitting the sand substitution in the mortars samples). Moreover, the foaming process
32 provides the formation of a highly coarse and porous surface of the polymeric particles which results in enhanced
33 bonding with the cementitious matrix. The investigations were carried out also considering the influence of aggregates
34 saturation and consequently the use of different water cement (w/c) ratios. Generally, if porous aggregates are used, it is
35 preferably to saturate them to avoid w/c changes due to the absorption of mixing water varying the effective water
36 content, influencing mechanical properties, rheology, density and porosity.
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

2. Experimental procedures

2.1. Materials

The materials used in this study to produce mortar were Portland cement (CEM I 42.5 N), quartz sand (CEN standard sand according to EN 196-1 [33], with density of 2610 kg/m^3) and lightweight aggregates (LWAs). LWAs were produced from waste material provided by BREPLAST S.P.A. (Pavia, Italy). The plastic material, supplied in densified pellets, was a polyolefin blend containing polypropylene (PP) and polyethylene (PE). LWAs manufacturing consisted of three following steps: foam extrusion process, strands grinding and aggregates sieving. Pellets and chemical foaming agent (Hydrocerol CF) at 2wt.% were dry blended (Figure 1a) and then extruded by a single screw extruder (BRABENDER DO-CORDER E330, $L/D = 20$ with a $D_{\text{screw}} = 20 \text{ mm}$, capillary die of 0.5 mm) (Figure 1b) operating at the following temperature profile: 165°C - 230°C - 170°C , varying screw speed rotation to obtain foamed strands with different diameters. Above the decomposition temperature of the foaming agent, 150°C , gases are produced which generates bubbles nucleation and growth in the molten polymer and stabilization outing from the extruder die due to the pressure and temperature gradients [34]. Filaments were collected by a winder (Figure 1c) and then grinded by a pelletizer. In the last step aggregates were sieved according to EN 933-1 [35] and separated in four different particle size grades: 2-1.4 mm, 1.4-1.0 mm, 1.0-0.50 mm and 0.50-0.18 mm. The four aggregates were mixed in order to reproduce, almost completely, the standard sand particle size distribution [33] (Figure 7).



Figure 1: a) Pellets and foaming agent in the hopper; b) single screw extruder die and c) winder collecting foamed strands

2.2. Mixtures preparations

LWAs were used both in saturated and unsaturated conditions and two w/c ratios were investigated. Saturated LWAs were soaked in part of the mixing water for 24 hours. Nomenclature of the studied mixtures is reported in Table 1. The numbers after the name indicate the w/c ratio (0.45 and 0.50) while s and ns stay for saturated and not saturated respectively, referring to LWAs condition. All the mortar samples were prepared according to the procedure described in EN 196-1; in order to better disperse artificial aggregates in the mixture natural and LWAs were dry mixed in advance. Two natural quartz sand volume replacement (10% and 25%) were investigated comparing lightweight mortars (LWMs) with control specimens, i.e. without LWAs.

Table 1: Investigated mixtures containing two natural sand volume replacement by lightweight aggregates (LWAs)

Mortar	w/c	LWA (%)	Saturated
Reference I	0.45	-	-
Reference II	0.50	-	-
LWMA I	0.45	10	x
LWMA II	0.50	10	x
LWMA III	0.50	10	-
LWMB I	0.45	25	x
LWMB II	0.50	25	x
LWMB III	0.50	25	-

2.3. Test methods

In order to characterize aggregates, their morphology, particle size distribution and physical properties were investigated. Natural and artificial aggregates morphology was investigated by scanning electron microscopy (SEM, LEO model 420). LWAs particle density (EN 1097-6, [36]) was measured by a helium pycnometer while bulk density was determined according to EN 1097-3 [37]. Fresh mortar workability was determined by flow table test, EN 1015-3 [38], considering the spread diameter on the table. Consistency was evaluated by the ratio between mortar diameter after and before the test. Mortar flexural strength was determined by three-point bending test while compressive tests were performed on the half prisms resulting from flexural tests [33]. For mechanical properties specimens of 40 mm x 40 mm x 160 mm were casted in steel molds and compacted by a jolting table; three specimens for each composition were tested. The oven-dry density ρ_d of hardened mortar was determined on specimens dried at 105°C until constant mass, EN 12390-7 [39]. Natural and lightweight aggregates interaction with cement paste was investigated by SEM pictures taken both on polished than fractured surfaces. Differential scanning calorimetry (DSC) was used to investigate LWAs thermal properties performing the following thermal cycle: heating/cooling/heating from -100°C to 250°C at 10°C/min under nitrogen atmosphere (100 ml/min). Thermogravimetric analysis (TGA) was carried out on LWAs and mortar samples of 15 mg, using a Q500 analyzer. Specimens were heated at 10°C/min from 25°C to 900°C under nitrogen atmosphere (20 ml/min).

3. Results and discussion

3.1. Aggregates characterization

As previously stated, particular attention should be paid to processing a polymeric blend as a result of the different melting temperature of each component. In particular, DSC analysis carried on LWAs showed three different melting peaks, as reported in Figure 2. The first sharp melting peak (126°C) is representative of polyethylene (PE) while the second one (162°C) of polypropylene (PP). Moreover, the presence of a shoulder (109°C) in the shape of the peak may be associated to the presence of heterogeneous crystalline phases.

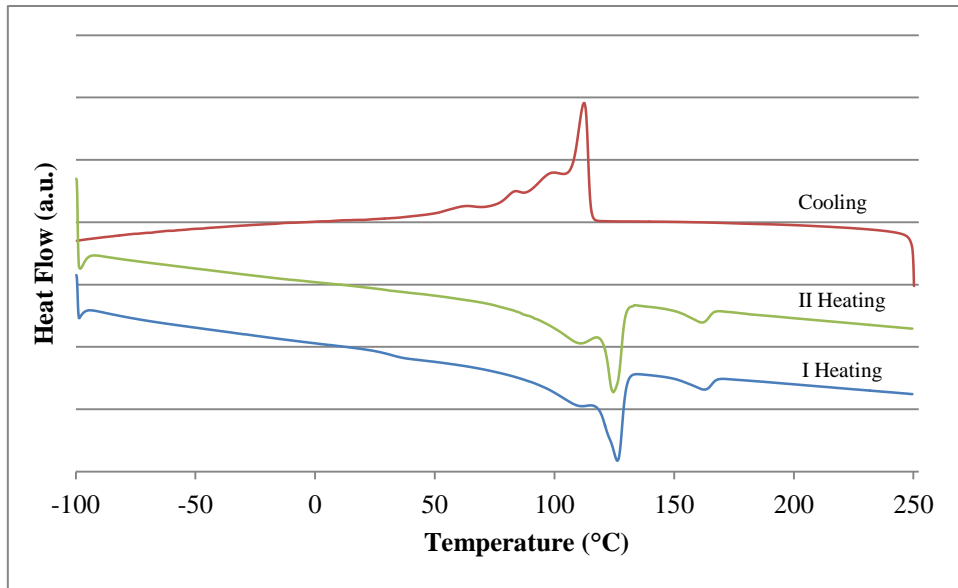


Figure 2: DSC thermograms of LWAs

Scanning electron microscopy images of the investigated material show an heterogeneous dispersion of PP droplets in the continuous PE matrix (Figure 3), confirming what revealed by DSC analysis. PE/PP incompatibility has been widely proved and explained in literature [2,3,5] and it represents the main reason for the unsatisfactory mechanical properties of these recycled mixed plastics.

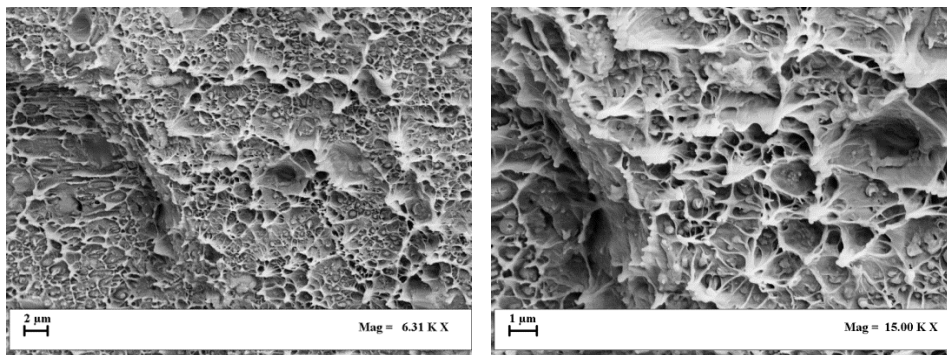


Figure 3: SEM micrographs showing aggregates foamed structure and PP droplets into PE matrix

TGA analysis was used to determine LWAs thermal degradation correlating weight loss percent and temperature (Figure 4). Degradation starts at 460 °C (T_{onset}) resulting in a weight loss of 90 % between 460-520 °C.

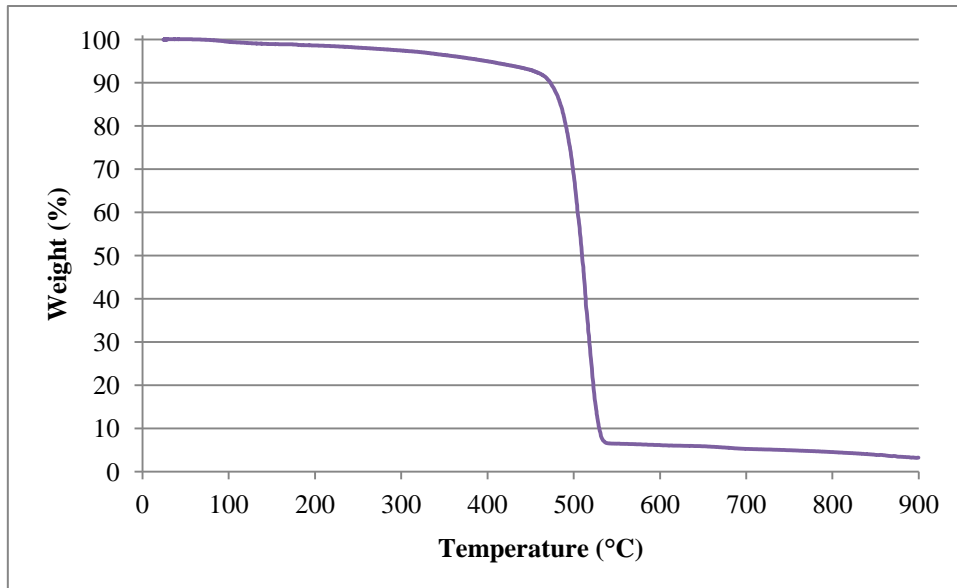


Figure 4: LWAs weight loss vs. temperature (TGA)

Natural sand have been crushed by natural processes of weathering and abrasion resulting in smooth and rounded particles (Figure 5). A satisfactory aggregate should be well graded with a good proportion between rounded and angular particles and a surface texture not too smooth. On the contrary, artificial aggregates present an elongated shape (Figure 6), i.e. cylindrical shape, as a result of the manufacturing process: extrusion produces foamed strands (Figure 1b) that later are grinded to become aggregates. Moreover, artificial aggregates surface is rougher due to the presence of surface cavities which increase cement paste ability to adhere and penetrate inside this voids, as will be later discussed.

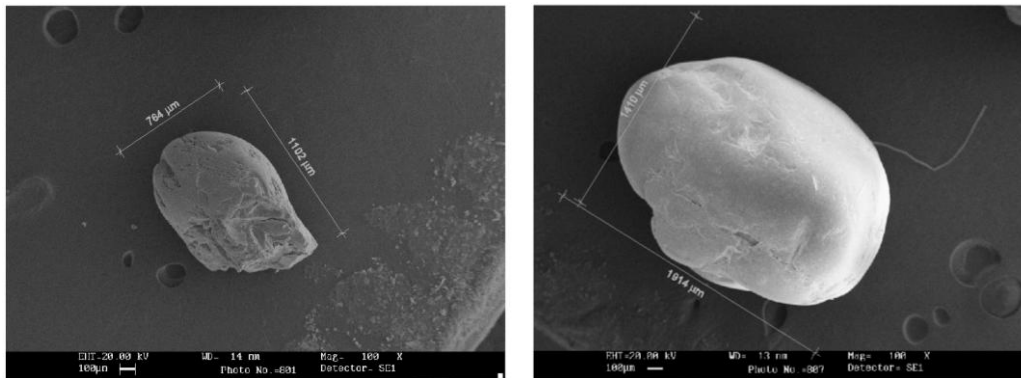


Figure 5: Natural quartz sand SEM pictures

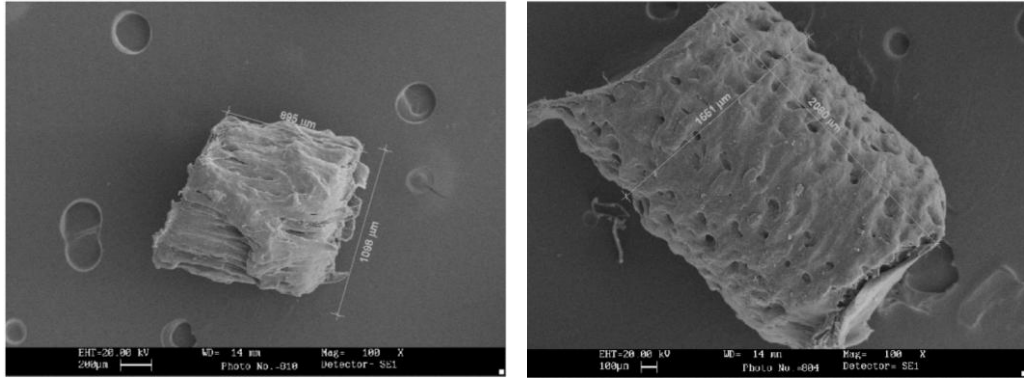


Figure 6: Lightweight aggregates (LWAs) SEM pictures

Aggregates grading, i.e. particle size distribution, is of wide importance for mortar density, porosity, aggregates distribution and also mechanical properties [4]. As discussed previously, many authors have investigated the use of artificial aggregates with particle distribution far or quite far from the natural aggregates one [9,12]. Natural and artificial aggregates particle distribution are reported in Table 2 and Figure 7. LWAs particle distribution (Figure 7) was almost the same of quartz sand grading curve but with less fines. As reported in Table 2, LWAs are coarser, i.e. the presence of coarse aggregates is higher, as evident also by the higher modulus of fineness. In this study authors excluded the use of fine artificial aggregates both for the difficulty in producing a such small particle size but also to avoid the use of a superplasticizer, which use will be investigated in a following work.

Table 2: Natural and artificial sand cumulative passing

Mesh size (mm)	Cumulative passing (%)	
	Natural sand	LWAs
2.00	100	100
1.60	93	-
1.40	-	82
1.00	67	63
0.50	33	22
0.18	-	0
0.16	13	-
0.08	0	-
Modulus of fineness	2.94	3.33

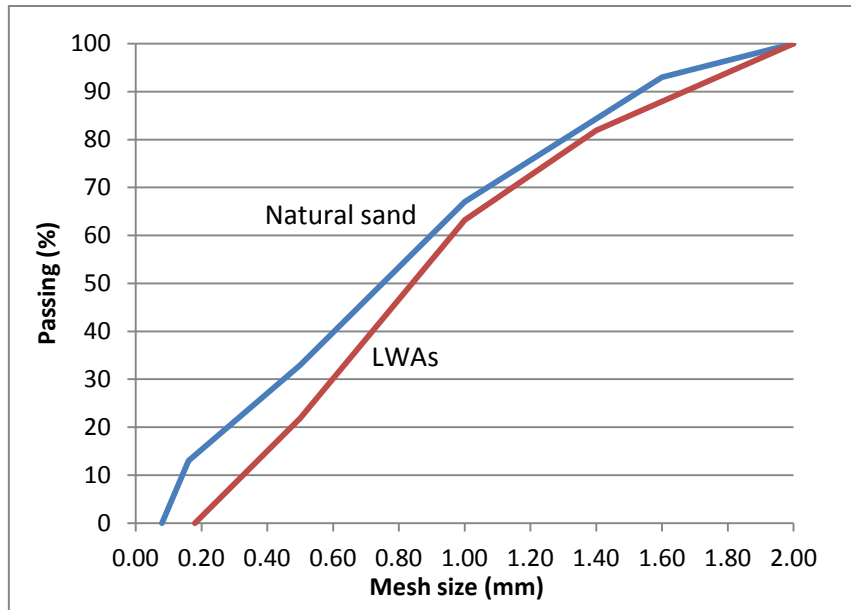


Figure 7: Aggregates particle size distribution (LWAs = LightWeight Aggregates)

Particle and bulk density of LWAs were investigated and results are reported in Table 3. At increasing particle size lower values of particle density were measured: fine aggregates are slightly heavier than coarse ones. As reported by several authors [14,22,23,28], one of the main issue is LWAs dispersion due to the low density which causes aggregates floating if not well dispersed into the matrix. Bulk density shows the same behaviour: fine particles have a higher bulk density than coarser ones. Artificial aggregates density is lower than natural quartz sand density of 65% approximately, considering an average particle density of 913 kg/m³ for LWAs.

Table 3: LWAs particle and bulk density

Mesh size (mm)	LWAs	
	Particle density (kg/m ³)	Bulk density (kg/m ³)
1.40/2.00	897	348
1.00/1.40	914	361
0.50/1.00	920	387
0.18/0.50	922	402

3.2. Workability of fresh mortar

Figures 8-10 show the results of the flow test carried out for the investigated mixtures. The porous structure of LWAs influences workability of fresh mortar due to the absorption of both mixing water and cement paste inside pores [22]. On the contrary, as discussed before, natural quartz sand has a smooth surface and water absorption is close to zero. Moreover, also aggregates shape affects mortar rheology: rounder particles produce a more workable mortar while elongated particles, as LWAs, give rise to higher friction and reduce consistency. To partially overcome these drawbacks, LWAs could be soaked and saturated into part of mixing water before mixtures preparation. For both w/c ratios, at increasing LWAs content a reduction of workability was observed and it was proportional to LWAs

substitution. Saturating LWAs, in the case of w/c ratio of 0.50, was possible to decrease the loss in consistency of about 3% (Figure 11).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

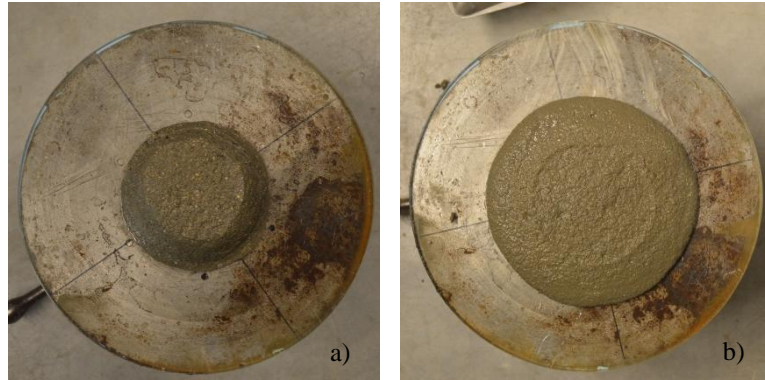


Figure 8: a) Reference I and b) Reference II

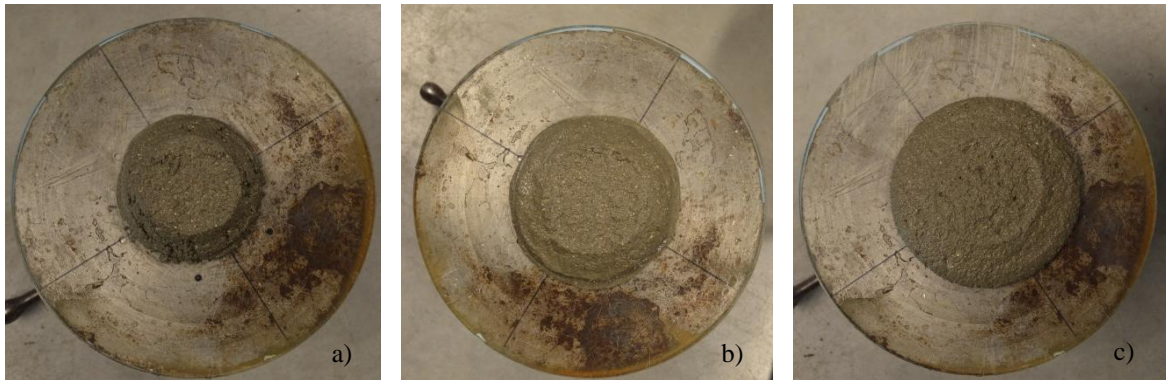


Figure 9: a) LWMA I; b) LWMA III and c) LWMA II

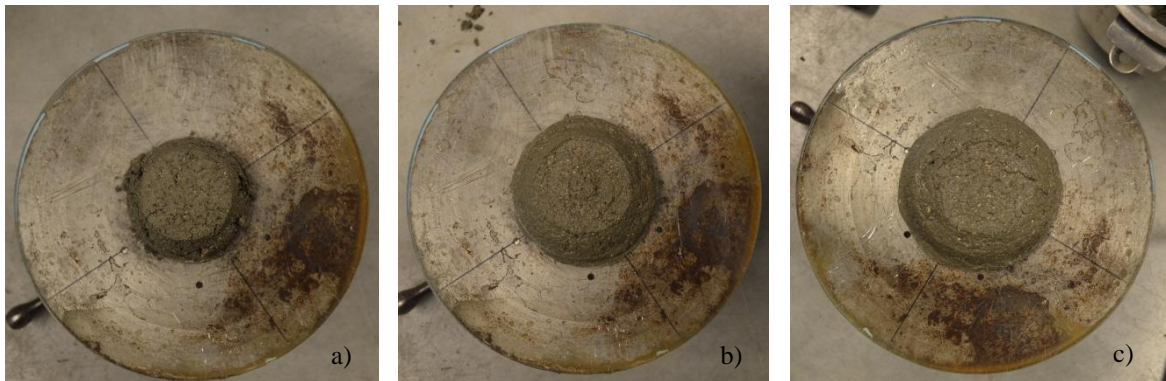


Figure 10: a) LWMB I; b) LWMB III and c) LWMB II

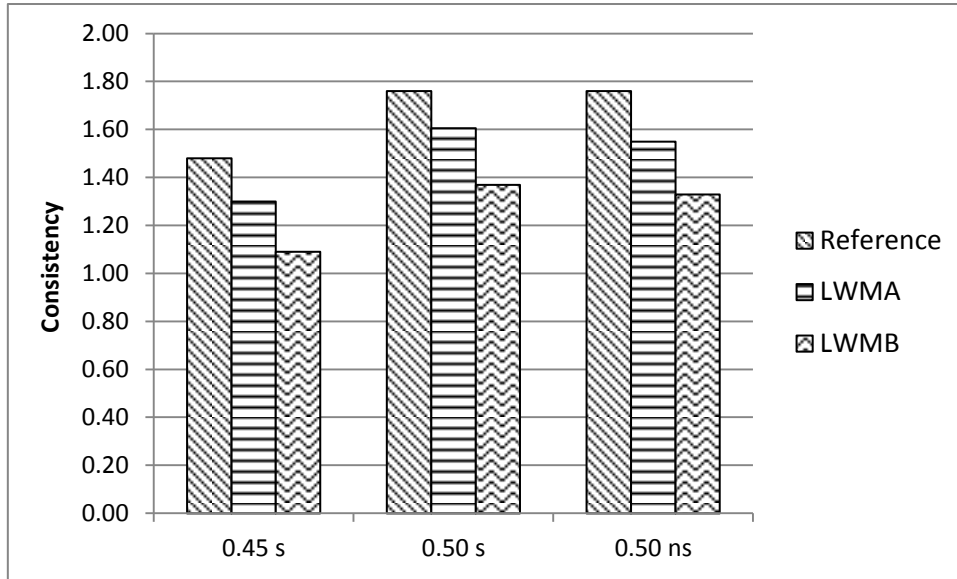


Figure 11: Fresh mortar consistency variation vs. w/c ratios (s = saturated and ns = non saturated)

3.3. Density of hardened mortar

Dry density values, ρ_d , of hardened mortar are reported in Table 4. Natural aggregates replacement leads to a sharp density decrease, in particular for mortars with the higher w/c ratio. It is generally known that lower w/c ratios correspond to denser cementitious pastes achieving a heavier mortar. Considering the w/c ratio of 0.5, when LWAs are not saturated (i.e., LWMA III and LWMB III), density decrease is lower due to the porous structure of aggregates which absorb water reducing the free water respect the mixtures in which aggregates are saturated. On the contrary, when LWAs are saturated, part of the water contained into pores is given back to the mixture increasing porosity and weakening the interfacial transition zone (ITZ). These assumptions are confirmed by the lower compressive strength and higher porosity (Table 4). In all the investigated mortar samples, at increasing sand replacement a linearly decrease of dry density was observed and mixtures with non saturated aggregates have an effective w/c of 0.46 (Figure 12). As results of the lower effective w/c ratio and higher density, also mechanical properties changes (§3.4).

Table 4: Mortars physical and mechanical properties (ρ_d = dry density; R_f = flexural strength and R_c = compressive strength)

Mortar	ρ_d (g/cm ³)	Porosity (%)	R_f (MPa)	R_c (MPa)
Reference I	2.212	17	6.93	58.38
Reference II	2.143	16	6.88	51.97
LWMA I	1.994	16	5.33	37.69
LWMA II	1.923	18	5.04	32.13
LWMA III	1.981	16	5.09	35.56
LWMB I	1.809	17	4.38	24.61
LWMB II	1.756	19	4.19	21.02
LWMB III	1.805	17	3.84	22.97

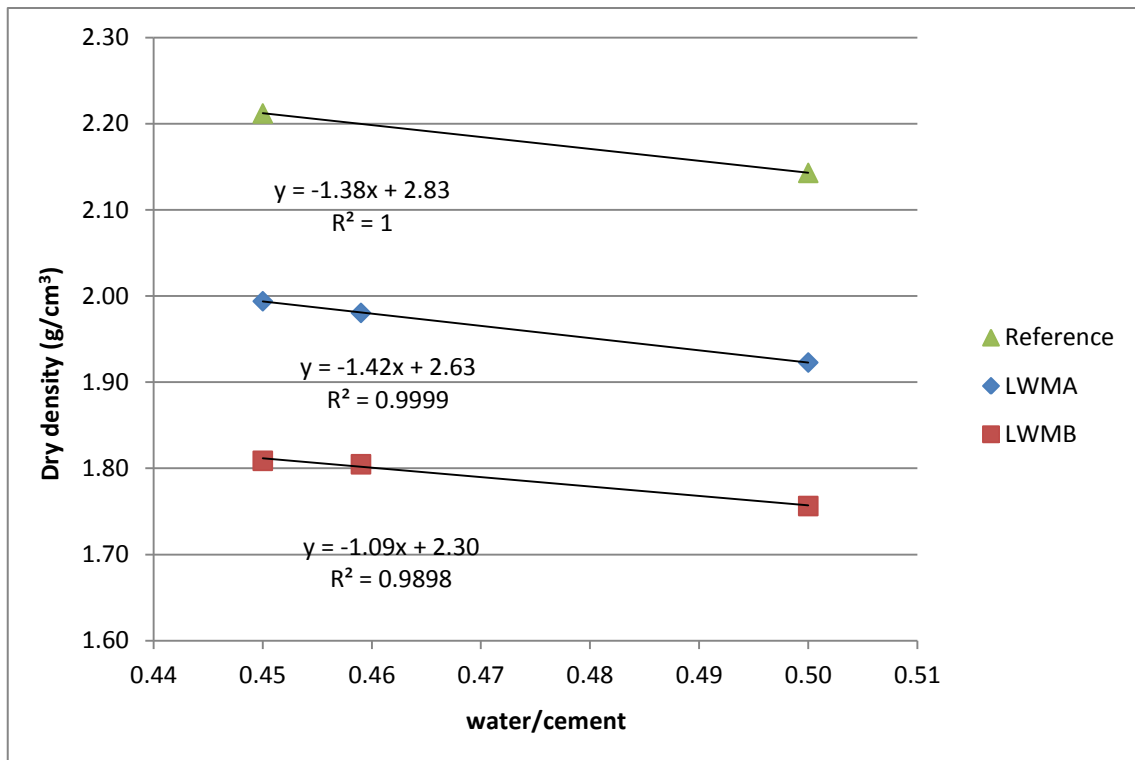


Figure 12: Mortar dry density variation at different w/c ratios and aggregates substitutions

3.4. Mechanical properties

The results of mechanical tests, i.e. flexural and compressive strength, are reported in Table 4. As expected, at increasing plastic content a decrease of mechanical properties was obtained. Figure 13 reports an example of load/deflection curves acquired during flexural test: at increasing LWAs content a less brittle behaviour was recognizable but a sharp decrease of flexural strength was attained. Aggregates saturation and w/c ratio are not influent on flexural strength while are of great importance for compressive strength. As stated before, varying w/c ratio and aggregates saturation relevant changes are observed for mortar porosity, density and ITZ between LWAs and cement paste. Compressive strength decrease is mainly due to natural aggregates substitution as results of LWAs lower mechanical properties. Moreover, also porosity increase is responsible of compressive strength decay.

Comparing flexural and compressive strength results reported in Table 4 is possible to appreciate the different behaviour exhibited by investigated mortar samples. Flexural strength decrease is less pronounced than compressive one because for flexural strength plays an important role the good adhesion between aggregates and cement paste but also artificial aggregates higher deformability. On the contrary, for compressive strength, are relevant porosity and aggregates mechanical properties. Thus, to enhance compressive strength is necessary to modify mortar porosity and/or aggregates mechanical properties.

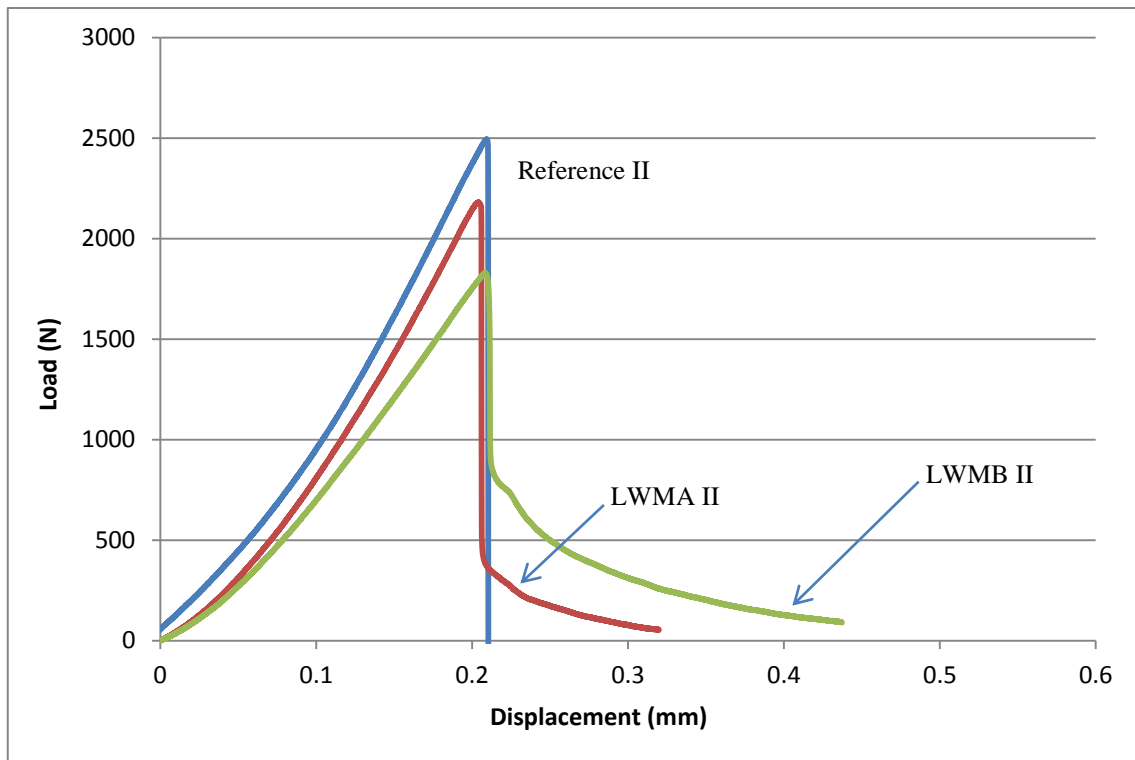


Figure 13: Example of load/displacement curve obtained from flexural test

Flexural and compressive strength are strictly correlated and a linear relationship could be found between these properties (Figure 14). Compressive strength decrease is proportional to LWAs content and density decrease (Figure 15).

The European standard EN 206-1 [40] defines lightweight concrete, i.e. produced using lightweight aggregate instead of all or part of the total aggregate, the concrete having an oven-dry density of not less than 800 kg/m^3 and not more than 2000 kg/m^3 . Moreover, structural lightweight concrete, according to ACI committee definition [41], should have a compressive strength higher than 17.25 MPa and an air dry density not exceeding 1840 kg/m^3 . The compressive strength and dry densities values of investigated LWMs are reported in Table 4. For all the mixtures, compressive strength values are higher than the standard minimum requirement and dry densities are lower than 2000 kg/m^3 .

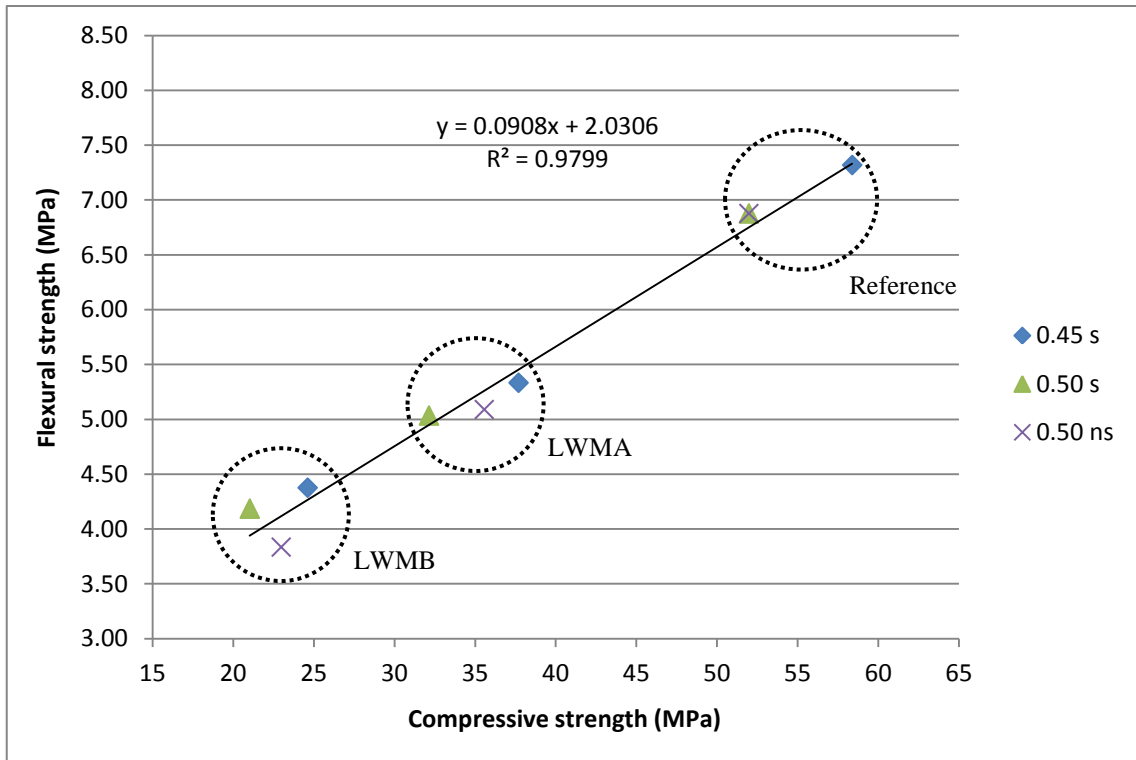


Figure 14: Correlation between flexural and compressive strength

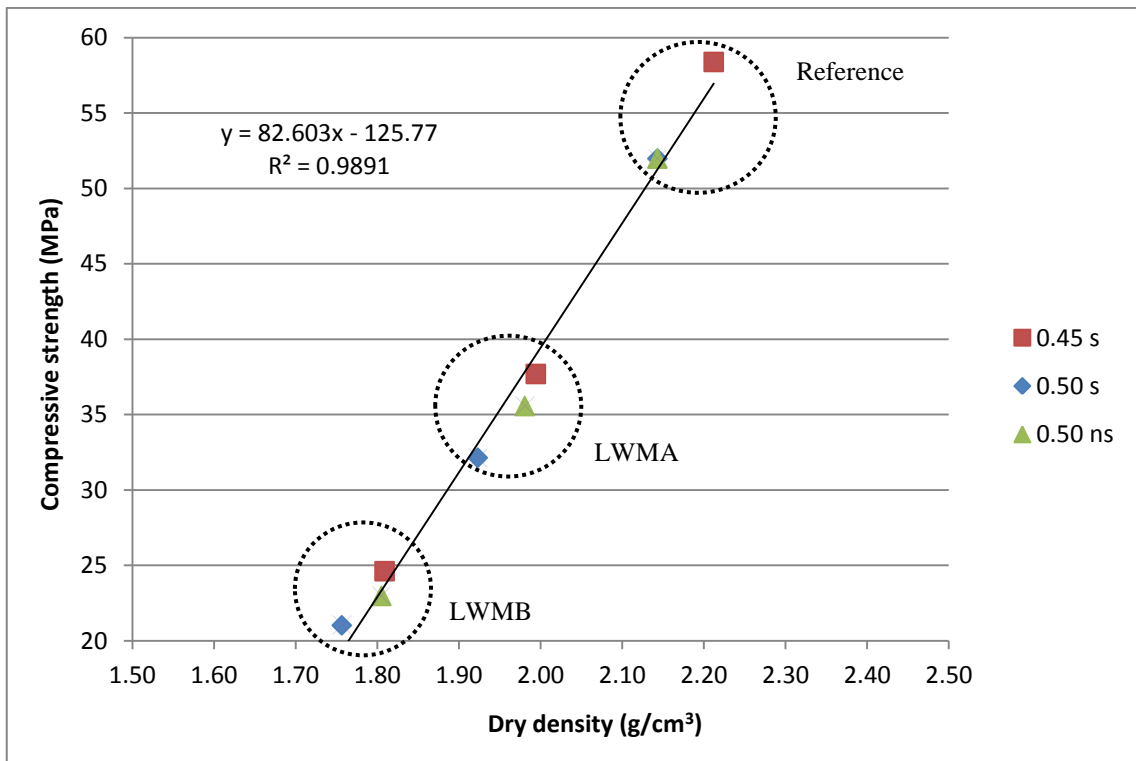


Figure 15: Compressive strength vs. dry density

3.5. LWAs/cement paste transition zone investigation

Figure 16 shows the natural and artificial aggregates distribution for LWMB III sample taken by optical and scanning electron microscope, respectively, on a polished specimen. Despite of their lower specific weight, observing LWMB cross section a good dispersion of artificial aggregates was recognizable thus segregation was avoided. Many authors [6,16,24,25] reported a weak adhesion between artificial aggregates and cement paste due to the increase of water content at the interface: a weak adhesion is generally responsible of porosity increase and decay of mechanical properties. As shown by Figure 17a, natural and LWAs present the same ITZ without any increase in distance between artificial aggregates surface and cement paste. Moreover, Figure 17b shows the increase of interfacial adhesion between LWAs and matrix, due to the interlocking positions offered by aggregates surface roughness.

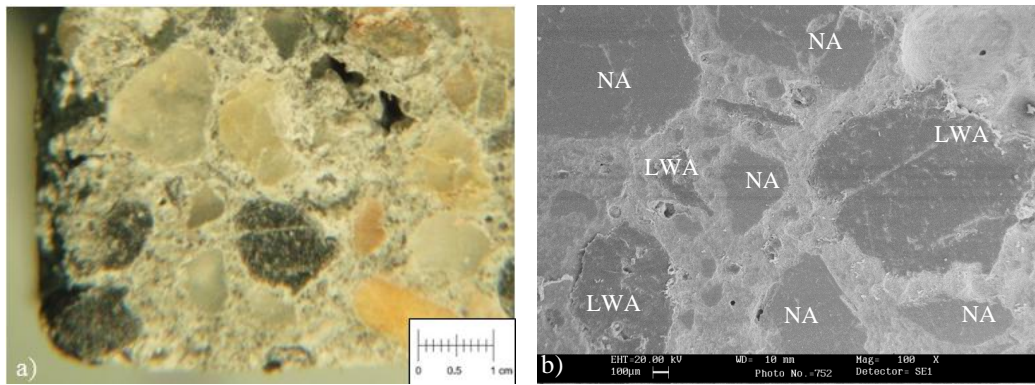


Figure 16: a) LWMB polished surface (optical microscope) and b) SEM picture of aggregates distribution in the same mortar sample

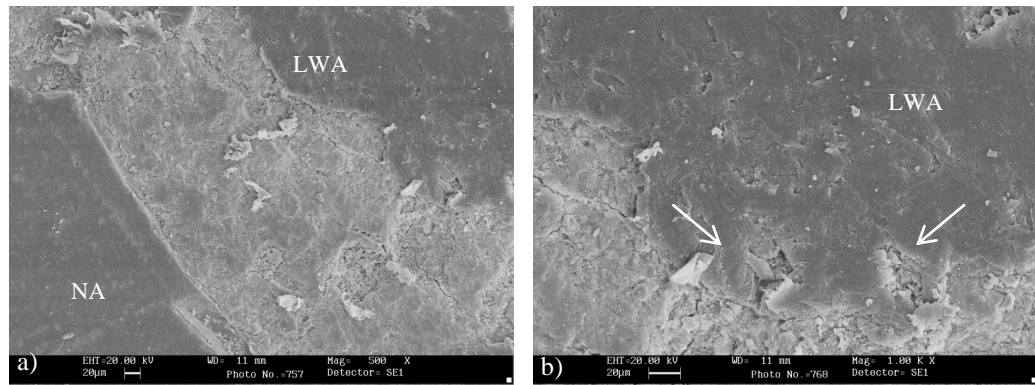


Figure 17: a) Natural and artificial aggregates ITZ and b) detail of cement paste penetrated into LWA

SEM pictures taken on fractured surfaces confirm what stated before: the ITZ between natural aggregates and cement paste (Figure 18) is the same than for artificial aggregates (Figure 19). Moreover, LWAs, offer interlocking positions while natural aggregates are smoother and only in the case of surface irregularities cement paste adhere onto them.

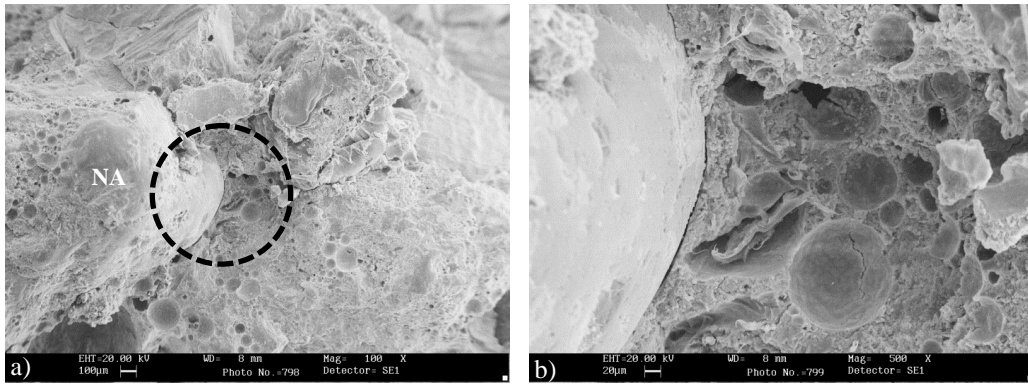


Figure 18: a) ITZ between natural aggregate (NA) and cement paste (fractured surface) and b) detail

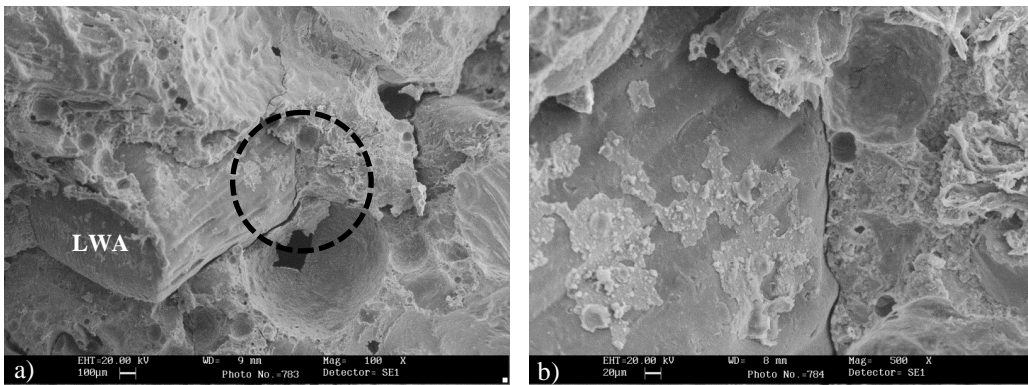


Figure 19: a) ITZ between lightweight aggregate (LWA) and cement paste (fractured surface) and b) detail

At higher magnifications (Figure 20) details of the hydration products grown into aggregates pores are shown.

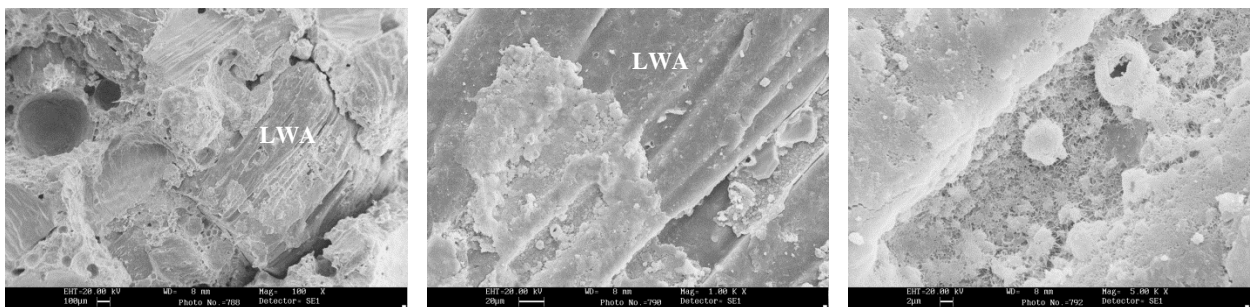


Figure 20: Detail of the hydration products grown into LWAs surface pores

3.6. Thermal analysis

TGA of LWAs (§ 3.1) revealed the temperature at which degradation starts and the range in which a weight loss of 90% was achieved: 460-520 °C. Considering this temperature range was possible to assess polymer content and distribution inside LWMs by TGA analysis [24]. TGAs were carried out on mortar samples pulverized and sieved (mesh opening of 0.50 mm) studying thermal degradation from 25 °C to 900 °C. As reported in Figure 21 weight loss percent, in the range 460-520 °C, is proportional to polymer content, considering LWAs passing at 0.50 mm (22 %, as reported in Table 2). This result confirm the good dispersion of LWAs into LWMs.

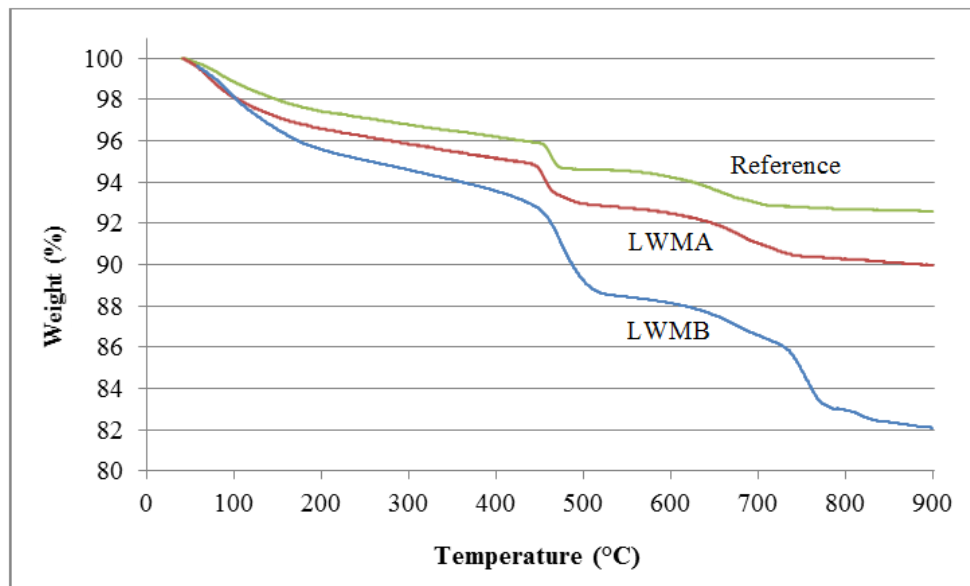


Figure 21: Thermogravimetric analysis on mortar samples

4. Conclusions

In this study, foamed plastic wastes were used as aggregate to obtain a lighter and sustainable concrete. Aggregates were manufactured by a foam extrusion process, in order to have artificial aggregates with a rough surface. In particular, lightweight aggregates (LWA) present a cylindrical shape, due to manufacturing process, and an irregular surface texture. On the contrary, natural aggregates are smooth and well rounded. The different shape and surface texture influence mortar workability: the two LWAs content (10 and 25 %) analysed lead to a workability reduction of 11 and 24%, respectively. The presence of saturated aggregates brings to a slight increase of mortar consistency (+3%) compared to mortar containing non saturated aggregates. The lower consistency was achieved for the mixture with the higher sand substitution and low w/c ratio. Increasing LWAs content, a sharp decrease of density was achieved, proportional to LWAs volume fraction. The presence of free water, when aggregates are saturated, produces an increase of porosity and consequently a decrease of compressive strength respect to mixtures containing unsaturated aggregates. At increasing LWAs content a decrease of mechanical properties was achieved but a less brittle behaviour was recognizable. However, for all the investigated lightweight mixtures, compressive strength values are higher than the minimum compressive strength required for structural concrete (17.25 MPa). LWAs saturation is not influent on flexural strength while a small influence has the use of a lower w/c ratio. SEM images reveal a good dispersion of LWAs, although their low density (65% lower respect natural sand quartz) and also a good adhesion due to the presence of interlocking positions. Moreover, no increase in ITZ was recognizable as the distance between artificial aggregates and cement paste is the same that natural aggregates and bulk matrix.

Acknowledgments

The authors are grateful to CONAI (Italian National Packaging Consortium) and COREPLA (Italian Consortium for the Collection and Recycling of Plastic packages) for supporting the research.

References

- 1 PlasticEurope, Plastics – the Facts 2015. (www.plasticseurope.org, consulted January 2016).
- 2 Bertin S, Robin JJ. Study and characterization of virgin and recycled LDPE/PP blends. *Eur Polym J.* 2002;38:2255-64.
- 3 Shanks RA, Li J, Yu L. Polypropylene–polyethylene blend morphology controlled by time–temperature–miscibility. *Polymer* 2000;41:2133-9.
- 4 He H, Stroeven P, Pirard E, Courard L. On the shape simulation of aggregate and cement particles in a DEM system. *Adv Mater Sci Eng* 2015;2015, <http://dx.doi.org/10.1155/2015/692768>. Article ID 692768, 7 pages.
- 5 Dintcheva NT, La Mantia F, Trotta F, Luda M, Camino G, Paci M, et al. Effects of filler type and processing apparatus on the properties of the recycled “light fraction” from municipal post-consumer plastics. *Polym Adv Technol* 2001;12:552-60.
- 6 Hannawi K, Kamali-Bernard S, Prince W. Physical and mechanical properties of mortars containing PET and PC waste aggregates. *Waste Manage* 2010;30:2312-20.
- 7 Reis J, Chianelli-Junior R, Cardoso J, Marinho F. Effect of recycled PET in the fracture mechanics of polymer mortar. *Constr Build Mater* 2011;25:2799-804.
- 8 Corinaldesi V, Donnini J, Nardinocchi A. Lightweight plasters containing plastic waste for sustainable and energy-efficient building. *Constr Build Mater* 2015;94:337-45.
- 9 Corinaldesi V, Mazzoli A, Moriconi G. Mechanical behaviour and thermal conductivity of mortars containing waste rubber particles. *Mater Des* 2011;32:1646-50.
- 10 Akçaözöğlü S, Akçaözöğlü K, Atiş CD. Thermal conductivity, compressive strength and ultrasonic wave velocity of cementitious composite containing waste PET lightweight aggregate (WPLA). *Compos Part B-Eng.* 2013;45:721-6.
- 11 Yesilata B, Isiker Y, Turgut P. Thermal insulation enhancement in concretes by adding waste PET and rubber pieces. *Constr Build Mater* 2009;23:1878-82.
- 12 Iucolano F, Liguori B, Caputo D, Colangelo F, Cioffi R. Recycled plastic aggregate in mortars composition: Effect on physical and mechanical properties. *Mater Des* 2013;52:916-22.
- 13 da Silva AM, de Brito J, Veiga R. Incorporation of fine plastic aggregates in rendering mortars. *Constr Build Mater* 2014;71:226-36.
- 14 Albano C, Camacho N, Hernández M, Matheus A, Gutiérrez A. Influence of content and particle size of waste pet bottles on concrete behavior at different w/c ratios. *Waste Manage* 2009;29:2707-16.
- 15 Ferreira L, de Brito J, Saikia N. Influence of curing conditions on the mechanical performance of concrete containing recycled plastic aggregate. *Constr Build Mater* 2012;36:196-204.
- 16 Saikia N, de Brito J. Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate. *Constr Build Mater* 2014;52:236-44.
- 17 Ismail ZZ, Al-Hashmi EA. Use of waste plastic in concrete mixture as aggregate replacement. *Waste Manage* 2008;28:2041-7.
- 18 Correia JR, Lima JS, de Brito J. Post-fire mechanical performance of concrete made with selected plastic waste aggregates. *Cement Concr Compos* 2014;53:187-99.

- 19 Sokołowska JJ, Piotrowski T, Garbacz A, Kowalik P. Effect of introducing recycled polymer aggregate on the properties of C-PC composites. *Adv Mat Res* 2013;520-6.
- 20 Lo Monte F, Bamonte P, Gambarova PG. Physical and mechanical properties of heat-damaged structural concrete containing expanded polystyrene synthesized particles. *Fire Mater.* 2015;39:58-71.
- 21 Silva RV, de Brito J, Saikia N. Influence of curing conditions on the durability-related performance of concrete made with selected plastic waste aggregates. *Cement Concr Compos* 2013;35:23-31.
- 22 Kan A, Demirboga R. A novel material for lightweight concrete production. *Cement Concr Compos* 2009;31:489-95.
- 23 Marzouk OY, Dheilly RM, Queneudec M. Valorization of post-consumer waste plastic in cementitious concrete composites. *Waste Manage* 2007;27:310-8.
- 24 Gadea J, Rodriguez A, Campos PL, Garabito J, Calderon V. Lightweight mortar made with recycled polyurethane foam. *Cement Concr Compos* 2010;32:672-7.
- 25 Choi Y-W, Moon D-J, Chung J-S, Cho S-K. Effects of waste PET bottles aggregate on the properties of concrete. *Cement Concr Res* 2005;35:776-81.
- 26 Choi YW, Moon DJ, Kim YJ, Lachemi M. Characteristics of mortar and concrete containing fine aggregate manufactured from recycled waste polyethylene terephthalate bottles. *Constr Build Mater* 2009;23:2829-35.
- 27 Mounanga P, Gbongbon W, Poullain P, Turcry P. Proportioning and characterization of lightweight concrete mixtures made with rigid polyurethane foam wastes. *Cement Concr Compos* 2008;30:806-14.
- 28 Madandoust R, Ranjbar MM, Mousavi SY. An investigation on the fresh properties of self-compacted lightweight concrete containing expanded polystyrene. *Constr Build Mater* 2011;25:3721-31.
- 29 Lo TY, Cui HZ. Effect of porous lightweight aggregate on strength of concrete. *Materials Letters.* 2004;58(6):916-9.
- 30 Bentz DP. Influence of internal curing using lightweight aggregates on interfacial transition zone percolation and chloride ingress in mortars. *Cement Concr Compos* 2009;31:285-9.
- 31 Ramesan A, Babu SS, Lal A. Performance of light-weight concrete with plastic aggregate. *Int J Eng Res Appl* 2015;5:105-110.
- 32 Wang R, Meyer C. Performance of cement mortar made with recycled high impact polystyrene. *Cement Concr Compos* 2012;34:975-81.
- 33 EN 196-1, Methods of testing cement: Determination of strength. September 1996.
- 34 Lee S-T, Park CB. *Foam extrusion: principles and practice*: CRC press; 2014.
- 35 EN 933-1, Tests for geometrical properties of aggregates: Determination of particle size distribution, sieving method. April 1999.
- 36 EN 1097-6, Tests for mechanical and physical properties of aggregates. Determination of particle density and water absorption. August 2013.
- 37 EN 1097-3, Tests for mechanical and physical properties of aggregates. Determination of loose bulk density and voids. October 1999.
- 38 EN 1015-3, Methods of test for mortar for masonry: Determination of consistence of fresh mortar (by flow table). June 2000.
- 39 EN 12397-7, Testing hardened concrete: Density of hardened concrete June 2002.
- 40 EN 206-1, Concrete: Specification, performance, production and conformity. March 2006.
- 41 ACI Committee 213. *Guide for Structural Lightweight Aggregate Concrete (ACI 213R-87 Reapproved 1999)*. American Concrete Institute, Farmington Hills, 1987.

Figure Captions

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Figure 22: a) Pellets and foaming agent in the hopper; b) single screw extruder die and c) winder collecting foamed strands

Figure 23: DSC thermograms of LWAs

Figure 24: SEM micrographs showing aggregates foamed structure and PP droplets into PE matrix

Figure 25: LWAs weight loss vs. temperature (TGA)

Figure 26: Natural quartz sand SEM pictures

Figure 27: Lightweight aggregates (LWAs) SEM pictures

Figure 28: Aggregates particle size distribution (LWAs = LightWeight Aggregates)

Figure 29: a) Reference I and b) Reference II

Figure 30: a) LWMA I; b) LWMA III and c) LWMA II

Figure 31: a) LWMB I; b) LWMB III and c) LWMB II

Figure 32: Fresh mortar consistency variation vs. w/c ratios (s = saturated and ns = non saturated)

Figure 33: Mortar dry density variation at different w/c ratios and aggregates substitutions

Figure 34: Example of load/displacement curve obtained from flexural test

Figure 35: Correlation between flexural and compressive strength

Figure 36: Compressive strength vs. dry density

Figure 37: a) LWMB polished surface (optical microscope) and b) SEM picture of aggregates distribution in the same mortar sample

Figure 38: a) Natural and artificial aggregates ITZ and b) detail of cement paste penetrated into LWA

Figure 39: a) ITZ between natural aggregate (NA) and cement paste (fractured surface) and b) detail

Figure 40: a) ITZ between lightweight aggregate (LWA) and cement paste (fractured surface) and b) detail

Figure 41: Detail of the hydration products grown into LWAs surface pores

Figure 42: Thermogravimetric analysis on mortar samples