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Characterization properties and fire behaviour of cement blocks with recycled polyurethane roof wastes

Lourdes Alameda Cuenca-Romero, Raquel Arroyo, Álvaro Alonso, Sara Gutiérrez-González, Verónica Calderón *

Departamento de Construcciones Arquitectónicas e I.C.T Escuela Politécnica Superior, Universidad de Burgos, C/Villadiego S/n, 09001, Spain

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ABSTRACT

In accordance with the European politics of reducing the amount of polymers and plastics wastes, the inclusion of compounds such as roof wastes as recycled and reusable materials to replace variable amounts of aggregates is interesting in the production of new construction materials due to their physical and chemical behaviour.

Prefabricated mortar blocks have made with Portland cement, sand, water and grinded roof polyurethane based wastes from the automobile industry that replace in different amounts part or all of the aggregates. To try to avoid the mechanical resistance limitation due to the use of roof wastes, the chemical properties of the binders have been modified with non-ionic surfactants that improve the effect on the hydration of the clinker. This variation produces an important change in the mechanical resistance to achieve recycled structural materials with a density between 18.7% and 62.7% lower compared to conventional lightweight mortars. In addition, these surfactants improve other properties including workability, compaction of the matrix, prevent the disintegration of the particles and help to improve the mechanical properties and durability against fire to reinforce the materials.

These eco-mortars have a good behaviour against temperature of the final envelope, measured in terms of non-combustibility test. With these results, the use of roof wastes can be consider as a sustainable alternative to the materials currently used and then with them we can be able to contribute to a more ecological business model in the building sector.

1. Introduction

According to the latest estimates contained in the Report prepared by Plastic Europe, the Facts 2020 [1], the demand for polymers and plastics in Europe reached 57.9 MTn in 2019, with 16% of world production. Of this large quantity of products of polymeric origin, approximately around 8% (exactly 7.9%) is polyurethane in the form of flexible, semi flexible or rigid foam, with the automotive manufacturing sector being one of the largest consumers of this material.

The polyurethane sector involves only in Europe 18.000 people and moves a turnover of about 4000 million euros. Worldwide, it involves 240.000 companies, with one million jobs and generates an economy worth of about 207 billion euros. Trials are underway to introduce recovery systems for polyurethane waste in order to divert it from landfills and treat it according to the other options at the end of its life. Main technologies for recycling polyurethane and its derivatives are energy recovery, mechanical recycling and chemical

* Corresponding author.
E-mail address: vcalderon@ubu.es (V. Calderón).

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recycling [2]. The lack of a collection, sorting and processing infrastructure has somewhat blocked the recycling of this waste.

Factors as the type of polymer, the environment and others has a large impact on degradation times of these wastes and there is not a media that can be estimated in a simple way. For this reason, even though always promoting a circular economy, there are governments that enquire prudence regarding the massive recovery of polymer waste taking into account the usage and the people involves [3]. In this way, some studies reflect about the use of antioxidants and stabilizers, which are used to prolong the working life of plastics, slow environmental degradation of plastics waste even further [4].

In addition, the construction sector plays an important role in the economy. It generates almost 10% of GDP (Gross Domestic Product) and provides 20 million jobs in Europe, mainly in micro and small companies. Moreover, the materials used in building and civil works represent 42% of our final energy consumption, approximately 35% of our greenhouse gas emissions and more than 50% of all the materials removed.

The limitless conformations and formulations of polyurethanes enabled their use in a wide variety of applications, although these polymers are suspected to release volatile organic hazardous substances [5]. Some studies show that the main pyrolysates originated from the decomposition of the isocyanate moiety part of the rigid polyurethane foam, demonstrate the presence of certain chemical components as methylenedianiline, diaminodiphenylmethane, aniline and phenyl isocyanate, compounds that include a benzene ring structure somewhere within their structure, either possessing a phenyl group or being a substituted aromatic compound itself. The smoke from a bio-based rigid polyurethane foam, where the foam contains no additives like flame retardants or smoke suppressants, could pose a potential threat to human health and the environment [6]. Consequently, when revising the polymer foam thermal degradation behavior or assessing the properties related to thermal stability, the use of appropriate personal safety equipment is strongly recommended and, if possible, an exhaust ventilation.

For all the above, the standards and rules that apply in construction sector for the installation of in-situ spray polyurethane foam insulation for the building enclosure and the must always be strictly adhered to [7,8].

To find alternatives to systematic accumulation or incineration of polyurethanes and aligned with previous similar investigations [9–11], this research falls on the field of the use of polyurethane waste from complete roofs generated in the automobile industry, valued as raw material in construction sector [12].

Preceding authors have investigated the effects of utilising poly-ethylene terephthalate as a partial substitute for sand in concrete with promising results about thermal behaviour and mechanical properties [13–16]. Other studies analyses the addition of ceramic wastes and fibers improving volume stability caused by shrinkage and reinforcing lime and cement mortars [17]. Even more, cement-based mortars containing slag aggregates and carbon fibers shown lower resistivity, better strain sensing capacity and lower dispersion than equivalent mortars containing limestone aggregates. [18]

The solution proposed in this research consists of manufacturing mortars blocks substituting large amounts of aggregate for crushed polyurethane roofs generated in the automobile industry (50%–100% aggregate replaced). The amount of waste used depends on the ending properties that must to be enough to accomplish with the current legislation.

Polyurethane is used in building and construction to make high-performance strong but lightweight materials. Moreover, is used for insulation (projected polyurethane) and does not degrade to compounds with active toxicity during the service life. In addition, polyurethane is a material with very low levels of emissions. Prefabricated materials are normally used for partitions or divisions, being covered with different layers of plasters, paints …. The contact with the people is not direct and the waste is embedded within a very stable cement matrix.

Therefore, this work approached a double sustainable direction: the reuse of polymer panels and the reduction of a large percentage the amount of aggregate as raw material, and the lower requirement of natural aggregates. Natural aggregates used for the construction involve around 70% of the total mineral raw materials used in the world with the consequent associated consumption of water and transport.

This research have a commitment with a circular economy network and with reuse of a waste found in large quantities, and the development of new sustainable innovation solutions for cement mortars in construction.

2. Materials and methods

The ecomortar blocks obtained are composed of the raw materials detailed below:

- Commercial Portland cement
- Sand aggregates
- Shredded waste with polyurethane matrix
- Surfactants additives
- Water

2.1. Characterization of raw materials

2.1.1. Cement

The cement is the CEM I 52.5 R. type according to the EN 197–1 [19], Portland Cement with a mass composition of 95–100% of clinker and 0–5% of minority components. These values refer to the cement core excluding calcium sulphate and any additives. The mechanical requirements are right with a compressive strength at 2 days more than 30 MPa and at 28 days more than 52.5 MPa. The beginning of setting is more than 45 min and the expansion is less than 10 mm, which meets the physical requirements according to the regulations. The chemical requirements are also adequate, with loss on ignition less than 5%, insoluble residue less than 5%, sulphate

content less than 4% and chloride percentage less than 0.10%, all these values with respect to the dry weight of the cement.

2.1.2. Sand aggregates

The sand aggregates used in the preparation of mortars follow the standard EN 13139 [20], with the use of particles smaller than 4 mm and with a sand with rounded and not very angular shapes. The content in fines for this 0/4 aggregate has a maximum percentage in passes through the sieve of 0.063 mm of 5%. The initial moisture of the sand is 23%. The bulk density after drying in an oven up to steady weight is 1670 kg/m^3 and the granulometric modulus is 3.78. The sand used not has suffered any type of treatment apart from drying in an oven before consumption. The drying process for the sand is set at 105 ± 5 °C remaining the sample in the oven overnight an elapsed time when the weight does no show significant change - for at least 12–16 h.

2.1.3. Shredded waste with polyurethane matrix

The polyurethane waste comes from recycled vehicle roofs, with a bulk density of 92.5 kg/m^3 and a density of 1681 kg/m^3. The elemental analysis determines an amount of carbon (3.1%), hydrogen (47.3%), and nitrogen (4.2%).

The samples have been analyzed by optical microscopy using a MORPHOLOGI G3 MALVERN microscope. A sample of 19 mm^3 is placed in a dispersion chamber, and automatically dispersed with compressed air on the microscope plate. Subsequent, through the use of a macro created to measure for the analysis covering the range of sizes that goes from 0.5 μm to 1000 μm, three replicates of the sample are automatically analyzed.

The waste diameter measure is complicated due to the agglomeration and volatility of the particles. However, the three replications of the measurement show a reliable statistic of the particle size distribution. According to the results, the most of the particles are below 2–3 μm (Fig. 1).

2.1.4. Surfactants

To try to avoid the mechanical resistance limitation due to the use of roof wastes, the chemical properties of the binders have been modified with non-ionic surfactants that improve the effect on the hydration of the clinker.

Two different types of non-ionic surfactants (C13-oxo alcohol ethoxylate type) provided by BASF group were used in a liquid state, one of them very hydrophilic surfactant and the other slightly hydrophilic to study their influence. Both of them produce an improvement in the hydration of the cement (they reduce the amount of water needed in dosages) and improve their properties.

They are characterised by the hydrophilic–lipophilic balance (HLB), as described in Table 1. The HLB value is calculated using Griffin's method: HLB = 20 Mh/M, where Mh is the molecular mass of the hydrophilic part of the molecule and M the molecular mass of the whole molecule [21]. The percentage of additive used is 1% in relation to the weight of cement.

2.1.5. Water

We added water in an amount that guarantee an appropriate consistency, good workability and a plastic state in the mixtures, in accordance with the EN 1015–3 [22].

2.2. Dosages and fabrication of ecomortar blocks

The proportions of cement, crushed polymer waste from recycled vehicle roofs, surfactant, sand and water are detailed in Table 2. The cement/aggregate dosage is 1/6 by weight, considering the aggregate as the addition of sand and the polymer waste. To obtain better results, we mixed on the one hand, the cement, the water and the additive, to maximize the effect of the surfactant on the cement. In principle, the properties of the polymer are not affected for this procedure. At that point, we added the mixture of waste and aggregate, and we continue with the fabrication of the mixture with the conventional method. The samples have mixed according time stablished into EN 1015–2 [23] for the determination of bulk sampling of mortars and preparation of test mortars.

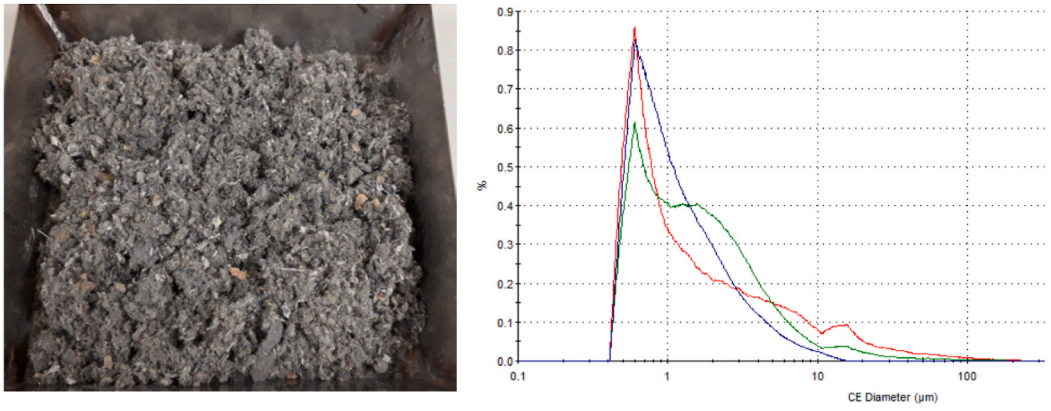

Fig. 1. Shredded waste with polyurethane matrix and relative frequency as a function of particle diameter (μm) for three tests carried out. The graphic is obtained with the waste automatically dispersed with compressed air on the microscope plate. Subsequent, through the use of a macro created to measure for the analysis covering the range of sizes that goes from 0.5 μm to 1000 μm.

Table 1
Surfactants additives characteristics.

Surfactant	Hydrophobic units	Hydrophilic units	HLB	Comments
S1	C13 = 200g	3 EO = 132g	6.1	Very high hydrophilic grade
S2	C13 = 200g	10 EO = 440g	13.8	Poor hydrophilic grade

Table 2
Dosages for large ecoblocks.

Dosages	Substitution of sand by waste PU (%)	Water/cement ratio	Cement (kg)	Sand (kg)	Polymer waste (kg)	Water (kg)	Surfactant (1%) (g)
Reference	0	0.64	5	30	0	3.2	0
50PUS1	50	0.84	6.67	20	1.12	5.63	66 (S1)
100PUS1	100	1.02	5	–	1.62	5.10	50 (S1)
50PUS2	50	0.72	3.75	12.3	0.63	2.73	38 (S2)
100PUS2	100	0.96	3.75	–	1.25	3.60	38 (S2)

In order to find the amount of water corresponding with an adequate workability of all mixtures, the consistency by means of water/binder ratio is determined by trial and error with the shaking table. The samples are tested within the specified workability period for these mortars.

There are not standard with the dimensions stablished to obtain mortar blocks. Consequently, as they are not standardized, we have used moulds with common and commercial dimensions put on site. Taking into account other similar products on the market, and considering a suitable dimensions, the ecomortar blocks have dimensions of (50 x 25 x 10) cm^3. In the case of tongue and groove joints, each piece has a slot (the groove) cut all along one edge with 1 cm deep and 2.5 cm wide, and a thin, deep ridge (the tongue) on the opposite edge with 1 cm deep and 2 cm wide. Fig. 2.

Mortars and concretes are usually susceptible to cracking, mainly due to the brittleness of the cement paste when loses mixing water through evaporation [24]. This fact does not occur in these recycled ecoblocks since the water requirement, initially greater due to the presence of hydrophobic polyurethane, remains constant and low due to the surfactants.

2.3. Methods of characterization of ecomortar blocks

The properties of the mixtures have been determined both in the fresh and hardened state with an experimental development specified in the following subsections.

2.3.1. Consistency

In order to find the amount of water corresponding with an adequate workability of all mixtures, the water/binder ratio is determined by trial and error with the shaking table, in accordance with the standard EN 1015–3 [22]. The final suitable consistency is

Fig. 2. Mortar blocks fabrication process. The eco-mortar blocks have dimensions of (50 x 25 x 10) cm^3. In the case of tongue and groove joints, each piece has a slot (the groove) cut all along one edge with 1 cm deep and 2.5 cm wide, and a thin, deep ridge (the tongue) on the opposite edge with 1 cm deep and 2 cm wide.

achieved when a diameter of (175 ± 10) mm is obtained. This procedure suppose much more effort than setting the same water/-cement ratio for all samples, but ensures and contribute to maximize the mechanical, physical, and durability properties in the hardened state.

2.3.2. Bulk density

Bulk density was measured in hardened state, according EN 1015–10 [25], using 40 mm × 40 mm x 160 mm test specimens, following a curing time of 28 days at a temperature of 20 °C, and a relative humidity of 98%.

2.3.3. Hardness shore C

Shore C hardness determines the surface hardness of mortar establishing the footprint reached by a force over sample surface, measured directly in Shore C units, from 0 (softest) to 100 (hardest).

2.3.4. Mechanical properties

Flexural strength and compressive strength were measured after 28 days of curing at 20 °C and 98% of relative humidity, as per EN 1015–11 [26] using an hydraulic Spanish press type Suzpecar MEM-101/SDC. For each dosage, the assessment include five different samples tested under flexion and ten samples under compression. The samples measured have dimensions of (40x40x160) mm^3 with a bottom support rollers separated at intervals of 100 mm. The resulting fragments in this test broke under compression using a load surface of (40x40) mm^2.

2.3.5. Suction and total absorption

The measurement of capillarity coefficient is the amount of water absorbed as a function of the surface in contact with the water and the exposure time. The specimens employed have a prismatic shape with dimensions (40 x 40 x 160) mm.

The water absorption coefficient by capillarity is equal to the slope of the line that joins the representative points of the means taken at 10 min and at 90 min, by means of the following expression: C = 0.1 (M2 - M1) $kg/m^2 \cdot min0.5$, according EN 1015–18 [27].

The total absorption is determined by complete immersion in water of these specimens to constant weight.

2.3.6. Micro computarized tomography (μCT)

This technique was used for a quantitative determination of sample macroporosity, this means pore sizes of over 200 μm. The equipment consisted of an X-ray system with a 225 kV/30 mA Yxlon tube and a steel–lead–steel metal cabin, such that operating with a maximum radiation of 225 kV/30 mA inside the cabin, the maximum doses of radiation at a distance of 100 mm on the external surface did not excess 2.5 μSv/h.

3D digital visualization model with macropores (>13.85 μm) was constructed by using μCT scanning combined with Avizo Software image processing, to calculate the porosity and the distribution of components into matrix samples [28].

2.3.7. Scanning electron microscopy (SEM)

The measurement equipment used is a HITACHI S-4800 FSEM, with a 20 KV acceleration voltage and 20 μA of current intensity. The working distance was adjustable and the EDX Bruker XFlash-5030 detector requires a silicon window. The samples are coating with gold to give it conductive properties.

2.3.8. Confocal laser scanning microscopy (CLSM)

The CLSM microscope used is a model Olympus LEXT OLS3000 with a light source as photo monochromatic laser beam characterized by 408 nm wavelengths. The light emitted from the sample passes through a very small opening, called a pinhole (diaphragm-pinhole), and located before the photodetectors. This allows the superposition of planes to reconstruct the surface of the samples, obtaining 2D and 3D images with high resolution allowing the study, among others, of roughness, profiles and surface alterations.

2.3.9. Non-combustibility test

This test is suitable to evaluate the behavior of construction materials at high temperatures. Test apparatus corresponds to standard EN ISO 1182 [29]. The samples are placed into a vertical oven used is composed of a cylindrical space 75 mm in diameter and 150 mm in height. The shape of the sample introduced into the oven was cylindrical, with a diameter of 40 mm and a height of 50 mm the temperature of the oven rises from room temperature to 750 °C in 2 h. Subsequently, the oven keep the temperature at 750 °C for other 60 min. The surface and center temperatures of the sample are recorded every 10 s. The flaming time and the mass loss are also measured. Test results of the building structure are classified according to standard EN 13501–1 [30].

Table 3
Density, shore hardness and mechanical properties obtained at 28 days.

Samples	Density (kg/m^3)	Shore hardness (Shore C)	Flexural strength* (MPa)	Compressive ç strength* (MPa)
Reference without waste	2050	94.3	5.3	11.9
50PUS1	1667	81.3	5.4	13.3
100PUS1	873	47.7	2.5	4.1
50PUS2	1250	84.5	3.4	5.6
100PUS2	763	59.1	1.7	3.7

*Flexural and compressive strength obtained from samples with dimensions (40 × 40 × 160) mm^3.

3. Results and discussion

3.1. Physical and mechanical properties

The properties in hardened state at 28 days are given in Table 3. As can be seen and as expected, lightweight ecoblocks are obtained, since the density decreases exponentially with the incorporation of waste, involving reductions of up to 57.4% for the sample 100PUS1 and 68.8% for the 100PUS2, respectively.

These eco blocks are considered structural materials since the compressive strengths are enough with respect to reference materials with similar uses (as thermoclays), reaching values greater than 5.0 MPa, but with the added advantage of having much lower densities. Furthermore, according to the UNE 998-2 standard, compressive strength for masonry mortars when structural properties are not required is fixed between 1 MPa and 7.5 MPa within the satisfactory values. In this sense and taking into account the extremely high percentages of waste polymer include in these eco-blocks - 50% and 100% of sand replacement – the compressive strength results obtained with values between 13.3 and 3.7 MPa is considered enough to put on site.

The effect of polymer waste and the surfactants on the development of mechanical strength in the samples at 28 days is shown in Fig. 3.

The flexural and compressive strength of 50PUS1 is significantly higher than that of the other samples, with the ranking of mechanical strength, from highest to lowest, as follows: 50PUS2 > 100PUS1 > 100PUS2. The presence of surfactant S1 improved compressive and flexural strengths due to its hydrophilic effect established by some studies that have shown the positively influence [31,32] Furthermore, the results allow a polynomial fit of the resulting curve, with the equation $y = 0{,}6185x^2 - 1{,}7674x + 4{,}8867$ and with a correlation coefficient of $R^2 = 0.9973$. This curve allows obtaining statistics on mechanical strength as a function of the type of additive employed, by means of hydrophilicities comprised between 3EO and 10EO hydrophilic units corresponding to the surfactants used.

3.2. Porosity properties and water behaviour

Porosity is considered one of the major factors controlling the hardened properties and durability of mortars. Commonly, cement materials with higher porosity values are believed to exhibit high permeability properties and hence, lower strength resistance may be achieved. In this regard, the pore structure has influence on the behaviour of these eco blocks. Hence, the effects of polymer waste and polymer surfactant modification on the porosity, determined from CAT, are discussed through the followings and linked with the water behaviour associated to the porosity.

Table 4 show the summary of results obtained for all the samples.

The proportion of surfactant modifiers strongly affected the pore size distribution. The relationship between water absorption and total porosity of the samples existed in the lineal correlation, confirming the role of changes in microstructure observed. The results also showed that the water absorption of the ecoblocks increased exponentially with increasing values of total porosity irrespective of the type of surfactant [33]. In general terms, a high porosity is not a favorable factor, even though it is true that depending on the structure of the open pores to see if the durability can be affected or not. On the other hand, the increase in porosity also brings with it the classification of these materials as lightweight mortars, with suitable water absorption characteristics according to this classification.

The capillary absorption values highlight the difference between S1 and S2 mortars. In practice the lower porosity diameter generates a lower capillary absorption coefficient in good agreement with results expected. They show that the capillary absorption coefficient of mortars depends on the amount of total pores. In any case, the water absorption classification for all the samples according standard EN 998–2 is W0 [34].

Some earlier work showed that polymers mortars have a hydrophilic behavior [35]. This characteristic seems to be another parameter which reduces the capillary absorption. The modified wettability of the liquid-solid interface tends to reduce the capillary pressure and, thus the capillary absorption [36].

The effect of polymer waste addition on the total porosity by means of computarized axial tomography (CAT) of cement mortars are

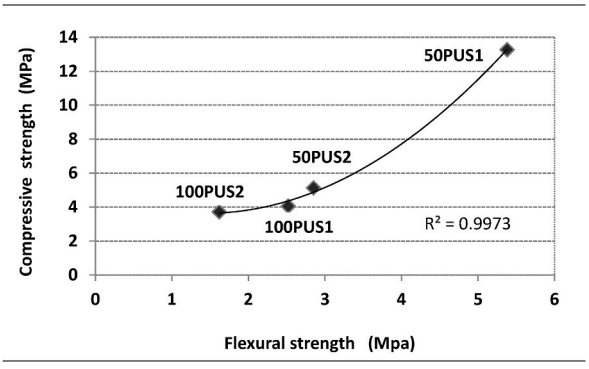

Fig. 3. Flexural strength versus compressive strength. The results allow a polynomial fit of the resulting curve, with the equation y = 0,6185x2 - 1,7674x + 4,8867 and with a correlation coefficient of R2 = 0.9973.

Table 4
Water properties and porosity of the samples.

Samples	Water absorption due to capillarity (Kg/m^2· min0,5)	Absorption (%)	Porosity calculated by CAT (%)
Reference without waste	4.15	11.5	11.9
50PUS1	4.24	12.2	12.5
100PUS1	7.15	24.2	15.8
50PUS2	9.95	48.6	35.7
100PUS2	11.35	59.5	40.1

shown in Fig. 4 Analysis shows higher porosity in mixes with surfactant S2 with less hydrophilic grade than S1. For each surfactant, the total porosity is found to be slightly bigger for polymer substitution of 100% that of the specimens with 50% of replacement, each series with closer porosity values. 50PUS1 shows the lowest porosity of all the samples and is comparable to the reference samples, with total values nearly 12% (11.9–12.5%). The explanation for the low porosity of samples with surfactant S1 is probably that the water curing enables cement hydration to take place, and subsequent air drying allows the formation of the polymer surfactant film in the aggregate-cement inter-phase [37]. In this way, a partially filling and sealing of the voids occurs and hence, resulting in lower porosity matrix and water absorption values of the polymer–cement systems [38]. As a result, the polymer emulsion with S1 has better filling properties which formed a cement matrix of a much smaller pore size compared to that of the S2 samples (see Fig. 4).

On the other side, a significant increase in porosity values is observed for 50PUS2 and 100PUS2. Accordingly, for a given sample, the water intrusion in the pores is directly related to the total porosity of the sample.

3.3. Structure and microstructural observations

The confocal laser scanning microscopy allows the research of roughness and surface alterations of the ecoblocks. The results obtained are reflected in Figs. 5–7, associated with distinctive morphologies. The figures show a general image of the analyzed sample (upper left corner) as well as three other representative images of the surface.

In a general way, when the percentage of waste PU increase, a greater number of agglomerates is detected. Predominantly, the particles appear to be in the same plane as the analyzed surface.

For the reference samples without waste in the dosage, agglomerates or individual fibber logically are not detected and the matrix is homogeneous with a very good cohesion.

All the samples have a random but homogeneous, integrated and cohesive distribution of raw materials. However, for 100% substitution dosages corresponding with 100PUS1 and 100PUS2 samples, in spite that the fact that the fibers are distributed randomly,

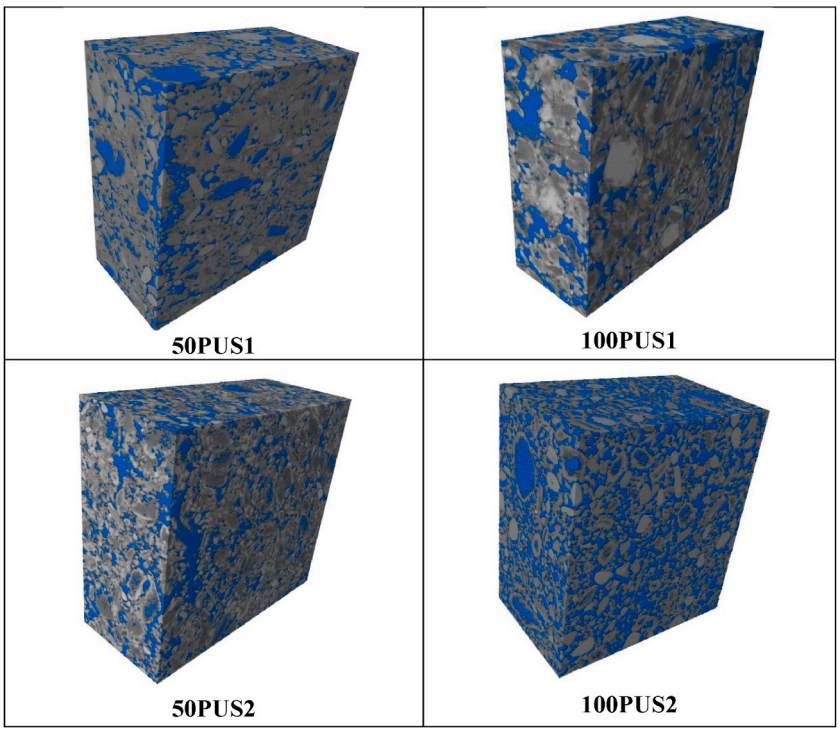

Fig. 4. Effect of polymer waste addition on the total porosity of cement mortars. Blue colour: porosity. Grey colour: mortar paste, registered at room temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

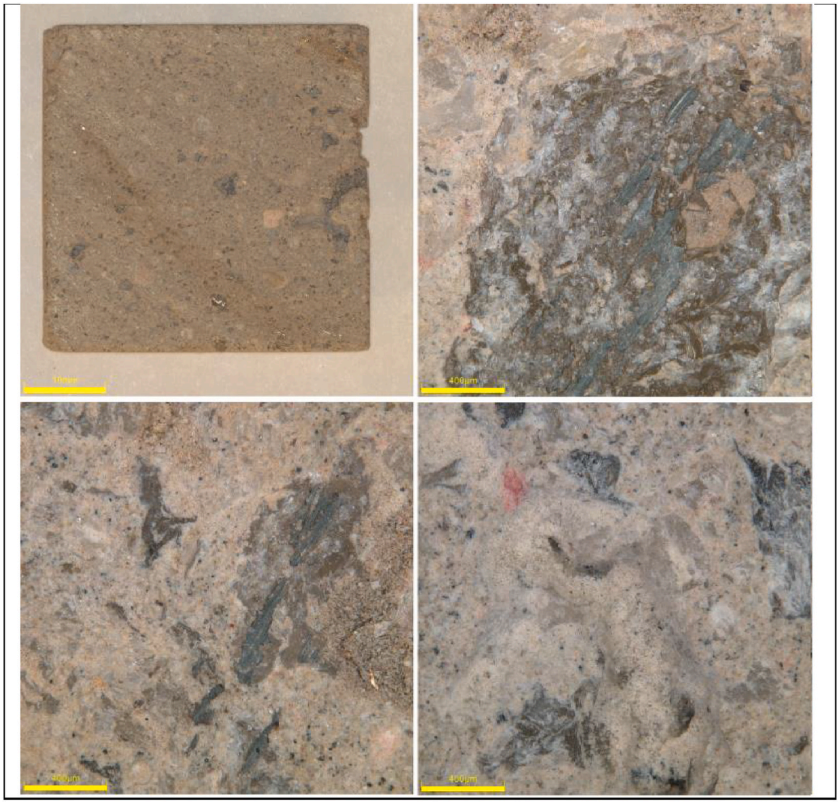

Fig. 5. Images obtained with the digital confocal microscope of the reference sample without PU wastes, take with a light source as photo monochromatic laser beam characterized by 408 nm wavelengths.

a higher concentration of them around the agglomerates is observed.

The surfactant S1 produce in general samples with many agglomerates with needle-like shape, randomly distributed. On the other hand, the S2 additive includes numerous agglomerates with "rounded" shapes and also homogeneously distributed (see Fig. 7).

3.4. Non-combustibility test results

The results obtained in the "Non-combustibility test" are described in Fig. 8.

Since the content of organic matter is, at least, of 50% - much bigger than 1% when no tests are required - these results allow to extrapolate the behavior of ecomortar blocks into a real situation [39]. In qualitative terms, results show a low loss of mass values since the standard consider the material applicable when the loss of mass is below 50%. [40] The other limit established by the standard to comply with the test is the increase of the temperature in the oven. All the samples achieve values below 50 °C except the 100PUS2. Considering the high amount of organic matter included in these samples, in any case results are extremely positive. Subsequently to the test, no changes in colour or cracks are detected after visual inspection.

Taking into account only their contribution to the flammability of the materials, these results indicate that all mixtures except 100PUS2 can be classified on fire as Euroclass A2, that is, non-combustible, without contribution to fire, according to the EN 13501–1.

A possible explanation for these results could be that the poor hydrophilic grade of surfactant S2 with respect to S1 does not allow the matrix to be satisfactorily compacted to obtain a material sufficiently to fire, when a substitution of 100% of aggregate for polymeric residue is used.

4. Conclusions

The study presented is in line with the principle of obtaining environmentally friendly materials with the purpose to obtain sustainable model within the construction sector.

The characteristics and nature of construction materials, based on cement, make possible to employ polyurethane insulating waste panels with remains of other materials (adhesives, metal oxides, remains of paint and/or plastering, etc.). The research carried out allows to obtain lightweight ecomortar blocks with industrial polyurethane waste originates from vehicle roofs industry.

The use of polymeric surfactants with different hydrophilic – lipophilic balance contribute to maintain the mechanical strength, obtaining recycled materials with enough mechanical properties between 13.3 and 3.7 MPa and, at the same time, with a lower density in relation to conventional lightweight mortars.

The density decreases between 18.7% and 62.7% as residue is added in relation to reference ecoblocks, which means a better

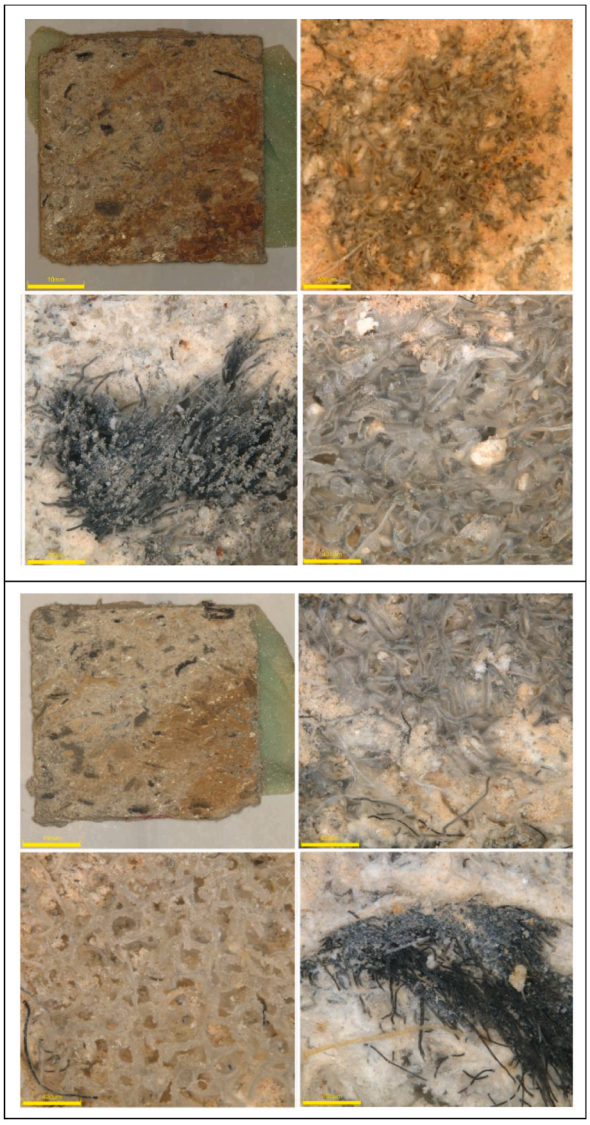

Fig. 6. Images and different materials observed for the surface of 50PUS1 sample (top) and 100PUS1 sample (bottom), obtained with a light source as photo monochromatic laser beam characterized by 408 nm wavelengths.

workability for the final put on site.

The porosity of the recycled samples, until 3.4 times bigger than reference samples, becomes bigger with the increase of residue is incorporated. That factor greatly favours the thermal insulation of the final product, as well as a good behaviour against temperature and against fire, measured in terms thermogravimetry and non-combustibility (reaction to fire).

In addition, with a massive recycling of polymeric wastes and subsequently with an environmental perspective, the final assessment is even more advantageous considering the reuse of this polymer by-product avoiding the consumption of other natural resources, energy and water. The contribution to sustainability that the recycling of this type of materials supposes and the improvement that the industrial waste management implies is fundamental.

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Authorship contributions

Please indicate the specific contributions made by each author (list the authors' initials followed by their surnames, e.g., Y.L. Cheung). The name of each author must appear at least once in each of the three categories below.

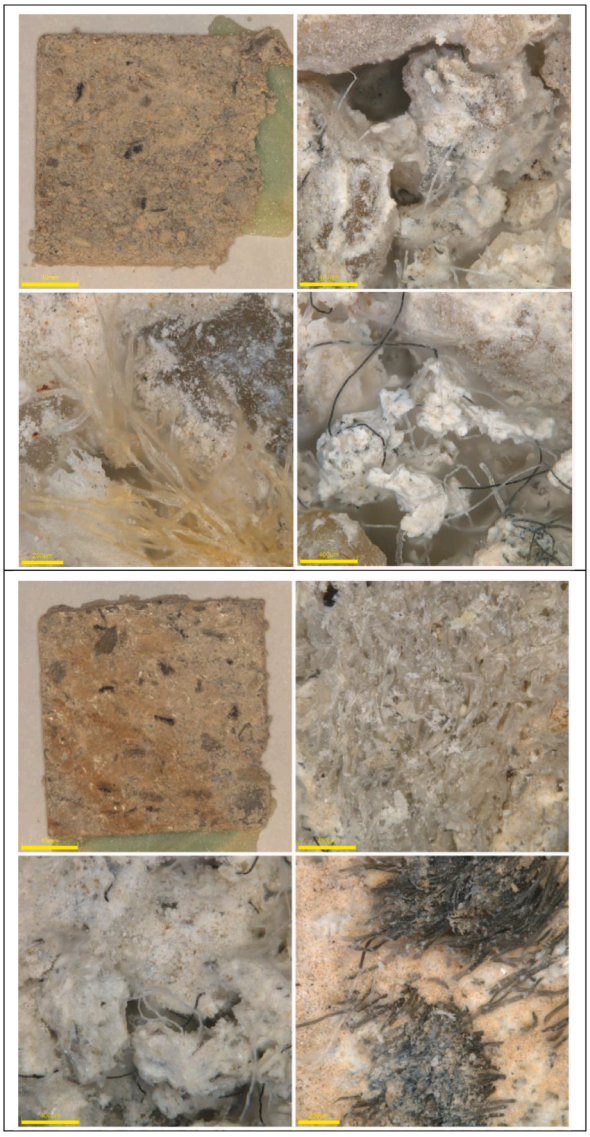


Fig. 7. Images and different materials observed for the surface of 50PUS2 sample (top) and 100PUS2 sample (bottom), obtained with a light source as photo monochromatic laser beam characterized by 408 nm wavelengths.

Category 1.

Conception and design of study: V. Calderón, S. Gutiérrez-González. Acquisition of data: L. Alameda Cuenca-Romero, R. Arroyo, A. Alonso.

Analysis and/or interpretation of data: V. Calderón, S. Gutiérrez-González, L. Alameda Cuenca-Romero.

Category 2.

Drafting the manuscript: L. Alameda Cuenca-Romero, R. Arroyo, A. Alonso.

Revising the manuscript critically for important intellectual content: V. Calderón, S. Gutiérrez-González.

Category 3.

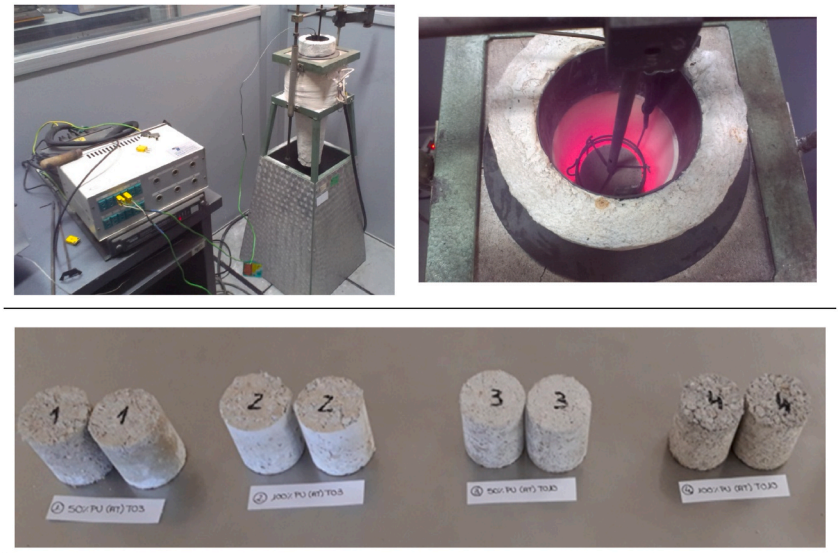
Approval of the version of the manuscript to be published (the names of all authors must be listed):

L. Alameda Cuenca-Romero, R. Arroyo, A. Alonso, S. Gutiérrez-González, V. Calderón.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the



Dosages	Oven temperature increase (Δt) (°C)	Persistence of the inflammation (tf) (s)	Loss of mass (Δm) (%)
50PUS1	41.6	368	10.72
100PUS1	48.5	1072	32.31
50PUS2	29.2	517	14.24
100PUS2	71.3	745	38.17

Fig. 8. Samples and results obtained in the non-combustibility test, taken into apparatus corresponds to standard EN ISO 1182.

manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the *Journal of Building Engineering*.

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