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Lightweight masonry mortars made with expanded clay and recycled aggregates

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HIGHLIGHTS

- Aggregate from concrete waste and rubble are used to fabricate sustainable lightweight mortars.
- Materials are evaluated by means of physical, chemical and mechanical properties.
- Recycled materials show potential to be used.
- The economic study demonstrates the viability of this alternative.

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ABSTRACT

One of the most extensive applications of recycled construction and demolition waste is as recycled aggregate in substitution of natural aggregate. An application for the fine fraction is investigated in this study by preparing lightweight mortars with different types of fine recycled aggregate from concrete waste and rubble. The properties of the materials are evaluated by means of physical and chemical characterization, their mechanical properties are tested, and the economic viability of the final product evaluated. In conclusion, despite the significant differences noted between the lightweight mortars and those incorporating natural aggregates, the former remain a technically and economically viable alternative.

1. Introduction

People have made constant use of natural resources for their benefit throughout history, unaware until relatively recently of the environmental damage and progressive degradation that they have been provoking. In this sense, the construction sector is one of the main polluters, due to the amount of waste that it generates, making it necessary to encourage the recycling of waste.

Conservation of the environment and of natural resources is one of the objectives to solve nowadays and for future generations. Lobbying by pressure groups is growing every day, as is public awareness of the need to develop the recycling of waste materials at the end of their useful life, transforming waste into a resource, reducing its environmental impact because of the exploitation of natural resources, and easing pressure on waste-disposal sites.

In accordance with the road map for a resource-efficient Europe, increasing recycling rates will reduce the pressure on demand for primary raw materials, help to reuse valuable materials which would otherwise be wasted, and reduce energy consumption and greenhouse gas emissions from extraction and processing. We may search a strategy to make the EU a 'circular economy', based on a recycling society with the aim of reducing waste generation and using waste as a resource, and we must to promote the waste prevention, reuse and recycling performances of the more advanced Member States, going beyond the minimum EU targets, waste reduction of 15%. Zero landfill in all Member States [1].

Construction activity is inextricably tied up with waste production. Thus, Construction and Demolition Waste (CDW) implied approximately 25%–30% of all waste generated in the EU, which was dumped in land-fill sites with a visual impact on the landscape [2]. Consequently, CDW is one of the heaviest and most voluminous waste streams generated in the EU and consists of numerous materials, including concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, asbestos and excavated soil, many of which can be recycled. Its correct management is therefore necessary to reduce the amounts that are generated and to exploit their potential as a resource.

As recently as the 1970s, various investigations had already studied CDW crushing processes, mixture designs, mechanical properties, and the durability of concrete made with recycled aggregates, improved strengths by lowering the water/cement

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ratio and/or by cement additions, and the use of mineral additions [3]. Properties such as cement paste adherence to the recycled aggregate and the elasticity modules are reduced as higher percentages of recycled aggregates are incorporated in the concrete mix while shrinkage due to drying increases [4].

Studying the use of recycled aggregates in substitution of natural aggregates has focused on aggregate, for which various applications have been found, such as in the case of structural concretes, in which the fine aggregates are left aside, which according to some studies can incorporate between 20% and 50% of CDW [5]. Another classification of recycled aggregate is in accordance with its composition, given that this parameter is decisive when establishing the quality of the aggregate, and its effect on the concrete and mortar in which it is incorporated [6].

Moreover, expanded clay is one of aggregate used in lightweight mortars, which is manufactured with natural clays that present a naturally expansive behaviour when subjected to temperatures of over 1200 °C. They are spherical in shape and have a closed and hardly porous exterior surface, in contrast with the interior that is highly porous and black in colour [7]. Other works fall on the manufacture of lightweight masonry mortars replacing aggregates with recycled polymer wastes crushed [8,9].

On the basis of the above, the novelty of this study centres on determining the effects of adding recycled aggregate of different sizes and from different sources to prepare lightweight mortars, on the physical and the mechanical behaviour of these mixes, and to estimate their real economic viability.

2. Characterization of raw materials

2.1. Materials used

- *Cement*: CEM I-42,5R, which implies early strength cement and a low Blaine specific surface of 3400 cm^2/g.
- *Washed Natural Sand (NS)* with the properties showed in Table 1. The NS presented lower values of fines as expected, given that the loss of weight was due to aggregate wear.
- *Commercial lightweight aggregate*: expanded clay supplied by the firm Argex (Spain), types 2/4 mm and 3/8 mm. The densities of expanded clay vary between 300 kg/m^3 for the lightweight components and 800 kg/m^3 for structural elements. The manufacturer's recommendations have been followed for the preparation of the lightened mortars with regard to dosages, percentages and types of expanded clay.
- *Recycled Concrete Aggregate (RCA)*, came from the crushing of unusable prefabricated components from the Gerardo group, Burgos.
- *Recycled Mixed Aggregate (RMA)* supplied by Igelcar S.L. from its recycling plant in Burgos.

Both recycled aggregates are subjected to primary crushing with a hydraulic crusher to obtain blocks of between 0 and 150 mm, with subsequent treatment by impact crushing yielding an aggregate of between 0 mm and 30 mm. Subsequently, the material was sieved to obtain a fraction of between 4 mm and 12.5 mm. Finally, the material was ground and screened to select a fraction equal to or below 4 mm. Table 1 shows the complete characterization.

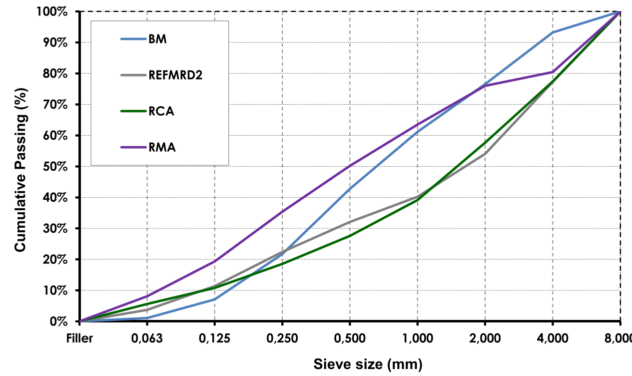

Fig. 1. Sieve size of the design mixtures.

2.2. Properties of different aggregates used

All the aggregates used for are previously dried in an oven at 40 °C. In accordance with the results showed in Table 1, the percentage of fines and the absorption of all the aggregates comply with the applicable and appropriate requirements for this type of compound [10]. The bulk density is within the standard EN 1015-10 parameters, between 2280 kg/m^3 and 2670 kg/m^3 for the recycled concrete aggregate (RCA), and 2350–2680 kg/m^3 for the recycled mixed aggregate (RMA).

In the case of the RCA, the adhered mortar paste has to be added and, in the case of the RMA, the remains of brickwork adhered to the mixtures. The soluble chloride ion content presented values within the limits established in EN 998-2 [11].

The limits for lightweight particles vary between 0.1% and 1%, with which the RCA complied, while they were easily surpassed by the RMA. Other works that cover this aspect report that they can reach higher values [12].

It may be seen from the granulometry a curve size that is higher in the REFM and the DM (Fig. 1). The discontinuities can be decisive in some properties, as the varied amounts of sizes should close the gaps left by those of a larger size, and so on successively until maximum compactness is achieved. In any case, it was decided to employ the aggregates even although the particle size has a diameter size slightly larger than usual of 4 mm, to avoid raise the price of the residue so that the materials would be economically competitive and would need no subsequent treatment.

3. Experimental

3.1. Composition of initial dosages

All the samples have a cement/aggregate ratio of 1/4 in weight, considering the aggregate as sum of all the types include in each mixture (natural sand, lightweight clay and/or recycled aggregate). Though the initial dosages were calculated by weight, the amount of discarded aggregates was substituted by an equivalent quantity of recycled aggregates in volume, taking into account the density values of different materials. The amount of water necessary for good workability was determined on the basis of the w/c ratio in accordance with current regulations [13].

- Base Mortar (BM): prepared with washed natural sand (NS) as single aggregate.
- Different Reference Mortar (REFM): the initial lightened mortars were prepared from the reference mortar by the substitution in volume of different proportions of natural sand by expanded clay. The remaining mortars were prepared in view of the different requirements and on the basis of the selection of samples from this section. Table 2 shows the different amount and types of clays used as initial lightweight aggregates.

Table 1
Results of the characterization of the fine aggregates for mortars.

Properties	NS	Expanded clay 2–4	Expanded clay 3–8	RCA	RMA
Fines (%)	1.08	0.00	0.00	4.71	4.81
Fineness modulus (%)	2.98	5.77	6.93	3.09	2.58
Bulk density (kg/m^3)	2640	358	300	2400	2450
Absorption (%)	0.22	26.2	24.9	2.40	2.49
Fragmentation resistance (%)	12	–	–	17.5	25.5
Adhered mortar (%)	–	–	–	67.97	56.38
Chlorine ion content (%)	–	<0.004	<0.004	0.0005	0.0006
Loss on ignition (%)	–	–	–	0.473	0.464
Water soluble sulphates (%)	–	–	–	7.07	6.86
Acid soluble sulphates (%)	–	<0.05	<0.05	0.50	5.11
Light contaminants (%)	–	–	–	0.62	2.99
Water solubility (%)	–	–	–	0.68	0.17
Organic matter content	No	No	No	No	No

Table 2
Dosage of the reference mortars.

Sample	Sand replaced by expanded clay 2/4 (% in volume)	Sand replaced by expanded clay 3/8 (% in volume)	Total sand replaced by clay (% in volume)
BM	Only natural sand		
REFMA1	0	25	25
REFMA2	0	50	50
REFMA3	0	75	75
REFMB1	25	0	25
REFMB2	50	0	50
REFMB3	75	0	75
REFMC1	25	25	50
REFMC2	12.5	37.5	50
REFMC3	37.5	12.5	50
REFMD1	37.5	37.5	75
REFMD2	18.75	56.25	75
REFMD3	56.75	18.75	75

3.2. Composition of modified mortar

- Mortar with recycled concrete aggregate (RCA). It is produced from the mixture REFMD2 which initially have a 75% of replacement of natural sand by different limes and with a cement/(total aggregate) ratio of 1/4 by weight. To obtain this RCA, the remaining natural sand is substituted in volume by recycled concrete aggregate. As a result, the mortar include 500 g of cement, 417.2 g of clay 2–4, 93.8 g of clay 3–8F, 436.8 g of RCA and a water/cement ratio of 0.76.
- Mortar with recycled mixed aggregate (RMA). This mortar is also obtained from the mixture REFMD2 replacing natural sand by recycled mixed aggregate in volume, with a cement/(total aggregate) ratio of 1/4 by weight. Consequently, this mortar has the same composition that preceding mortar with 500 g of cement, 417.2 g of clay 2–4, 93.8 g of clay 3–8F, 378.2 g of recycled mixed aggregate, and a water/cement ratio of 0.81.

3.3. Mortar obtaining procedure

Mortar mixing was done with a Proetic C0087 mechanical mixer. Prismatic specimens of 40 mm × 40 mm × 160 mm were prepared. The specimens were removed from the moulds after 24 h and then left to cure in a wet chamber at a temperature of 20 ± 3 °C and at a humidity of 90 ± 5%. At least five valid dosages of each sample were prepared.

4. Results obtained for the reference mortars

Fig. 2 shows the results of the test performed on the reference specimens (REFM) before their subsequent modification.

Apparent density is one of the critical parameters when determining the viability of these mixtures as lightweight masonry mortars (L) according to EN 998-2, which dry bulk density tested in accordance with EN 1015-10 shall be equal to or less 1300 kg/m^3 [14]. Standard specimens in accordance with EN 1015-11 were prepared to measure their compressive mechanical strength [15].

A consistency of 175 mm ± 10 mm, a minimum compressive strength of 18 MPa and a maximum bulk density in hardened state of 1600 kg/m^3 were established as conclusive parameters for the selection of the dosages. As shown in Fig. 2 and 10 mixtures were prepared on the basis of those parameters that complied with the requirement for compressive strength and 5 dosages met the requirement for maximum density. If we combine both factors, only three of the specimens, REFMA3, REFMB3 and REFMD2, met the two earlier ones. On that basis, mortar REFMD2 was selected to centre efforts on subsequent variations, taking into account that it was lightest of the three mortars.

It has been chosen a high limit on mechanical strength taken into account the possible decrease in mechanical properties after replacement of recycled aggregates. On the other hand, also with the aim to be able to use these mortars not only as masonry mortar but as prefabricated materials in future research about this interesting topic.

5. Results obtained for the modified mortars

Having selected mortar REFMD2, the aggregate composition of which consisted of 25% NS and 75% recycled aggregate. On the one hand, a lightweight mortar was prepared with the incorporation of 75% recycled concrete aggregate (mortar RCA) and, on the other hand, a lightweight mixed aggregate mortar was obtained with the addition of 75% mixed recycled aggregate (mortar RMA). Finally, a base mortar (BM) only with NS was fabricated, to gain a broader view of the results.

These modified mortars were characterized in their fresh and hardened state, the results of which are shown in Table 3.

5.1. Water/cement ratio

The water/cement ratio was seen to increase with the addition of recycled aggregate, reaching 22.9% for the RCA mortars and 33.5% for the RMA mortars. The presence of expanded clay in the REFM implied a reduction of water of 6.7% with regard to the BM. The quality of recycled aggregate had a notable influence on the quantity of water that the mixtures required.

As extra water was used in the concrete made with recycled aggregate than in the concrete with natural aggregate to maintain the same slump. This increase in water content has an effect on the strength. It is believed that if admixtures were used to increase workability, while maintaining the same amount of water, then the recycled concrete would have had higher strength than observed.

5.2. Air contain of fresh mortar

The percentage of occluded air in each mortar was measured in accordance with standard 1015-7 [16] at a temperature of 20 ± 1 °C and at a relative humidity of 50 ± 1%. The inclusion of recycled aggregate led to greater amounts of occluded air within the mortar matrix in comparison with the BM and the mortar lightened with expanded clay, reaching a maximum with the RMA, although quite similar to the percentage of occluded air recorded for the RCA.

5.3. Water absorption

The highest absorption coefficients were reached with the recycled mortars, due to the higher absorption that the recycled aggregates usually present with regard to the natural aggregate. Likewise, the mortar base (BM) retained more water that the reference mortar (REFM), due in all likelihood to the influence of expanded clays.

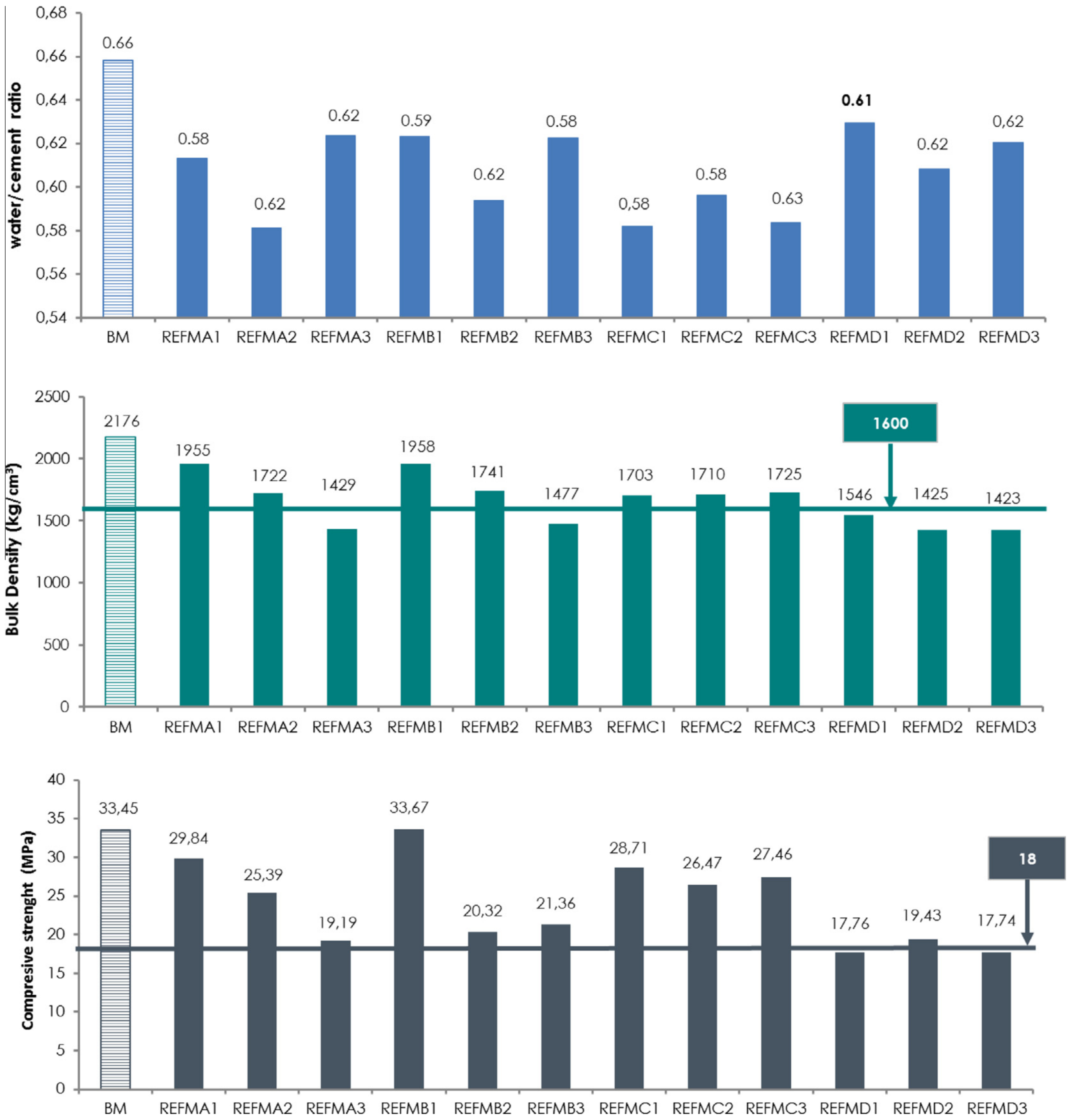

Fig. 2. Water/cement ratio, bulk density and compressive mechanical strength of the reference mortars.

Table 3
Physical results for mortar specimens. Water/cement ratio, air contain and bulk density for fresh mortars and bulk density, water absorption and water penetration height for hardened mortars.

Test	BM	REFMD2	RCA	RMA
Water/cement ratio	0.659	0.615	0.756	0.821
Air contain of fresh mortar (%)	6.2	17.7	22	23
Bulk density of fresh mortar (kg/m^3)	2108	1420	1280	1290
Bulk density of hardened mortar (kg/m^3)	2106	1340	1710	1140
Water absorption (%)	0.11	0.08	0.16	0.18
Water penetration height (mm)	11.6	5.0	9.6	7.7

In Table 3 it could be observed that the values for water penetration and total absorption for reference mortar BM are 11.6 mm and 0.11% respectively, values much higher than those obtained for mortars REFMD2, with data of 5.0 mm and 0.08% correspondingly. This fact could be explained taking into account the bulk density of hardened mortar, which is 2106 kg/m^3 for BM and 1340 kg/m^3 for REFMD2. The decrease in density implies the progressive presence of larger pores that produce a reduction in the amount of suitable capillary pores. Consequently, the lightweight mortar REFMD2 have bigger amount of porous and with larger size into the matrix but with less suction ability. In contrast, results obtained for RCA and RMA samples are closer to the reference BM values.

5.4. Mechanical strength

Standardized specimens of all dosages were tested at 28 days, at 90 and at 365 days, so as to evaluate their variations over a considerable interval of time, so as to provide a clear picture of their mechanical behaviour. The measurements of each blend were repeated to obtain values which have a reproducibility of at least 90%.

The values obtained are shown in Fig. 3. Loss of compressive strength due to the presence of expanded clay and recycled aggregates fluctuated between 53% and 44%, due to the lightened BM, while the loss due to the substitution of the NS of the REFM by the recycled aggregates of the DM, implied only 15%, in the worst circumstances.

The reduction in flexural strength due to lightweight additions varied between 53% and 38%, while the substitution of natural aggregate by recycled aggregates was, once again in the worst case around 25%; these values are according other similar studies in concrete products [17,18].

The compressive strengths of concrete made with recycled coarse aggregate depend on the mix proportions but generally showed higher percentage loss than natural aggregate, but

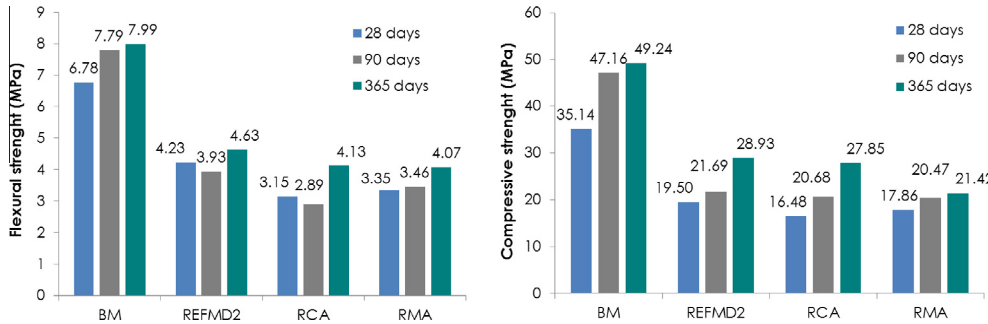

Fig. 3. Evolution of mechanical strength over time, at 28 days, 90 days and 365 days.

remained within the acceptable limits. In general, the strength of recycled concrete are lower than that of conventional concrete made with natural coarse aggregate.

If the compressive strength at 3 months is considered in relation to compressive strength at 28 days, the increase was 34% for the BM, 11% for the REFM and 25% and 15%, respectively, for the RCA and RMA mortars. The results for flexural strength varied between increases of 15% increase for the BM and as little as 3% for the RMA with very small and similar reductions for the REFM and the RCA, of 7% and 8%, respectively. Likewise, the compressive strength of the RMA mixture improved, by around 20% at 28 days and by around 5% at 90 days.

At 365 days, the compressive strength had increased by around 40% with regard to that obtained at 28 days for the BM. The RCA mortar presented an increase in its compressive strength of 69% above that obtained at 28 days and an increase of 35% above that at 90 days.

It is important to underline the slight final differences in compressive strength between the REFM specimens and the RCA mortar specimens, which imply a competitive advantage for the use of the recycled product, and the slight increase recorded for the compressive strength of the RMA at 365 days.

Therefore, as expected, the reduction in strength occurred with the lightweight additions to the mortar in all of its variants, with no great differences between the data obtained for the reference mortar, without recycled aggregate, and those reached by the mortars with recycled aggregate.

Moreover, a correlation between water and mechanical strength of recycled-aggregate was found. When analyzing the ratios between the mechanical strengths at 28 days and the water/cement ratio (Fig. 4), the reduction in mechanical strength was seen to be directly related with the increase in the required amount of mix water, which is logical, as a greater quantity of water implies bigger porosity of the material in the hardened state.

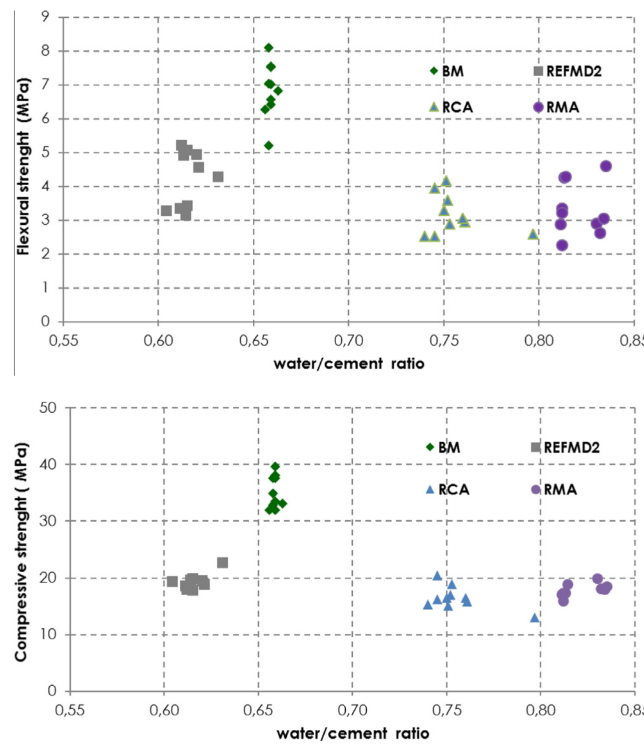

Fig. 4. Relation between the mechanical strengths and the water/cement ratio.

5.5. Shrinkage

After 24 h of sample fabrication, the specimens are removed from the moulds and the length shrinkage is measured as initial value. Subsequently, samples are cured with more than 90% of humidity and 20 °C of temperature during 28 days, performing a second measurement of length. Then the specimens are cured at laboratory conditions, performing measurements at 32, 35, 42 and 56, 112 and 224 days after fabrication. To measure the length of the specimen was used an extensometer with accuracy of 1 μm. Before the measurement, the extensometer must be calibrated at the beginning and end of the process using a calibrated bar.

Dimensional changes were analysed to follow the expansion of the mortars over time and to determine how lightweight and recycled aggregate additions influenced this behaviour. The variations in the length of the specimens produced by expansion and contraction are presented in Fig. 5.

Except for the BM mortar, the remaining mortars in the test presented expansion at 38 days, which was probably due to the curing of the specimens in water; a circumstance that can induce swelling.

When a mortar specimen is immersed in water, it undergoes an increase in weight and an increase in volume as a consequence of water adsorption by the hydrated cement gels, which unlike dry shrinkage, tend to become spongy and to produce this swelling.

Except in the mortars that included RMA, the expansion values were relatively small, such that the expansion may be considered to be due to excessive swelling, while in the case of the RCA it may be due to both swelling and the formation of ettringite [19].

Ettringite is a hydrous calcium aluminium sulphate crystalline mineral formed by the hydration of Portland cement. Ettringite formation by reaction of internal or external sulphate with anhydrous or hydrated calcium aluminates has an expansive character. However, not necessarily the ettringite formation produces damaging expansion. When it occurs immediately (within several hours) in a fresh mixture there is no expansion and is advantageously used for setting time retardation of Portland cement.

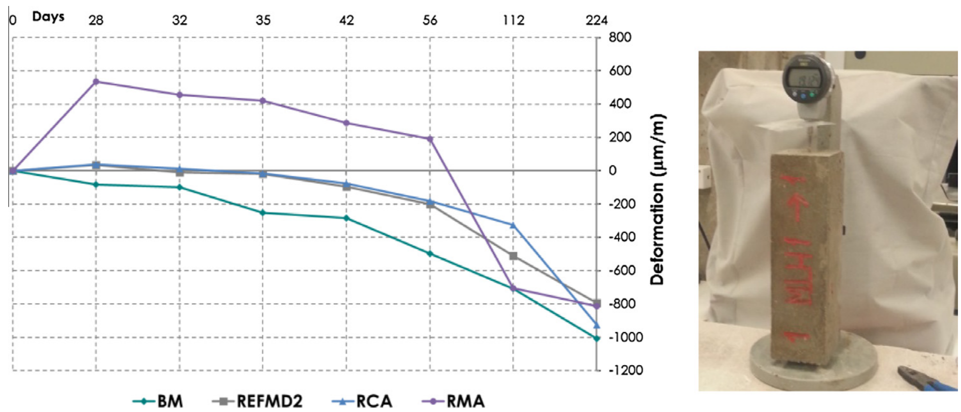

Fig. 5. Evolution of the dimensional changes over time.

On the other hand, when ettringite forms heterogeneously at late ages (after months or years), in a rigid hardened concrete, it can produce cracking [20].

The quantity of sulphates in the recycled mixed aggregate (5.12%) that are soluble in acid probably influences those expansions in such a way that they are greater than in the other mortars. Studies on concretes with recycled mixed aggregates which analyze expansion due to sulphate content, have, following their tests, concluded that increased expansion is proportional to the content of sulphates [21].

Shrinkage became visible in all the mortars after the curing process, except in the RMA mortars, confirming that after 224 days, all the mortars stabilized and presented very similar percentage shrinkage.

In spite that the fact that no problems with long age ettringite formation has been observed after flexural and compressive specimen test at 365 days, further work will focus on the durability test of these materials, with the aim of determining their behaviour under long aging test.

6. Study of economic viability

The viability of these materials was evaluated in an economic study that considered both a quantitative and a qualitative evaluation of the product, as well as the competitive advantages in the field of sustainability, arising from the use of the recycled aggregate in the composition of the fabricated mortars.

The final price of the mortar depends on various factors: the raw material costs, the fabrication costs and the cost of its on-site application. Only the costs of materials and the fabrication process have been taken into account to complete the economic study. The costs of its on-site application would otherwise mean considering multiple variables for its determination as they vary in accordance with each completed unit of construction work.

The construction costs are composed of direct and indirect costs. The direct costs value the constructive units under one heading of the work and are obtained from the addition of the costs of all of its budget items: workforce, materials, machinery, and auxiliary costs. The indirect costs cannot be attached to one specific unit of work, but rather to the whole project or to one overall part [22]. These indirect costs were obtained by applying a percentage to the direct costs that was equal for all units of the work.

The simple unitary costs of the raw materials were collected by requesting their prices from wholesalers and distributors of construction materials, while the renderings and the cost of labourers was taken from the database on regional pricing. All the prices of the material are installed on site, so no cost increases attributable to transport costs are necessary.

The cost of the recycled aggregate was obtained by requesting prices from various Recycling Plants. In the case of the RMA, all these plants store large amounts and prices are relatively low. The same cannot be said for the sands taken from RCA, as this type of aggregate is not very common. This sand RMA was not available from geographic zones nearby, so its final price was increased by transport costs, which were over and above the cost of the material.

The auxiliary prices that refer to m^3 of the various mortars are shown in Table 4. As may be confirmed, the economic study shows that the lightweight additions to the BM, to obtain the RM, imply a small cost increase while the substitution of NS by recycled aggregates slightly reduces their cost.

The study took no account of the construction waste disposal tax that the Waste Management Recycling Plants collect for waste disposal. This amount designated a "waste disposal tariff" constitutes income for the Plant, as the final reception point responsible for processing and valuation.

In any case, we consider that these recycled aggregates are cost-effectively viable. In addition, these materials open the opportunity

Table 4
Mortar cost for m^3.

Type		Description	Price (Euro)	Amount	Cost (Euro)	Total €
BM	Tn	Cement CEM I 42.5	98.25	0.38	37.34	73.1 €/m^3
	Tn	Washed sand	7.70	1.54	11.86	
	m^3	Water	0.36	0.25	0.09	
	h	Day labourer	12.95	1.80	23.31	
	h	Electric concrete mixer	1.20	0.40	0.48	
REFM	Tn	Cement CEM I 42.5	98.25	0.38	37.34	91.5 €/m^3
	Tn	Washed sand	7.70	1.54	11.86	
	m^3	Expanded clay 3–8	20.80	0.23	4.78	
	m^3	Expanded clay 2–4	20.80	0.66	13.73	
	m^3	Water	0.36	0.26	0.09	
	h	Day labourer	12.95	1.80	23.31	
	h	Electric concrete mixer	1.20	0.40	0.48	
RCA	Tn	Cement CEM I 42.5	98.25	0.34	37.34	83.9 €/m^3
	Tn	Recycled concrete aggregate	10.36	0.30	3.11	
	m^3	Expanded clay 3–8	20.80	0.19	3.95	
	m^3	Expanded clay 2–4	20.80	0.75	15.60	
	m^3	Water	0.36	0.26	0.09	
	h	Day labourer	12.95	1.80	23.31	
	h	Electric concrete mixer	1.20	0.40	0.48	
RMA	Tn	Cement CEM I 42.5	98.25	0.36	37.34	82.5 €/m^3
	Tn	Recycled mixed aggregate	3.38	0.27	0.91	
	m^3	Expanded clay 3–8	20.80	0.20	4.16	
	m^3	Expanded clay 2–4	20.80	0.78	16.22	
	m^3	Water	0.36	0.30	0.11	
	h	Day labourer	12.95	1.80	23.31	
	h	Electric concrete mixer	1.20	0.40	0.48	

to reach a more sustainable production and decrease the use of natural resources as well as to contribute to solve a problem, though further research is deemed to analyze the final economic viability.

7. Conclusions

The use of recycled aggregates in the fabrication of lightweight mortars for construction has been shown to be a viable alternative means of contributing to sustainable development, avoiding the negative impact of these waste materials in the natural environment. The transformation of construction or demolition waste into a raw material is a valid option, to avoid over-exploitation of natural resources, and is a means of encouraging recycling, so as to obtain useful products for application in the construction sector.

With regard to the specifications of the recycled aggregates, it may in general be affirmed that its performance is somewhat inferior to natural aggregates. The water absorption values, fines content, the presence of mortar adhering to particles, the sulphur content and the presence of impurities, all determined the final quality of the waste. Nevertheless, the fines obtained from recycled concrete presented a better performance than mixed recycled aggregate.

The addition of expanded clay as an additional material for lightweight mortars reduced the water-cement ratio, a positive effect that was neutralized by adding mixtures of recycled aggregate. The increase produced in the water/cement ratio when adding the recycled aggregate was a function of its materials and source, which are circumstances that determine both its composition and its properties.

The inclusion of expanded clay in the mortar mixtures produced an increase in the content of occluded air because of its properties, a quantity that increased when recycled aggregate was also included, due to mortar adherence to its contents.

The inclusion of expanded clay was also the cause of a significant reduction in density, which increased as quantities of recycled aggregate were included in the mix, due to its apparent individual density which was also lower than in the natural aggregate.

The water absorption of the mortars increased when recycled aggregate was added to the mix. However, the presence of expanded clay reduced the absorption. In all the mortars, the highest levels of water absorption are presented at early ages, with only slight variations between them.

With regard to mechanical behaviour, the mechanical properties of the lightweight mortar with additions of expanded clay were weaker as a consequence of the increased gaps in the mixture, due to the internal porous structure of the expanded clay and the irregularity of its granulometry. The variation in mortar strength between the reference mortars and the recycled mortars was not significant, nor were there considerable differences in the mechanical properties in accordance with the type of aggregate in use, the presence of which was of little importance if we compare it with the other mortar components.

There was a direct relation between the water/cement ratio used in the design of the mixtures and their mechanical strength, which was reduced as the mix water content increased. Hence, the quality of the recycled aggregate in use hardly influenced this behaviour at all.

The lightweight mortars with expanded clay and the lightweight mortars with recycled aggregates presented lower shrinkage levels at all ages, these mortars being the only ones that presented no expansion at 28 days. The shrinkage rates of all the mortars tended towards equality over time.

The use of recycled aggregates in substitution of natural aggregates in the preparation of lightweight mortars has both a quantitative and a qualitative justification, taking into account the competitive advantages offered by the exploitation and reuse of waste materials.

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