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Feasibility Study on the Production of Sustainable Mortars Packaged with Recycled AAC Aggregates

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Abstract. Building sustainability is one of the current global goals due to the variety and the quantity of the resources consumed in all the construction phases. Mortars – for masonry and plasters applications – are one of the most "produced" and high-impact composite building materials, since they are used both in traditional and modern constructions. Moreover, the production processes of binders and aggregates used to package mortars require the consumption of energy and resources and lead to the management of a huge amount of waste. In order to reduce the environmental weight of the mortars, the scientific world has been focusing, over the last years, on the substitution of natural aggregates with lightweight-recycled ones. Several studies have shown that this substitution improves some performances (thermal insulation and vapour permeability) and decreases other ones (compressive and flexural strength) as a result of the mortars density reduction. Moreover, the variability of recycled-aggregates materials (ceramic, plastic, concrete) and of the composition of mortars allows many different possibilities. However, little is known about the effective convenience of the market placement of these products. The aim of this study is to measure the environmental and economic sustainability of mortars made with natural hydraulic lime and a partial substitution of the natural sand with recycled aggregates from the production waste of Autoclaved Aerated Concrete bricks. These mortars were physically and mechanically characterized in a previous research phase and they were classified according to UNI EN 998-1 and 2. In particular, mortars with 25% by weight of AAC at most were suitable for masonry applications. The present study investigates the synergic possibility of packaging pre-mixes with recycled AAC aggregates in establishments where AAC is produced, moving from the unconventional perspective of the manufacturer. At first, LCA analyses are performed on these scenarios, in order to prove the strong decrease in the environmental impact of both production phases – AAC production, where waste is reduced, and mortar packaging, where the use of natural aggregates is limited – then the research moves to the analysis of the economic sustainability of the implementation of this production line. For this purpose, two cases are considered: an AAC manufacturer who does not produce pre-mixes, and an AAC manufacturer who produces pre-mixes, but does not own machineries to recycle Autoclaved Aerated Concrete bricks. Following a cost analysis related to the introduction of the production line of pre-mixes with recycled AAC in the two cases, hypotheses of market prices for this product are formulated in order to assess its economic sustainability, by performing a market analysis, and verifying the compatibility of the payback periods that derive from the related investments.

IOP Conf. Series: Materials Science and Engineering **960** (2020) 042006 doi:10.1088/1757-899X/960/4/042006

1. Introduction

Constructions industry is responsible for the consumption of natural resources and the production of waste both from materials manufacturing and buildings construction [1]. With specific regard to mortars, the inputs of their production processes are mass - aggregates, binder and water - and energy resources – fuel, electricity -, which are the results, in turn, of other impacting processes. Aggregates, in particular, are responsible for 7% of total global energy consumption [2] while their transportation alone accounts for about 40% of the total energy consumption by the industry [3]. In the outputs, along with the products, a great amount of waste is generated. The flow results in an environmental pressure which is becoming "unsustainable" for the natural systems. Recycling industrial by-products or waste appears a valuable solution [4].

Over the last years, several researchers have investigated the use of different types of recycled aggregates from construction and demolition works [5]–[6] and from building materials manufacturing [7]-[10]. The investigations have suggested that recycled conglomerates exhibit the same performances of natural ones [2] and that the use of waste or by-products increases the environmental sustainability of the constructions industry. Actually, numerous life cycle analyses have been developed about "sustainable" conglomerates: the results have underlined that the conglomerates packaged with recycled aggregates, as predictable, are generally less impacting on the nature than the conventional ones [1][11]. Despite the rising interest and the availability of numerous different technological solutions, a few attempts have been made to place these products on the market and to investigate the economic aspects of their production line.

In order to assess both the environmental and the economic sustainability of a recycled-aggregates mortar production, this paper compared a commercial conventional pre-mixed mortar to an experimented one which was packaged with AAC bricks by-products. Firstly, an LCA of both solutions was developed with the aim to measure the environmental impacts of the production lines of the two mortars. Then, an economic analysis was carried out in two scenarios in order to calculate the payback periods of the investments - of an AAC manufacturer - related to the introduction of a new production line for the sustainable mortar. In one case the AAC manufacturer invested to start the production of pre-mixes and to transform AAC off-cuts in aggregates. In the second case, he already produced pre-mixes and needed machineries to grind AAC off-cuts. The results of this work may be used to point out the effective feasibility of the recycling processes of by-products aggregates in the industrial production of the mortars.

2. Materials

Two mixes were studied in the present paper: a reference mortar already available on the market and an experimented one, hereinafter referred to as RM and 2HL, respectively. 2HL was classified as M2,5, according to table 1 of UNI EN 998-2. The commercial pre-mixed mortars are normally formulated with a blended binder (cement and hydraulic lime), natural sand and fibre-reinforce or additives. The use of cement results in high mechanical performances, with a compressive strength of 5 MPa at least. The commercial products which appeared comparable to 2HL were those specific to restoration works. Actually, they are packaged with hydraulic lime and exhibit lower stiffness and compressive strength. RM, then, was chosen due to its mineralogical composition, which was similar to 2HL one, as well as for its compressive strength.

2.1. Reference mortar

The chosen RM was a dry pre-mixed mortar suitable for raising masonry. It was classified as a prescribed-composition mortar for general purposes according to UNI EN 998-2 indications. This type of mortar, as aforementioned, is normally used for restoration due to the absence of cement and its compatibility with the traditional materials. The mass percentages of binder (natural hydraulic lime) and aggregates (natural siliceous sand) were 23% and 77%, respectively, for 1 kg of dry powder. The volume

IOP Conf. Series: Materials Science and Engineering **960** (2020) 042006 doi:10.1088/1757-899X/960/4/042006

of water needed for the mixing, as reported in the technical datasheet, was of 4,5 litres to the commercial packaging unit of 25 kg sack.

2.2. Experimented mortar

In a previous stage of research, the physical and the mechanical properties of mortars with Autoclaved Aerated Concrete (AAC) recycled aggregates were assessed. The mortars were packaged using a natural hydraulic lime NHL3,5 as binder, a siliceous sand and the AAC bricks production off-cuts as aggregates. In the current paper, the 2HL mix was chosen to be compared with RM due to its compressive strength which was of 4,53 MPa and guaranteed an M2,5 class.

3. Methodology

The analysis of the present paper consisted of three phases: firstly, the functional units of dry RM and dry 2HL were defined and the mix proportioning of 1 m^3 of wet mortars was developed in order to compare the resources depletion of each solution; secondly, a Life Cycle Assessment of RM and 2HL production processes was carried out to measure their environmental impact; finally, an evaluation of the economic sustainability of the implementation of 2HL production was performed considering two scenarios in relation to AAC manufacturers.

3.1. Dry and wet proportioning of RM and 2HL

A modified absolute volume method [12] was used to define the mix design of 1 m^3 of RM and 2HL. Binder, aggregates and water volumes were considered in the equation (1). An assumption was made: the densities of the binder and the siliceous aggregates of RM were the same as 2HL. All the aggregates were considered dry with a grain size between 0 and 4 mm. Moreover, the water adsorption of the siliceous sand was neglected as the one of AAC was measured in a previous experimental campaign and it was 0.73. The dry density of AAC was evaluated in the same campaign and it was 860 kg/m^3.

$$1 = \frac{m_B}{\rho_B} + \frac{m_{SS}}{\rho_{SS}} + \frac{m_{AAC}}{\rho_{AAC}} + \frac{m_W}{\rho_W} \quad (1)$$

m_B: mass of the binder (kg)
m_{SS}: mass of the siliceous sand (kg)
m_B: mass of the AAC aggregates (kg)
m_W: mass of the water (kg)
ρ_B: density of the binder (kg/m^3)
ρ_{SS}: dry density of the siliceous sand (kg/m^3)
ρ_{AAC}: dry density of the AAC aggregates (kg/m^3)
ρ_W: density of the water (kg/m^3)

The aggregates-binder and the water-binder ratios by mass of RM were computed from the technical datasheet information, while they were set for the experimented mortar. The masses of binder, aggregates and water per 1 m^3 of wet mortar for RM and 2HL were computed. Finally, the dry composition of the commercial unit of 25 kg was computed for both of the mixes. Table 1 reports the mix design parameters of RM and 2HL.

3.2 LCA analysis

Despite the instinctively more environmentally efficient nature of the experimented mortar 2HL, which was packaged using a lightweight recycled aggregate, an LCA was carried out in order to compare the scenario of 2HL production with the RM one. The analysis was performed with the software *OpenLCA*, using the database *ELCD Greendelta* and the methodology Ecological Scarcity Method. The latter was chosen in order to provide the entity of the mathematical relative comparison between the two mortars through its single output parameter, constituted by the eco-points UBP (from the German *UmweltBelastungsPunkte* [13].

Table 1. Mix design parameters of 1 m^3 of RM and 2HL

	ρ_B kg/m^3	ρ_{SS} kg/m^3	ρ_{AAC} kg/m^3	W_{SS}	W_{AAC}	a	b	c
RM	2600	1610	///	0	///	0.78	3.35	///
2HL	2600	1610	860	0	0.73	0.77	3	0.125

RM: reference mortar; 2HL experimented mortar; B: binder; SS: siliceous sand; AAC: Autoclaved Aerated Concrete recycled aggregates; W: water adsorption coefficient; a: water-binder ratio by mass; b:aggregates-binder ratio by mass; c:AAC-total aggregates ratio by mass

The functional unit of the LCA was represented by the common productive unit for premixed mortars, that is to say 25 kg (dry weight), as aforementioned. The system boundaries were chosen according to guidelines from the scientific literature, which proved particularly effective when dealing with recycled materials [2][11][14], and following the *cradle to gate* model. The operational phase and the end-of-life were not considered in this analysis: on one hand, it can be assumed that the reference mortar and the experimented mortar do not differ in relation to this aspect, and - on the other hand - no specific hypotheses have been made in regard to the use of the mortar. Moreover, the analysis focused on the role of the producer of mortar and the production processes impacts.

Production of RM

The production stages of RM are reported in the diagram in figure 1. The following processes were considered:
- obtainment of limestone, including the quarrying and its transportation to the factory;
- production of hydraulic lime;
- obtainment of siliceous sand;
- production of the mortar through the homogenization of aggregates and binder;
- packaging and storing of dry mortar sacks.

For the transportation of the materials, a distance of 50 km – a commonly used mean distance – was hypothesized.

Production of 2HL

The production stages of 2HL are reported in the diagram in figure 2. The following processes were considered:
- obtainment of limestone, including the quarrying and its transportation to the factory;
- production of hydraulic lime;
- obtainment of siliceous sand;
- production of AAC recycled aggregates by milling the AAC off-cuts;
- production of the mortar through the homogenization of aggregates and binder;
- packaging and storing of dry mortar sacks.

It can be noticed that all the phases related to the production of AAC off-cuts were not present in the LCA of the experimented mortar: in fact, they can certainly be classified as materials from an external pool, as they constitute *residual resources* of another production, which are not specifically realized for this purpose; rather, their use in the experimented mortar prevents landfilling as an end-of-life, which would lead to further environmental impacts, instead to be deducted from the LCA. Likewise, a distance of 50 km for transportation was considered for all the materials except for AAC aggregates, for which no transportation was applied: this follows the hypothesis of the combined production of AAC and of the experimented mortar, in the same establishment where the off-cuts are milled and recycled.

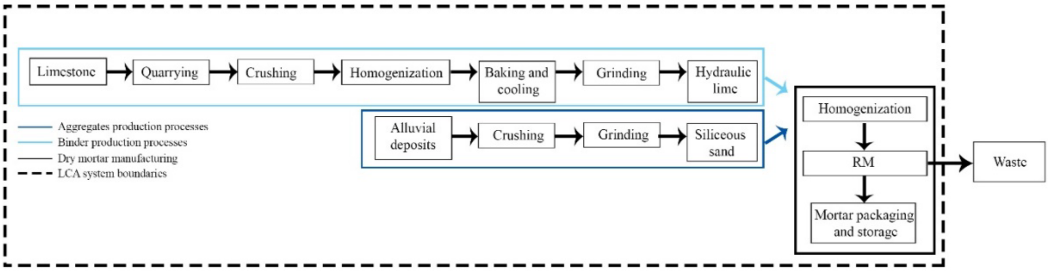

Figure 1. System boundaries of the reference mortar (RM) LCA are represented

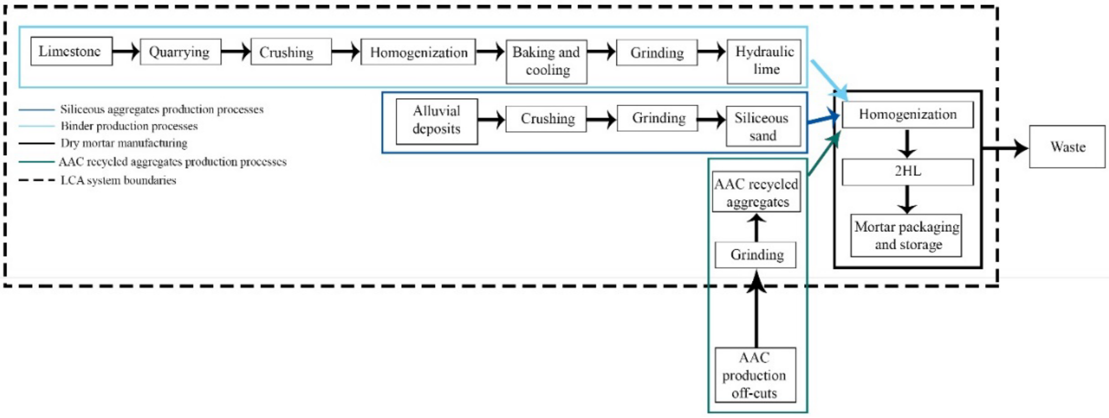

Figure 2. System boundaries of the experimented mortar (2HL) LCA are represented

3.3 Economic analysis

The economic assessment is exemplified in Italy, in order to take into account local parameters – such as regulations and market characteristics – that contribute to the realism of its practical consequences. The choice to hypothesize the possibility that AAC manufacturers produce a new commercial line by recycling the off-cuts of their main productive process moves from the individuation of two advantages: one is a common trend in the building industry, and is constituted by the advantage in the re-use of materials, reducing the economic expenditure – in addition to the environmental impact – of natural resources; the other one is quite specific for AAC, and is related to its higher cost of landfilling. Since it contains gypsum its waste belongs, according to Italian regulations, to the class of disposal CER 170802, to which a cost of disposal of 0.60 €/kg corresponds; compared to general construction waste, which normally belongs to CER 170904 – with a cost of 0.20 €/kg – it is three times higher. Considering that each 25 kg sack of 2HL premixed mortar contains 2.34 kg of AAC, its production avoids for the producer a cost of 1.40 €, which can be added to the net profit related to the sale of the product.

The definition of the net profit includes, on the other hand, a non-negligible degree of uncertainty and variability. In particular, the variables are related to:

- actual future desirability of the product;
- manufacturer's market networks;
- geographical collocation of the establishment;
- density of competitors in the area;
- dynamic variations in the market sector.

The mortar 2HL is designed as a mortar for masonry for non-structural uses, which then constitutes the target market for this product. According to ISTAT, the Italian National Institute of Statistics, the gross income related to the production of mortar in Italy in 2019 was 512,000,000 €; according to the same source, 14,452,680 buildings are present in Italy, and data on its composition are only available for the residential sector, which however constitutes the 84.3% of the total (12,187,698 buildings), therefore the percentage can be extended to the whole building asset. So, since in the residential sector 6,975,977 are made in masonry, it can be considered that 57.2% of Italian buildings are masonry buildings. Finally, considering that mortars for structural uses constitute the 20% of the demand, it can be concluded that the 45.76% of the production of mortar belongs to the target market, which then has an economic weight of 234,291,000 €.

The introduction of a new type of mortar with more sustainable characteristics has a partially surrogate value in relation to existing typologies of dry premixed mortars for masonry, though it is characterized by the advantaged of being partially constituted by recycled materials, an aspect that contributes to fulfil the CAM, Italian Minimum Environmental Criteria which require a minimum percentage of recycled materials in interventions and new constructions; thanks to this aspect it can be assumed that, by keeping the same mean unitary value of similar products in the market – which, following a market analysis, was established to be 0.12 €/kg, then 3 €/sack – it can reach a satisfying market share, proportionally to the number of competitors. At the same time, in European countries the 55% of the premixed dry mortar industry is owned by the top 10 producers [15], then applying this paradigm to the Italian market, where 45 producers have been detected, it can be roughly hypothesized that 45% of the industry is divided among 35 manufacturers, to each of whom a proportional market share belongs.

The last term to consider is the investment needed to start the production line, which should be recovered in a period of 10 years, usually considered as an acceptable pay-back time. Concerning this aspect, the analysis was split into the two possible scenarios, respectively: of an AAC manufacturer who does not produce premixes (Scenario a hereafter), and of one who does produce premixes, but without recycled aggregates (Scenario B hereafter). The partial investments are constituted by a grinding machine with a minimum section of 1.08 m^3, which is the dimension of AAC off-cuts, which has been found to have a cost of 80,000 €, and mixing and homogenization machineries for mortar packaging, which are only necessary for the first scenario, as they are already available in the second one, and have a total cost of 30,000 €. In order to evaluate the pay-back time, the cash flows were anticipated by adopting the latest interest rate by Banca d'Italia, equal to 7.12%. In order to provide a qualitative evaluation of the feasibility of these two investment scenarios, the minimum mean annual income was evaluated by applying an inverse formula of economic discount, considering a 20% net profit, which results in 0.6 €/sack.

4. Results and discussions

4.1 Dry and wet proportioning of RM and 2HL

Table 2 shows the results obtained from equation (1) by using the parameters of Table 1. The results underlined an exiguous variation of binder content to m^3 of mortar which can be neglected, as the binder was 0.6% higher in 2HL than in RM. The water-binder ratio was similar for both of the mixes: since this index is directly proportional to the durability of mortars and concretes [16][17], the durability of 2HL -which has not been tested yet- can be hypothesized the same as RM, for which the aforementioned parameters are reported on the technical sheet. The substitution of the sand with AAC in 2HL resulted in a consistent reduction of the total mass of the fresh-state mortar. Actually, the AAC aggregates density is 46% lower than the siliceous sand one: this guaranteed in 2HL, with the same proportion by volume of aggregates to m^3 (0.64 in both cases), the reduction of 6% of the mass resources to m^3. The 2HL mix design lowered the siliceous sand of about 217 kg to m^3 of wet mortars, or equivalently of 3 kg to 25 kg of dry mortar, driving to a natural resources-saving of 21% and 16%, respectively. a higher percentage of AAC, in order to increase the sustainability of the mortar, has been already tested: the lower density of the mortars, however, decreased the compressive strength of the mixes and they were not suitable to masonry applications [18].

Table 2. (a) Mix composition of 1 m^3 of wet RM and 2HL; (b) Mix composition of 25 kg of dry RM and 2HL

(a)	B		SS		AAC		Water	
	kg	m^3	kg	m^3	kg	m^3	kg	m^3
RM	308.1	0.12	1031.2	0.64	///	///	241.1	0.24
2HL	310.1	0.12	814	0.50	116.3	0.14	239.9	0.24

(b)	B		SS		AAC	
	kg	dm^3	kg	dm^3	kg	dm^3
RM	5.75	2.21	19.25	11.96	///	///
2HL	6.25	2.40	16.41	10.19	2.34	2.73

RM: reference mortar; 2HL experimented mortar; B: binder; SS: siliceous sand; AAC: Autoclaved Aerated Concrete recycled aggregates.

4.2 LCA analysis

The diagram of figure 3 reports the results of the LCA through the total eco-points scored by RM and 2HL. In the latter, the substitution of about 22% of the sand volume with AAC resulted in a UBP value 15% lower than the RM one. In order to further analyse the two mortars, the diagram in figure 4 was developed. It charts the eco-points for each of the impact categories of the methodology Ecological Scarcity Method. In particular, the UBP were assessed for the emissions into the environmental components of air, surface water and top-soil and for the depletion of energy and natural resources. As reported in figure 4, the more consistent variations were observed in the emissions into air and in the depletion of natural resources. Actually, the UBP values of RM in these two categories were about 21% and 19% higher, respectively, than 2HL ones. This result underlines the key-role played by the use of recycled aggregates instead of natural ones in the production of low-carbon footprint building materials. The manufacturing processes which employ recycled resources and industrial by-products or waste are particularly useful to the goal of low emissions and concentrations of hazardous gases [19]. Moreover, the transportation of raw materials from their locations to the factory highly affects the emissions into the air [20]. The AAC off-cuts, which could be immediately available *in situ* to the manufacturer of both AAC bricks and premixes, reduce the mass of aggregates to be moved. Finally, the substitution of natural aggregates with recycled AAC allows preserving the resources whose scarcity is progressively increasing. Moreover, the experimented mortar exhibited a reduction of about 13% of emissions into surface water while the emissions into top soil of the two mortars were similar: 2HL allowed a moderate improvement as its UBP was 3% lower than RM one. Conversely, the energy resources consumption of 2HL process was 14% higher than RM.

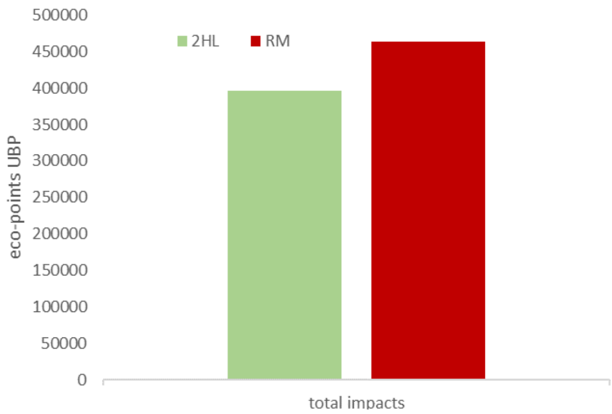

Figure 3. LCA analysis of RM and 2HL: UBP values of total environmental impacts are charted

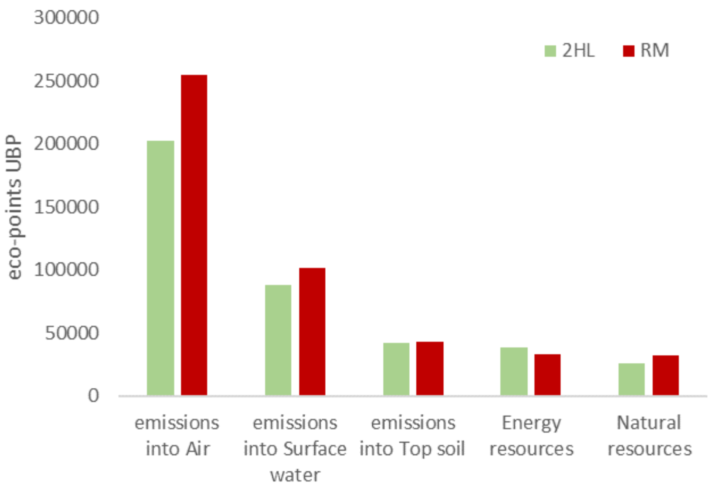

Figure 4. LCA analysis of RM and 2HL: UBP values of environmental impacts in emissions and resources consumption are charted.

4.3 Economic analysis

In the first scenario, the minimum mean number of produced sacks per year is 3.688, while in the second scenario it is 2.682. Table 3 reports the details of the saving related to the avoidance of landfilling for AAC off-cuts, net profit from the sale, and minimum annual profit, the consequent number of sold sacks per year and consequent income and the related market share in the two scenarios.

Table 3. Parameters of the economic analysis of the introduction of a production line of mortar with recycled AAC aggregates

	SL	NP	NS	AP	AI	MS
	€/sack	€/sack	n	€	€	%
Scenario A	1.4	0.6	3.688	7.390	11.066	0.010
Scenario B			2.682	5.375	8.049	0.008

SL: unitary saving from the avoidance of landfilling; NP: unitary net profit from sale; NS: minimum number of sold sacks per year; AP: minimum annual profit; AI: minimum annual income; MS: minimum market share

In both scenarios, the market share that results from calculations is characterized by a very low entity: considering 35 minor competitors, this is certainly a realistic threshold. Certainly, despite the slight numerical difference, the manufacturer from Scenario B is already present in the market, and so his perspectives of the required reception on the market are more likely to be fulfilled. Aside from this observation, in both cases, the possibilities to restore the initial investment in a period of 10 years can be claimed to be realistic.

5. Conclusions

The paper suggested an approach to the green design that blends together the synergies that can help in making practical applications possible and widespread. The role of the manufacturer – which was the main focus both in the definition of the LCA boundaries and in the perspective and purpose of the economic analysis – has a central function in a more massive spread of sustainable solution in the construction industry.

In accordance with the results of the dry and wet proportioning and the previous research stages, the paper demonstrates that it is possible to design a sustainable pre-mixed mortar - with a partial substitution of the natural aggregates with AAC off cuts – suitable to masonry applications. Actually, 2HL and RM were formulated with the same binders, the volume of aggregates per m^3 and water-binder ratio and their compressive strength was comparable. The use of AAC, which is less dense than sand, implied the reduction of resources per m^3 of about 6%: the formulation of 2HL can allow to save natural scarce resources and to cut the energy consumptions related to the aggregates transportation from their location to the manufacturing site.

The LCA analysis of the two mortars underlined that 2HL formulation lowers the emissions into three environmental components and the resources consumption. These results suggest that the reuse of AAC bricks off-cuts as aggregates for pre-mixed mortars – otherwise landfilled- can allow the AAC manufacturers to develop a "green" building material and to avoid the disposal costs of the industrial by-products. However, further studies are needed to define more deeply the crushing and grinding processes of AAC bricks to make them suitable to mortars, as regards – in particular – the energy consumptions related to the mechanical transformation of AAC in order to have the appropriate grain size distribution.

The economic analysis provided the magnitude required to affirm that an investment aimed to place a more sustainable product, as is the experimented one, on the market and to reduce waste would also be widely recovered in an acceptable period, despite a certain degree of uncertainty that could be covered by future, more detailed market analyses and case studies on the specific market sector. However, it can be noticed that, for each functional unit of product, the economic benefit deriving from the reuse of off-cuts instead of landfilling is even higher than the net income related to the sale of the mortar itself, providing hints for the necessity to find alternative 'after-life' solutions for other products with a high expense for landfilling.

References

[1] W. J. Park, T. Kim, S. Roh, and R. Kim, "Analysis of life cycle environmental impact of recycled aggregate," *Appl. Sci.*, vol. 9, no. 5, 2019.
[2] M. U. Hossain, C. S. Poon, I. M. C. Lo, and J. C. P. Cheng, "Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA," *Resour. Conserv. Recycl.*, vol. 109, pp. 67–77, 2016.
[3] J. M. Mankelow, D. Oyo-Ita, and M. Birkin, "Assessing the Carbon Footprint of Transporting Primary Aggregates," *Proc. 15th Extr. Ind. Geol. Conf. EIG Conf. Ltd*, pp. 41–45, 2010.
[4] M. Barbuta, R. D. Bucur, S. M. Cimpeanu, G. Paraschiv, and D. Bucur, "Wastes in Building Materials Industry," *Agroecology*, no. June, 2015.
[5] S. Jesus, C. Maia, C. Brazão Farinha, J. de Brito, and R. Veiga, "Rendering mortars with incorporation of very fine aggregates from construction and demolition waste," *Constr. Build. Mater.*, vol. 229, 2019.
[6] J. Silva, J. de Brito, and R. Veiga, "Recycled red-clay ceramic construction and demolition waste for mortars production," *J. Mater. Civ. Eng.*, vol. 3, no. 22, pp. 236–244, 2010.R. A. Robayo-Salazar, J.
[7] B. Tewar, P. M. Shah, and P. B. Patel, "Effect of Partial Replacement of Sand with Wastage of Manufactured AAC Block in Concrete," *Mater. Today Proc.*, vol. 4, no. 9, pp. 9817–9821, 2017.
[8] B. Coppola, L. Courard, F. Michel, L. Incarnato, P. Scarfato, and L. Di Maio, "Hygro-thermal and durability properties of a lightweight mortar made with foamed plastic waste aggregates," *Constr. Build. Mater.*, vol. 170, pp. 200–206, 2018.
[9] M. C. S. Nepomuceno, R. A. S. Isidoro, and J. P. G. Catarino, "Mechanical performance evaluation of concrete made with recycled ceramic coarse aggregates from industrial brick waste," *Constr. Build. Mater.*, vol. 165, pp. 284–294, 2018.
[10] J. De Brito, A. S. Pereira, and J. R. Correia, "Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates," *Cem. Concr. Compos.*, vol. 27, no. 4, pp. 429–433, 2005.

[11] C. Jiménez, M. Barra, A. Josa, and S. Valls, “LCA of recycled and conventional concretes designed using the Equivalent Mortar Volume and classic methods,” *Constr. Build. Mater.*, vol. 84, pp. 245–252, 2015.

[12] ACI 211.1-91 Standard practice for selecting proportions for normal, heavyweight, and mass concrete. 2002.

[13] R. Frischknecht and S. Büsser Knöpfel, “Swiss Eco-Factors 2013 according to the Ecological Scarcity Method,” *Fed. Off. Environ. FOEN*, p. 256, 2013.

[14] G. M. Cuenca-Moyano, S. Zanni, A. Bonoli, and I. Valverde-Palacios, “Development of the life cycle inventory of masonry mortar made of natural and recycled aggregates,” *J. Clean. Prod.*, 2017.

[15] L. Ferdinand, “The global drymix mortar industry”, *ZKG International*, 2010.

[16] N. Hani, O. Nawawy, K. S. Ragab, and M. Kohail, “The effect of different water/binder ratio and nano-silica dosage on the fresh and hardened properties of self-compacting concrete,” *Constr. Build. Mater.*, 2018.

[17] Y. Y. Kim, K. M. Lee, J. W. Bang, and S. J. Kwon, “Effect of W/C ratio on durability and porosity in cement mortar with constant cement amount,” *Adv. Mater. Sci. Eng.*, vol. 2014, 2014.

[18] M. Nicolella, C. Scognamillo, and F. Vitale, “Compatibilità e sostenibilità degli interventi di retrofit energetico su edifici tutelati,” in *I centri minori… da problema a risorsa Strategie sostenibili per la valorizzazione del patrimonio edilizio, paesaggistico e culturale nelle aree interne. Small Towns...from problem to resource. Sustainable strategies for the valorisation of building, land*, FrancoAnge., Milano, pp. 1277–1286, 2019.

[19] R. Robayo-Salazar, J. Mejía-Arcila, R. Mejía de Gutiérrez, and E. Martínez, “Life cycle assessment (LCA) of an alkali-activated binary concrete based on natural volcanic pozzolan: a comparative analysis to OPC concrete,” *Constr. Build. Mater.*, vol. 176, pp. 103–111, 2018.

[20] S. H. Teh, T. Wiedmann, A. Castel, and J. de Burgh, “Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia,” *J. Clean. Prod.*, 2017.