Eco-mechanical indexes for sustainability assessment of AAC blocks

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Eco-mechanical indexes for sustainability assessment of AAC blocks

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Abstract. This paper aims to provide a proper set of eco-mechanical indexes to evaluate both the mechanical performances and the environmental features of autoclaved aerated concrete blocks. To this purpose, a detailed review of existing sustainability indexes − originally developed for concrete − is first presented, and subsequently different possible eco-mechanical indexes are specifically developed for autoclaved aerated concrete masonry blocks, also in order to compare their performances with those of lightweight aggregate concrete blocks. The obtained results highlight that, based on currently available information, only few parameters appear to be effective in defining the overall sustainability performances of AAC blocks. While several researches were indeed carried out in these last years regarding material structural properties, there is still a lack of environmental data, which should be necessarily deepened in future research work to obtain more reliable results.

Keywords: Autoclaved Aerated Concrete, Eco-Mechanical Indexes, Ecological Performances, Mechanical Performances, Concrete Masonry.

1. Introduction

In the present work eco-mechanical indexes are proposed for the sustainability assessment of Autoclaved Aerated Concrete (AAC) blocks.

AAC material was introduced in the construction market since the mid-1920's, when the production process was patented. The material is obtained from a mix of sand, cement, water, gypsum, lime, and aluminum powder, which are poured in molds. Chemical reactions between aluminum, calcium hydroxide and water cause the production of hydrogen bubbles, which give the characteristic porosity of the material. When the material is sufficiently hardened, it is cut in blocks or panels. Their subsequent treatment in autoclave at 180 °C and 10 bar for 8-10 hours transforms sand and calcium hydroxide into calcium silicate hydrate (tobermorite), improving the mechanical properties of the material.

Porosity of AAC causes low compression strength (1-6 MPa) compared to normal-weight concretes, but permits to reach low density (about 350-800 kg/m^3) and interesting thermal properties (in terms of conductivity coefficient λ). As an example, AAC blocks with a density approximately equal to 400 kg/m^3 can reach thermal conductivity values that can be 10-20 times lower than normal-weight concrete [1]. Therefore, in some countries AAC blocks permit to build external walls (having or not a bearing function) without adding an extra-layer of insulation, thus reducing costs and environmental impact. Furthermore, contrary to multilayered walls, recycling AAC blocks is quite simple, since site waste and rubble can be broken up, ground into powder and re-used in the manufacturing process [2]. For these reasons, AAC is gaining an increasing interest in the construction market as a valuable alternative in the manufacturing of products that are at the same time thermally attractive and characterized by a good construction efficiency.

In more details, AAC blocks are nowadays often used for the realization of non-structural walls (cladding and infill panels) within concrete frame structures, especially in seismic regions. In fact, the low specific weight of the material permits a reduction of seismic masses and, consequently, of seismic actions. Usually, this allows to save concrete and reinforcement of the structures with economic and environmental benefits. As a consequence, the advantages related to the use of AAC for external and partitioning walls should be evaluated considering the whole building, including structures. Some proper software tools have been proposed in the literature to the scope [3]. Since results depend on the features of the building, and on its geographical position, several representative case studies should be analyzed to obtain general conclusions. An analysis of this type could provide useful information on the importance of the involved variables, their relationships and weights. However, such a type of analysis is not so easy to be performed and is very time consuming.

AAC blocks are also used for bearing walls in low-to-medium rise masonry buildings in seismic and non-seismic areas [4-8]. Because of their low density, the size of the blocks can be large: this permits faster masonry work and a reduction of the number of mortar joints, which are usually thin.

In the present work, the attention is exactly focused on the use of AAC for masonry load bearing walls. The paper represents a first attempt in trying to provide a quick practical tool for the evaluation of material efficiency (in terms of both structural and environmental performances), also with respect to other alternative solutions, like blocks in lightweight aggregate concrete (LWAC), with or without integrated insulation. To the purpose, eco-mechanical indexes are introduced (see, e.g. [9] for a comprehensive review). This approach, first presented by Damineli et al [10] and subsequently modified by Fantilli and Chiaia [11] and Chiaia et al. [12], is commonly adopted for the sustainability assessment of concrete elements, through a concurrent combination of green aspects and mechanical properties.

As a first step of an ongoing research carried out by the Authors (focused on the definition of structural and environmental performances of AAC blocks), the concept of eco-mechanical index is herein extended to the case of AAC, starting from the work by Fantilli and Chiaia [11]. The attention is mainly concentrated to the individuation of the most significant variables to be considered, especially when indexes are adopted as a preliminary tool to choose the best construction strategy among different alternatives, like AAC vs. LWAC blocks.

2. Assessment of AAC performances through the definition of ecological and mechanical indexes

The assessment of sustainability performances of a given construction solution requires the introduction of a new holistic approach, which considers concurrently environmental and mechanical requirements. The building industry is currently touched by the ongoing sustainability debate, which is particularly vital for concrete structures, as the production of this material is responsible of a high energy consumption and causes large emissions of CO_2 [13]. An increasing sustainability of building structures therefore requires a reduction of the environmental impact associated with raw materials production, as well as with building erection, maintenance and operation processes. Moreover, an increase of the durability of the structure at its maximum technical performance is also desirable. For these reasons, environmental aspects must be considered along with other “classic” design aspects, such as strength and ductility requirements.

2.1 Eco-mechanical indexes overview

In case of traditional concrete structures, environmental issues have been recently addressed through the definition of proper sustainability indexes (among others, e.g., [10-12, 14-19]). As a generic statement, a set of environmental and mechanical indexes should be first evaluated and compared:

$$\text{Material sustainability potential} = \frac{\text{lifetime performance}}{\text{environmental impact}} \; . \tag{1}$$

This definition [18] addresses clearly the three basic pillars of sustainability – considering the environmental aspects, expressed by the environmental impact, as well as social and economic aspects, embodied in the lifetime and performance parameters.

Broadening the basic pillars of sustainability, the objective of conciliating environmental with economic and social demands into the building sector have been chased since the early 2000s by the research group of Pons et al [19]. They have been working in this direction in order to define a general model for a complete sustainability analysis of concrete structures, named MIVES. MIVES is a Multi-Criteria Decision Making method able to consider all sustainability aspects, including economic, environmental and social ones, and incorporating a value function to homogenize all the indicators and consider the degree of satisfaction. Within MIVES framework, a Sustainability Index SI is defined according to Equation 2:

$$SI = V(P_x) = \sum_{i=1}^{N} \alpha_i \, \beta_i \, \gamma_i \, V_i(P_{i,x}) \; , \tag{2}$$

where $V(P_x)$ measures the degree of sustainability (value) of the alternative x weighed with respect to various criteria $P_x = (P_{1,x}; P_{2,x}; \ldots ; P_{N,x})$ considered; α_i are the weights of each requirement i, β_i are the weights of each criteria i and γ_i are the weights of the different indicators i. These weights are the preference, respectively, of these requirements, criteria and indicators. $V_i(P_{i,x})$ are the value functions used to measure the degree of sustainability of the alternative x with respect to a given criterion i.

Nevertheless, in the most of the real cases, social and economic aspects related to building construction and management are extremely arduous to be evaluated, especially during the preliminary design stage or even before, during the developing of the optimum mix-design of the raw materials. On the contrary, Equation 1 offers a simple way to assess the advantages and disadvantages of a certain material, taking into account its mechanical properties (lifetime performance), as well as its potential as a sustainable solution (environmental impact).

Based on this concept, simplified Eco-Mechanical Indexes (EMIs) were developed in recent years, as better discussed in [11]. These indexes were devoted to an easy and quick identification of the most virtuous construction solutions, characterized by the lower embodied energy and resource consumption, while ensuring adequate structural performances. EMIs were exclusively developed for structural concrete, as a tool for improving the mix-design of the material, so as to obtain a good balance between mechanical and ecological aspects. In more detail, a generic eco-mechanical index can be defined as:

$$EMI = \frac{MI}{EI} \tag{3}$$

where MI = Mechanical Index and EI =Ecological Index.

In the first works on this topic, MI comprised just the compressive strength of concrete, while other parameters were neglected. However, according to *fib* Bulletin 67 [14], concrete properties should be combined with structural performances, so including not only concrete strength, but also the results of other structural tests on materials. Similarly, EI was initially simply related to CO_2 emissions.

Based on these considerations, Chiaia et al [12, 17] proposed an improvement of Equation 3, by introducing also other significant mechanical and ecological parameters in the evaluation of MI and EI, and linking them through proper correlation functions *g()* and *f()*:

$$EMI = \frac{f(MI)}{g(EI)}. \tag{4}$$

The correlation functions could be either a simple product of the different parameters, each one multiplied for a proper weighting coefficient, or logarithmic functions, so to take into account that the considered parameters could be of different order of magnitude [12].

2.2 Evaluation of ecological parameters for the definition of the ecological index EI

According to *fib* Bulletin 67 [14], the most crucial aspect in the determination of the ecological index *EI* is to define which environmental parameters should be taken into account to evaluate the sustainability of a given structure. So far, scientific investigations have been conducted only for structural concrete elements, while there is a lack of information specifically focused on AAC and LWAC masonry blocks.

According to several researchers and code rules [10, 15, 20], the most relevant ecological parameters are CO_2 footprint, embodied energy and water consumption used to produce concrete, but also other available parameters, such as biodiversity, toxic substances, resource depletion, as well as raw materials, electricity, safety, total cost and thermal conductivity can be use in the definition of *EI*. Consequently, the proposal of a general evaluation method for concrete blocks (AAC or LWAC) should first aim at determining the environmental impact in a standardized manner, using the so-called "eco-balance", as described in the European standards EN ISO:14040: 2006 [21], ISO 14044: 2006 [22], ISO 21930: 2007 [23]. The impact of every substance released to the environment can be so ascribed to one of the different impact categories, which have been internationally accepted.

Table 1 gives an overview on the most widely used environmental impacts for typical concrete blocks. For every country, exact data on a specific concrete block (included AAC and LWAC ones) can be derived from the Manufactures, using the Environmental Product Declarations EPD, that involves a Life-Cycle Assessment (LCA) for the evaluation of environmental aspects. CO_2 footprints (GWP), Embodied Energy (TNRE) and water consumption (W) of concrete components could be otherwise taken from environmental databases; however, in this work it has been preferred to directly derive these data from EPDs of Manufactures.

Among a very large variety of LCA parameters (see Table 1), it is first necessary to individuate the most significant factors to be included in the evaluation of the Environmental Index *EI* for the considered material. Comparative studies have shown that the environmental impacts of AAC manufacture are dominated both by the use of thermal energy and the connected emissions, and by bonding agent manufacture. Quicklime and cement manufacture are indeed based on energy-intensive combustion processes, that are responsible of relevant CO_2 emissions.

Table 1 Environmental data for assessing AAC ecological performances.

Parameter	Unit	
Global warming potential	(kg CO_2-Eq.)	GWP
Total non-renewable primary energy	(MJ)	TNRE
Cumulative energy demand (renewable)	(MJ)	TRE
Acidification potential of land and water	(kg SO_2-Eq.)	AP
Abiotic depletion potential for fossil resources	(MJ)	ADP
Depletion potential of the stratospheric ozone layer	(kg CFC_{11}-Eq.)	ODP
Use of secondary materials	(kg)	RM
Use of net fresh water resources	(m^3)	W
Non-hazardous waste disposed	(kg)	NHW
Hazardous waste disposed	(kg)	HW
Radioactive waste disposed	(kg)	RW
Components for re-use	(kg)	SM

The Global Warming Potential (GWP) associated to the production of 1 m^3 of AAC is indeed dominated more than 90% by carbon dioxide emissions, which are mainly originated from the manufacturing process and the production of thermal energy from natural gas. More than 2/3 of carbon dioxide emissions can be attributed to bonding agent manufacture and this is divided equally between quicklime and cement manufacture. Nonetheless, the manufacture of AAC requires less energy than other masonry products, thereby reducing the use of fossil fuels and associated emissions of carbon dioxide.

Acidification Potential (AP) from the manufacture of 1 m^3 of non-reinforced AAC is dominated up to 50% by sulphur dioxide emissions and to 40% by nitric oxides. Around 1/3 of the AP comes from the energy provision processes for manufacturing, while the production of quicklime and cement bonding agents causes around 40% of the AP.

Looking at the Embodied Energy, in case of AAC it is more appropriate to refer to Total Non-Renewable Primary Energy (TNRE). The dominance of the non-renewable energy produced in the works and used during the process of manufacturing of AAC blocks is indeed evident in this impact category: more than 1/3 of the Total Non-Renewable Primary Energy is directly caused by thermal energy requirements.

Secondary Raw Materials (RM) are not generally used during manufacture, neither secondary fuels. Moreover, all production offcuts are fed back into the production circuit; hence, RM parameter could not be taken into account for defining ecological index *EI* for AAC.

With regards to the use of fresh water (W), about 1/3 of total water amount is used in manufacture of AAC and it is mainly imputable to the electricity supply pre-chains. A further 1/3 is attributable to quicklime and cement production, and the proportion of direct water requirement for AAC manufacture directly in the plant is less than 1%.

Finally, the overall assessment of the accumulation of wastes, accounting for non-hazardous and hazardous ones (including mining waste materials, mineral processing residues, municipal waste and the domestic refuse, and commercial waste contained therein), needs to be evaluated. Non-Hazardous Waste NHW represents the greatest proportion in AAC production. Mining waste materials accumulate mainly in the electricity supply pre-chain from extraction of energy sources and also in the bonding agent manufacture pre-chains during raw material and energy source extraction. Radioactive waste accumulates exclusively through electricity production in nuclear power plants, therefore it is negligible for the considered case.

Based on this discussion, it is clear that several ecological LCA parameters reported in Table 1 can be neglected for the scope of this work. The most suitable parameters to be considered in the definition of eco-mechanical indexes for AAC blocks are only those summarized in Table 2.

Table 2. Environmental properties selected for the definition of *EI*.

Selected Parameter for EI	Unit	
Global warming potential	(kg CO_2-Eq.)	GWP
Total non-renewable primary energy	(MJ)	TNRE
Acidification potential of land and water	(kg SO_2-Eq.)	AP
Abiotic depletion potential for fossil resources	(MJ)	ADP
Use of net fresh water resources	(m^3)	W
Non-hazardous waste disposed	(kg)	NHW
Hazardous waste disposed	(kg)	HW

It should be however noted that the greatest limitation of the data reported in the Environmental Product Declarations for AAC and LWAC is that they are obtained considering as system boundary for LCA only the life-cycle phases of product manufacture (module A1-A3), while product installation (module A4-A5), the use stage (module B) and the disposal (module C) are not considered. This constraint is relevant since currently there is a global lack of a Cradle to Gate evaluation both for AAC and for LWAC blocks.

2.3 Evaluation of mechanical parameters for the definition of the mechanical index MI

Mechanical indexes can be conceived as synthetic parameters representative of the sustainability of the investigated material referring to social aspects [24]. Since AAC blocks are often used for the realization of load bearing masonry walls both in seismic and non-seismic areas, it is indeed crucial that their characteristics are able to secure adequate safety and serviceability (i.e. durability) margins to the resulting structure, so ensuring a satisfactory building performance. This means that the reduction of environmental impact in the design and production of the blocks should not compromise the mechanical performances of the material, and that the final product should be anyway characterized by well-defined mechanical properties.

Generally speaking, for masonry structures the most important mechanical property is the compressive strength f_c, which should be declared by Producers on the technical sheets of the block. To some extent, also the post-peak energy absorption capacity in compression (or, equivalently, the fracture energy in compression G_{fc}) can be a parameter of interest, since it is related to structural ductility. This is particularly true when it is necessary to evaluate the performances of new "recipes" with respect to more traditional solutions, like for example Fibre-Reinforced Aerated Concrete (FRAC) in spite of plain AAC. In this case, the effects related to the addition of short polymeric fibres in the admixture can be indeed hardly quantified by only measuring the material strength, since the latter is only slightly modified by the presence of fibres, and it also depends on the adopted curing procedure, which is different for FRAC and AAC (in the production of FRAC, the autoclaving process is substituted by curing at room temperature, to avoid fibre potential damage). The optimization of fibre amount in the admixture can be then evaluated by examining the post-peak response, since the presence of fibres increases the ductility, by reducing at the same time the crack opening.

However, the determination of the post-peak energy absorption capacity in compression is not so straightforward, since it requires the knowledge of the complete stress-strain relationship in compression. Traditional compression tests performed during material production and characterization are usually simply aimed at the determination of the pre-peak response of the material, until the reaching of the compressive strength f_c, and are performed under loading control. On the contrary, the determination of the post-peak branch can be only achieved working under displacement control, and also in this case the control of the softening branch can be difficult, especially in case of brittle materials like concretes. For this reason, fracture energy in compression G_{fc} is a parameter that can be certainly taken into account during the research and developing stages for tailoring a new mix-design of a given product, but that can be hardly used in practice for a quick comparison of alternative solutions (like for example AAC and LWAC blocks), since it is not available in the technical sheets of the products and cannot be approximately derived from other material properties.

Even if masonry structures are mainly subjected to compressive stresses, it could be useful to introduce also a parameter related to fracture toughness in the definition of the mechanical index *MI*. As highlighted in several research works and design codes (e.g. [25-29]), toughness exerts indeed a significant influence on the resistance of AAC against damage during transport and handling, and it affects the loadbearing behaviour under accidental or seismic loads. Fracture toughness represents an important material property also in presence of static loads, since it governs crack formation and propagation, and consequently it is strictly related to durability issues. Cracking of AAC walls is indeed a quite common problem, especially in case of building internal partitions, due to floor deformability.

A possible parameter representing fracture toughness, which derives from linear elastic fracture mechanics (LEFM), is the fracture energy in tension G_{ft}. This property is obtained experimentally, from the area under the complete force-crack mouth opening displacement (CMOD) curve. However, in absence of experimental data, G_{ft} can be roughly estimated through empirical expressions, on the basis of other material properties. For example, in case of lightweight concretes (like those used for the realization of LWAC blocks), G_{ft} can be calculated as a function of the mean value of material tensile strength, and depends on the type of sand adopted in the mix [30]. As far as AAC is concerned, only limited information is available, since G_{ft} is affected by autoclaving process conditions [31]; however, an almost linear relation with density can be adopted as a first approximation (as suggested, e.g., in [25, 27, 31, 32]).

3. Determination of mechanical and ecological parameters for AAC blocks

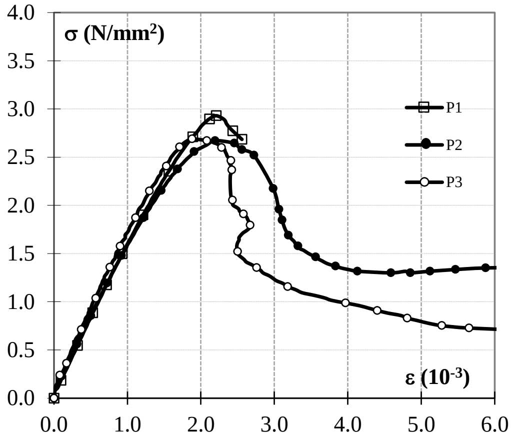
3.1. Assessment of AAC mechanical parameters

In this work, mechanical properties of AAC blocks (to be used for the definition of *MI*) are derived on the basis of the results of experimental tests carried out by the Authors on AAC samples with an average density $\rho \approx 550$ kg/m^3 produced by an Italian Manufacturer (see also [28] for more details about the experimental program).

3.1.1. Experimental characterization of the behaviour in compression. Material characterization in compression is performed on three prismatic AAC specimens with square basis, having an edge length of 40 mm and a height of 80 mm, cut from the central part of AAC blocks.

Compression tests are performed under displacement control, so to get the complete stress-strain curve, as reported in Figure 1a. Average deformations are measured over the whole specimen height, and over a central 25 mm gauge length through 4 LVDTS placed on specimen corners, as shown in Figure 2a. In all cases, failure occurs due to the spreading of diagonal frictional cracks (Figure 2b).

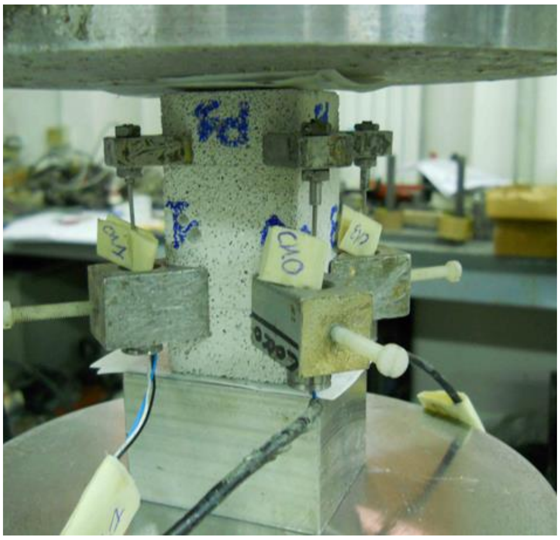
The most important parameters, which define specimen behaviour in the pre and post-peak stage, are the compressive strength f_c, the elastic modulus E_c, the plasticity number k (defined as the ratio between the elastic modulus E_c and the secant modulus from the origin to the peak stress, E_{c1}), and the fracture energy in compression G_{fc}. The corresponding values obtained from the tests are summarized in Figure 1b. It should be noted that the compressive strength obtained from tests on prisms is about 10% lower than that reported on technical sheets provided by Manufacturers, since during production f_c is usually derived from standard cubes cut from AAC blocks, according to UNI EN 772-1 and UNI EN 771-4 ([33-34], see also [28]).



	f_c (MPa)	E_c (MPa)	k (-)	G_{fc} (N/m)
P1	2.93	1581	1.30	4.67
P2	2.67	1549	1.17	7.10
P3	2.69	1700	1.19	4.97
mean	**2.80**	**1610**	**1.22**	**5.58**

(a) (b)

Figure 1. (a) Stress-strain curves resulting from compression tests on AAC prisms; (b) results of the uniaxial compression tests.


(a)

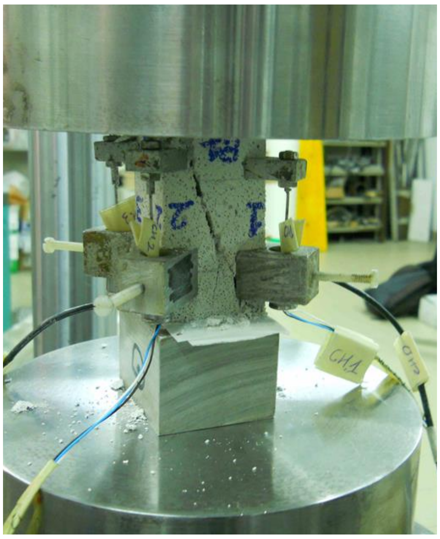
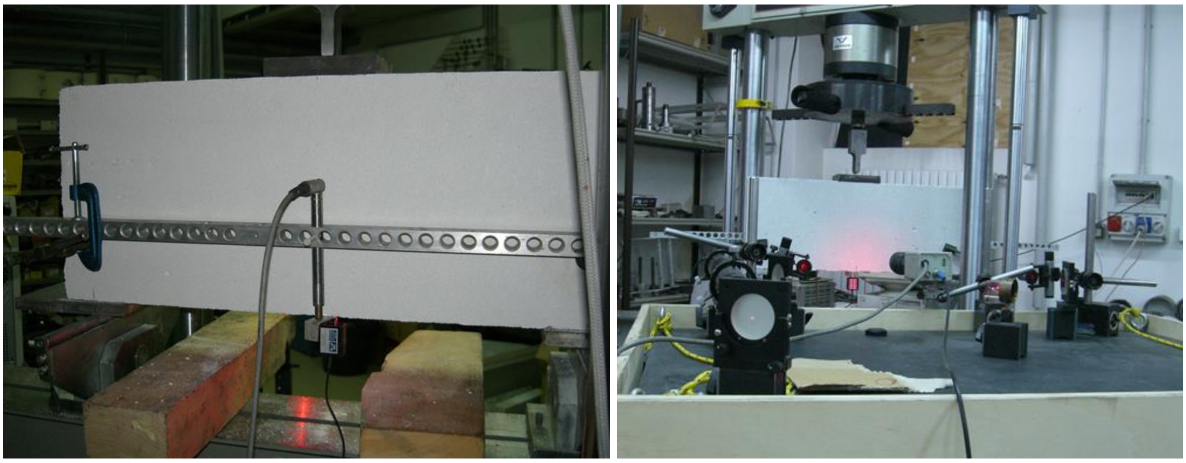

(b)

Figure 2. Compression tests on prismatic AAC samples: (a) test setup; (b) failure mode.

3.1.2 Experimental characterization of the behaviour in tension. The flexural tensile strength $f_{ct,fl}$ and the fracture energy in tension G_{ft} of the material are obtained from three-point bending tests on 3 AAC notched beams, having nominal dimensions L x H x b respectively equal to 620 x 251 x 100 mm. In all cases, the net span of the beams L_n is kept equal to 540 mm, while the average notch height is a = 12.8 mm. These tests are carried out under Crack-Mouth Opening Displacement (CMOD) control (with a speed of 1μm/min), by using an Instron 8862 universal testing machine. In order to measure the midspan deflection δ, a LVDT is applied on a specific device fixed onto supports (Figure 3a); moreover, an ESPI measurement system is used to observe cracking onset and propagation (Figure 3b; see also [28] for more details on the followed procedure).



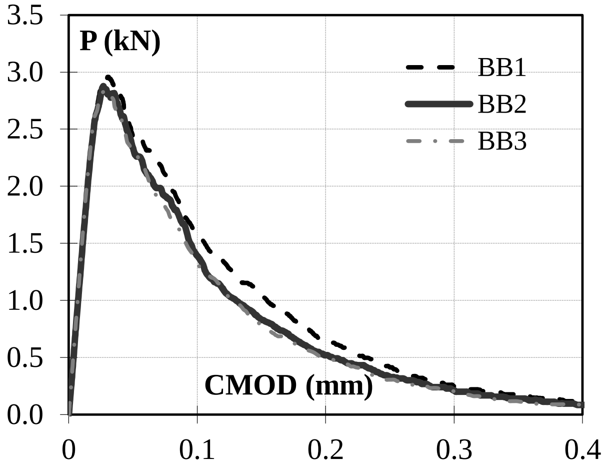
(a) (b)

Figure 3. Three-point bending tests on AAC notched beams: (a) detail of the LVDT used for the monitoring of midspan deflection; (b) ESPI setup.

Figure 4a reports the load-CMOD curve for the three investigated specimens, while the main mechanical properties defining AAC behaviour in tension and obtained from the tests are summarized in Figure 4b. According to linear elastic analysis, the flexural strength $f_{ct,fl}$ can be deduced as:

$$f_{ct,fl} = \frac{3\,P_u\,L_n}{2\,b\,(H-a)^2} \tag{5}$$

where P_u is the peak load, L_n is the net span of the beam, b is the specimen width, while (H-a) is the distance between the tip of the notch and the top of the cross-section. The same beams without notch tested under three-point bending have provided an higher value of the flexural strength, which is in average equal to $f_{ct,fl}$ = 0.6 MPa [28].



(a)

	$f_{ct,fl}$ (MPa)	G_{ft} (N/m)
BB1	0.42	4.8
BB2	0.40	4.6
BB3	0.39	9.3
mean	**0.41**	**6.2**

(b)

Figure 4. (a) Load-CMOD curves resulting from three-point bending tests on AAC notched beams; (b) summary of the main properties defining AAC behavior in tension, as obtained from the tests.

3.2. Assessment of AAC ecological parameters

As concerns the AAC samples with average density $\rho \approx 550$ kg/m^3 previously presented, no ecological data have been evaluated so far. Thus, the Authors do not have any EPD from the Manufacturer, neither environmental impact data to use for comparison with other AAC blocks. A complete Life

Cycle Assessment for the AAC blocks already characterized from a mechanical point of view is part of an ongoing research carried out by the Authors, and will be ready in the near future.

Meanwhile, the ecological parameters to be used in the definition of the environmental index *EI* presented in this work have been deduced by referring to data available in the literature and relative to comparable typologies of AAC masonry units. In more detail, three different commercial AAC blocks (named AAC1, AAC2 and AAC3 in the following) are chosen on the basis of three main criteria, that is same block thickness (equal to 300 mm), almost equal compressive strength ($f_c \approx 3.4$ MPa, as determined on cubes – being so comparable to that of blocks analysed in Section 3.1), and similar gross density (ranging between $445 \leq \rho \leq 600$ kg/m^3).

Finally, the selected blocks are characterized by thermal conductivity ranging between $0.1 \leq \lambda \leq 0.11$ W/(m·K). This last parameter is particularly interesting and makes AAC an eco-friendly material, since its low value allows to decrease the residential energy consumption and raise the energy efficiency in buildings constructed with AAC blocks. Therefore, external walls made of AAC masonry blocks with distributed thermal resistance can be a promising alternative for increasing the envelope level of thermal protection and decreasing the thickness of required thermal insulation.

4. Application of eco-mechanical indexes to different construction solutions: comparison between AAC and LWAC masonry block performances

As already mentioned, this work tries to summarize AAC performances through the definition of specific ecological and mechanical indexes, which can be combined with each other in order to obtain the most sustainable solution from both a social and an environmental point of view. Specifically, the main goal of the work is to understand which parameters should be considered in the definition of these eco-mechanical indexes, so as to identify a sort of "optimum" expression. Several possible alternative definitions are presented in Section 4.2.

Eco-mechanical indexes can serve two main scopes. First, they can be used in tailoring the mix adopted for the production of material, so as to reduce the environmental impact without compromising mechanical performances, which is crucial especially in case of blocks with a load bearing function. In addition, these indexes can represent a quick and easy tool to perform a preliminary evaluation of the most sustainable solution among different, but alternative construction techniques, such as for example AAC and LWAC masonry units.

Due to the abovementioned lack of original environmental data for the analyzed AAC blocks, the considered eco-mechanical indexes are not applied herein for the improvement of the material, while the attention is instead focused on the comparison among the performances of different concrete products available on the market for the realization of load-bearing masonry blocks in non-seismic areas. Once identified the "optimum" index, it can indeed represent a useful tool for the preliminary identification of the best building solution, orienting the construction workers in the choice of the "most virtuous" block among possible alternatives that seem formally equivalent to each other.

4.1. Eco-mechanical performances of AAC and comparison with other sustainable concrete masonry components

The attention is focused herein on three typologies of concrete masonry units (CMUs), that is to say AAC, LWAC with integrated thermal insulation made of mineral wool (indicated in the following as LWAC1), and LWAC hollow blocks without thermal insulation (named LWAC2).

As far as AAC blocks are concerned, mechanical indexes are defined on the basis of some of the experimental properties discussed in Section 3.1, while environmental parameters are taken from EPDs data of similar products, as discussed in Section 3.2. In this way, three possible solutions, named AAC1, AAC2 and AAC3 are obtained, characterized by the same mechanical parameters (the experimental ones), but with more or less efficient environmental performances (taken from the literature).

The data relative to the two considered LWAC blocks (LWAC1 and LWAC2) are directly taken from their EPDs and technical sheets provided by the Producers. On this point, it should be noted that there is a discrepancy between the amount of available environmental and mechanical parameters: while the first ones are more or less all provided in the technical documents, only the compressive strength of the blocks f_c is generally given. For this reason, in this work the other mechanical properties of LWAC1 and LWAC2 blocks are calculated starting from the declared mean value of f_c (equal to 2 MPa for both the types of units), according to the relationships provided for lightweight aggregate concretes by design codes. In more detail, the elastic modulus E_c and the tensile strength f_{ct} are calculated according to [35], while the fracture energy in tension G_{ft} is obtained according to [30], by hypothesizing that both the LWCAs contain lightweight sand.

Tables 3 and 4 briefly summarize the main data relative to both mechanical and environmental parameters for the 5 considered block typologies. For every block here presented, the selected system boundaries comprise manufacture of the concrete blocks, including the extraction of raw materials and auxiliaries and/or processing aggregates to form the product ready for shipping until it leaves the actual plant, according to the cradle to gate assessment. The results presented in Table 4 thus include the provision of all materials used – preliminary products – (phase A1 of LCA of the system boundary); transport processes to and in the plant (phase A2 of LCA of the system boundary); manufacturing processes including energy, waste, emissions (phase A3 of LCA of the system boundary). The usage and disposal stages of the block manufactured are not taken into consideration in this study, since no data are available for the time being, and therefore need to be supplemented for a further assessment within the context of the building use, when the blocks will be engaged.

Table 3. Mechanical properties of the 5 CMU typologies considered in this work.

	AAC1	*AAC2*	*AAC3*	*LWAC1*	*LWAC2*
ρ (kg/m^3)	445	600	480	450	600
f_c (MPa)	2.8	2.8	2.8	2.0	2.0
E_c (MPa)	1610	1610	1610	596	1060
G_{ft} (N/m)	6.2	6.2	6.2	2.51	2.71

Table 4. Environmental properties of the 5 CMU typologies considered in this work.

		AAC1	*AAC2*	*AAC3*	*LWAC1*	*LWAC2*
GWP	(kg CO_2-Eq.)	2.19E+02	1.68E+02	1.63E+02	8.40E+01	1.19E+02
AP	(kg SO_2-Eq.)	2.19E-01	2.08E-01	2.10E-01	1.59E-01	3.51E-01
ADP	(MJ)	1.70E+03	1.20E+03	1.13E+03	4.14E+02	7.74E+02
TNRE	(MJ)	1.80E+03	1.29E+03	1.21E+03	4.78E+02	8.91E+02
W	(m^3)	7.87E+01	5.28E-01	5.60E-01	n/a	1.39E+02
NHW	(kg)	4.69E+02	8.02E+00	1.56E+01	n/a	1.86E+01
HW	(kg)	n/a	1.10E-02	2.78E-04	n/a	2.58E-02

As concerns the Global Warming Potential (GWP), Table 4 shows that the most valuable block in terms of Low Carbon emission is the LWAC1 one, which registers the smaller amount of KgCO_2 - Eq. GWP is dominated by the processes associated with cement manufacturing, alongside with other essential factors that in case of LWAC1 also includes the impact of thermal insulation and aggregates.

Referring to Acidification Potential (AP), the block presenting the lower impact is once again LWAC1. In this case, AAC blocks register quite similar results, while LWAC2 block is characterized by the highest value of the examined parameter.

LWAC1 appears to be the better option also with regards to Abiotic Depletion Potential (ADP) for fossil resources. This parameter refers to the consumption of fossil resources, which embodies the energetic consumption during the manufacture of cement and aggregates.

As concerns the parameter of Non-Renewable Energy (TNRE) – which takes into account the processes of energy consumption during the manufacture of block, as well as during the manufacture of cement and aggregates – the most environmental responsible block is still LWAC1, having a TNRE just equal to 4.78E+02MJ.

Water consumption (W) registers the lower value in case of block AAC2 having a W just equal to 5.28E-01, but data for LWAC1 are not available.

Finally, Hazardous and Non-Hazardous Waste (HW and NHW) register the aggregated lower value for AAC2, even if some data are not available for AAC1, nor for LWAC1 blocks.

4.2. Application of different eco-mechanical indexes for the evaluation of the sustainability of AAC masonry blocks with respect to LWCA ones

In this Section, the Authors propose some Eco-Mechanical Indexes *EMIs* to assess the global environmental and mechanical performance of AAC blocks with respect to LWAC blocks. The proposed indexes are summarized in the left part of Table 5, which reports the corresponding values obtained for the five considered solutions, based on the mechanical end environmental data reported in Tables 3 and 4. Indexes have been chosen according to the criteria set out in the following.

As regards environmental parameters, GWP and TNRE are always considered in the definition of all *EMI*s, since they are recognized as the most significant Environmental Indexes (*EI*). Similarly, the most important Mechanical Index (*MI*), describing the behavior of blocks in compression, is recognized to be the compressive strength f_c.

The influence of mechanical parameters is investigated through the definition of the first 3 indexes EMI_1-EMI_3, which are characterized by the same denominator (i.e. by the same environmental parameters), while the terms at numerator are varied (that is, f_c for compressive behavior, G_{ft} for tensile behavior, f_c G_{ft} for both of them). On the contrary, indexes from EMI_4 to EMI_8 want to clarify the influence of different environmental parameters, for a given *MI* at numerator (i.e., f_c). Finally, EMI_9 represents a sort of "global index", which includes all the most significant mechanical and environmental parameters at the same time.

Table 5. Proposed eco-mechanical indexes and corresponding values for the considered solutions.

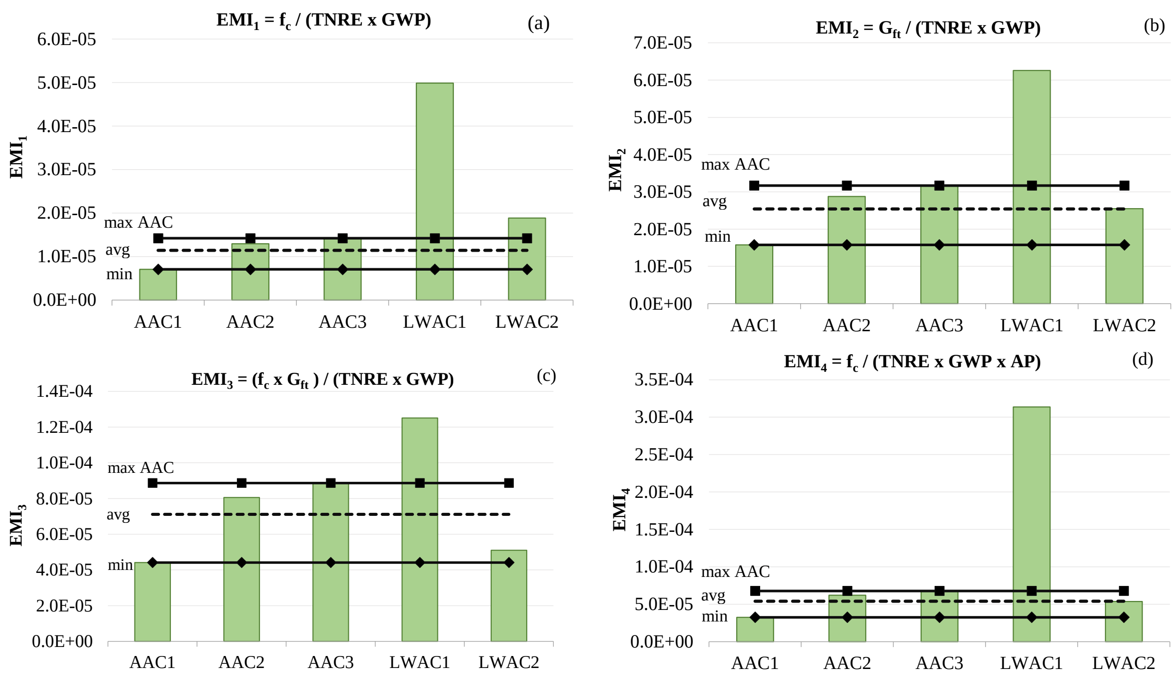
Eco-Mechanical Index (EMI)	Units	AAC1	AAC2	AAC3	LWAC1	LWAC2
$EMI_1 = f_c$ / (TNRE x GWP)	[MPa /(MJ $kgCO_2$-Eq)]	7.08E-06	1.29E-05	1.42E-05	4.99E-05	1.89E-05
$EMI_2 = G_{ft}$ / (TNRE x GWP)	[(N/m) / (MJ $kgCO_2$-Eq)]	1.58E-05	2.88E-05	3.17E-05	6.26E-05	2.55E-05
$EMI_3 = (f_c$ x $G_{ft})$ / (TNRE x GWP)	[MPa (N/m) / (MJ $kgCO_2$-Eq)]	4.41E-05	8.05E-05	8.86E-05	1.25E-04	5.10E-05
$EMI_4 = f_c$ / (TNRE x GWP x AP)	[MPa / (MJ $kgCO_2$-Eq $kgSO_2$-Eq)]	3.23E-05	6.21E-05	6.77E-05	3.14E-04	5.37E-05
$EMI_5 = f_c$ / (TNRE x GWP x W)	[MPa / (MJ $kgCO_2$-Eq m^3)]	8.99E-08	2.45E-05	2.54E-05	n/a	1.36E-07
$EMI_6 = f_c$ / (TNRE x GWP x NHW)	[MPa / (MJ $kgCO_2$-Eq kg)]	1.51E-08	1.61E-06	9.13E-07	n/a	1.01E-06
$EMI_7 = f_c$ / (TNRE x GWP x ADP)	[MPa / (MJ $kgCO_2$-Eq MJ)]	4.16E-09	1.08E-08	1.26E-08	1.20E-07	2.44E-08
$EMI_8 = f_c$ / (TNRE x GWP x HW)	[MPa / (MJ $kgCO_2$-Eq kg)]	n/a	1.17E-03	5.12E-02	n/a	7.31E-04
$EMI_9 = (f_c$ x $G_{ft})$ / (TNRE x GWP x AP x ADP)	[MPa (N/m) / (MJ $kgCO_2$-Eq $kgSO_2$-Eq MJ)]	1.19E-07	3.23E-07	3.73E-07	1.90E-06	1.88E-07

For reading convenience, the same data are plotted in terms of histograms in Figures 5-6. The graphs also report the maximum, minimum and average values of each considered *EMI*, with reference to the 3 different AAC solutions (AAC1-AAC3 in Table 5). As can be seen, even if these three solutions are characterized by the same mechanical parameters and by a comparable density, the environmental performances can differ significantly from each other, depending on the greater or lower "virtuosity" of the Producers. Moreover, the gap between maximum and minimum values is more pronounced when some specific environmental parameters are included in the definition of *EMI*. This is the case of water consumption, as well as of the production of hazardous and/or non-hazardous wastes, which can significantly vary from one Manufacturer to the other.

A more detailed examination of the results reported in Figure 5 leads to the following observations. With reference to index EMI_1 (Figure 5a), it can be stated that all the three AAC solutions, as well as LWAC2, are comparable to each other. LWAC1 clearly shows the best eco-mechanical performance, mainly because its GWP is negligible if compared to other GWP values. Similar results can be also obtained when considering indexes EMI_2 and EMI_3 (Figures 5b,c). In both cases, the average value obtained for AAC blocks is now equal or even higher than that corresponding to LWAC2, since the lower GWP and TNRE associated with LWAC2 are counterbalanced by the better behavior of AAC in tension (with higher values of G_{ft}).

The contribution of acidification potential is taken into account for the first time in the definition of an eco-mechanical index in EMI_4 (Figure 5d). Quite homogeneous values of this index are obtained for AAC1, AAC2, AAC3 and LWAC2 blocks. A higher value of EMI_4 is registered also in this case for LWAC1.

A comparison among the considered construction solutions is more difficult when referring to index EMI_5 (Figure 5e), since water consumption in different productions is extremely variable. LWAC2 production is certainly characterized by a larger water consumption (around 138 m^3) with respect to AAC manufacture (whose average values is around 27 m^3), and this represents an indubitable advantage in terms of sustainability for AAC blocks, also taking into account the limited available water resources. However, the same data relative to AAC production appear to be much dispersed, varying between 0.53 m^3 (AAC2) and 79 m^3 (AAC1), highlighting that this parameter should be better investigated in future research. For this reason, so far water consumption seems not to be a significant index to be considered in the comparisons.



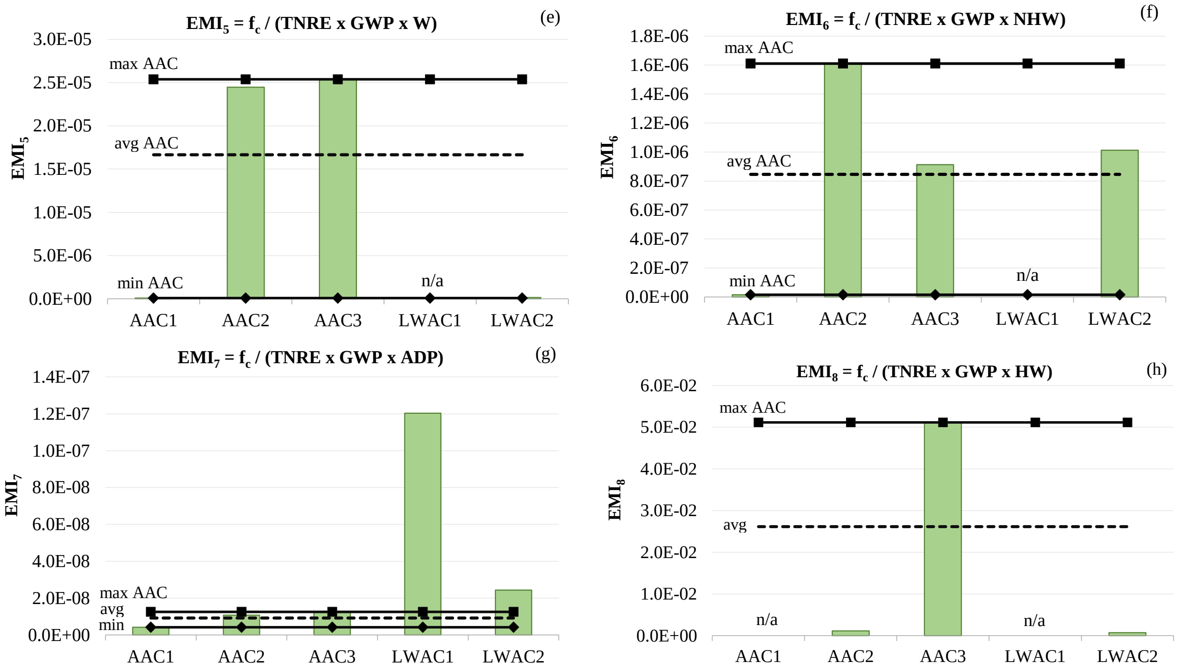


Figure 5. Comparisons of eco-mechanical performances of AAC and LWAC blocks, obtained by considering different EMIs.

*EMI*6 and *EMI*8 indexes (Figures 5f and 5h) includes the effect of wastes disposed in phase A1-A3 for each block considered. The assessment of the waste accumulation is usually shown separately in EPD charts for the three main categories of disposed non-hazardous waste (Figure 5f), hazardous waste for disposal (Figure 5h) and disposed radioactive waste (negligible for the considered cases). Non-hazardous waste represents the greatest proportion both in AAC and LWAC production, whilst the fraction of hazardous waste is generally negligible, as clearly shown in Table 4. Also in this case, the so obtained eco-mechanical indexes are hardly comparable to each other, since the range of variability of waste production is extremely large, even in case of similar productions (see, e.g., AAC1 and AAC2 for NHW, or AAC2 and AAC3 for HW). Moreover, no data are so far available for some block typologies (relatively to both NHW and HW for LWAC1, and relatively to HW for AAC1). Therefore, also the eco-mechanical indexes *EMI*6 and *EMI*8 appear to be not so significant and should be neglected.

Index *EMI*7 takes into account the effect of ADP. As can be seen, the three AAC blocks are characterized by almost coincident values of this index, which are also comparable to that obtained for LWAC2. LWAC1 shows once again the best performance, related to its better ecological parameters (GWP, TNRE and ADP are indeed significantly lower with respect to the other examined products).

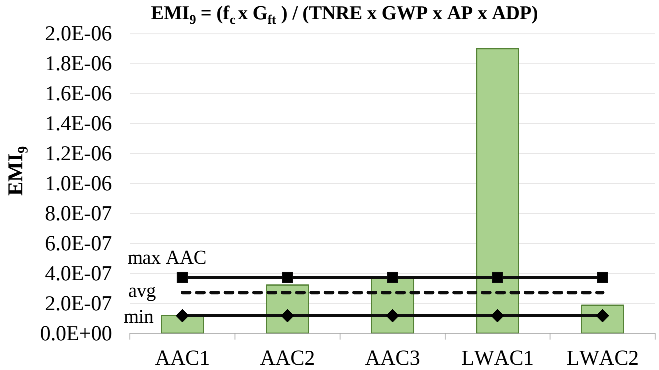


Figure 6. (a) Comparisons of eco-mechanical performances of AAC and LWAC blocks, obtained by considering all the significant mechanical and environmental parameters.

Finally, a sort of “global” index, taking into account all the most significant mechanical and environmental parameters, is reported in Figure 6. As can be seen, water consumption, as well as non-hazardous and hazardous waste are excluded from index definition for the abovementioned reasons. This global index shows that the average eco-mechanical performance of AAC is better than that of LWAC2, so evidencing that AAC block can actually represent a sustainable solution in the construction market. Further research work on the Life Cycle Assessment of AAC blocks already characterized by the Authors from a mechanical point of view could further confirm this assumption, providing more data to be analyzed.

However, based on the information so far available, LWAC1 blocks with integrated thermal insulation appear to be characterized by significantly lower values of all the considered environmental parameters with respect to both AAC and LWAC2 blocks, so seeming the most virtuous construction solution.

5. Conclusions

The present work represents a first attempt in the assessment of sustainability of masonry structures realized with AAC blocks, also in comparison with other competitive solutions, like those involving the use of LWAC blocks. To this aim, eco-mechanical indexes, already developed in the literature with reference to traditional concrete structures, are herein extended to the considered concrete masonry blocks.

The obtained results show that the parameters used to elaborate the eco-mechanical indexes should be carefully selected, by individuating the most significant mechanical and ecological aspects for the analyzed material. However, these results should be regarded as preliminary data, since they are affected by some main limitations, which are discussed in the following.

First of all, for both AAC and LWAC blocks, a general exertion in deriving complete mechanical data from the data sheets of the Manufacturers should be evidenced. For these reasons, in case of AAC, complete experimental data obtained by the Authors have been considered, while in case of LWAC, the main mechanical properties have been derived on the basis of the declared compressive strength, according to Code relations (but this has obviously limited the number of parameters to be included in the evaluation of *MI*).

Moreover, the lack of original environmental data provided by the Producer for the considered AAC blocks has just allowed the Authors to evaluate block ecological performances *EI* referring to literature data (i.e. based on the EPDs of similar AAC blocks available on the marked). In this sense, a further limitation is related to the reduced availability of EPDs, which often differ from each other for the analyzed life cycle stages, making comparative reading ineffective also for similar blocks. To obtain more significant results, it is therefore necessary to perform a detailed EPD evaluation for the considered AAC blocks, already characterized by the Authors from a mechanical point of view. In this way, it will be possible to fully investigate the whole performances of a specific type of masonry block, by selecting among a wide range of both mechanical and environmental parameters.

Finally, it remains to be defined how much the environmental impact of the blocks is embodied in the remaining part of their life cycle, also considering the use phase. Some partial information, which are however inadequate, can be deduced by evaluating the insulation properties of the blocks themselves, but more detailed studies including other significant environmental aspects are certainly needed. Similarly, more information should be acquired on the disposal phase, for which no reliable data are so far available.

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