Acta Polytechnica CTU Proceedings **33**:370–376, 2022
`https://doi.org/10.14311/APP.2022.33.0370`

Published by the `Czech Technical University in Prague`

EXPERIMENTAL INVESTIGATION ON THE MECHANICAL BEHAVIOUR OF AAC BLOCKS FOR SUSTAINABLE CONCRETE MASONRY

Elena Michelini*, Daniele Ferretti, Alice Sirico, Roberto Cerioni

University of Parma, Department of Engineering and Architecture, Parco Area delle Scienze, 181/A, 43124 Parma, Italy

* corresponding author: `elena.michelini@unipr.it`

Abstract.

To satisfy the increasing demand of energy efficient buildings, AAC manufacturers are nowadays encouraged to produce blocks with ever lower densities. However, a compromise between energy-saving requirements and mechanical performances is needed to ensure structural safety, as well as an adequate structural durability. This paper reports a comprehensive experimental study on AAC mechanical properties (compressive and tensile strengths, as well as fracture energy), and on their dependency from material density and moisture content. The collected data are compared with some well-known analytical relations taken from the literature, which are often used for the calibration of mechanical parameters required for mathematical and/or finite element modelling of AAC load-bearing masonry, as well as of AAC masonry-infilled framed structures. These comparisons highlight some critical issues in the formulation of analytical relations having a general applicability; however, it was found that RILEM suggestions are appropriate for the considered AAC productions, at least for densities greater than 400 kg/m^3.

Keywords: Autoclaved aerated concrete, mechanical properties, sustainable concrete masonry.

1. Introduction

The increasing interest in energy efficient buildings has promoted a growing use of innovative masonry products in the construction market. This tendency to search for new and non-standard masonry techniques is related to the widespread awareness that a large proportion of thermal losses in buildings is due to masonry walls. Therefore, one of the most efficient strategies for the reduction of greenhouse gases produced by space heating is the adoption of products with increased thermal insulation performances [1–3]. Among them, Autoclaved Aerated Concrete (AAC) is becoming a quite common solution for the realization of sustainable concrete masonry units (CMUs), to be used in the construction of new buildings, as well as in the retrofitting of existing ones [4–10]. AAC is a porous lightweight concrete whose cellular structure is generally obtained through a gas-producing chemical reaction of sand, lime, gypsum, and cement slurry, with the addition of an expanding agent (usually aluminium powder). Other waste materials, such as fly ash, bottom ash, air-cooled slag, slate waste, glass or perlite waste, agriculture and industrial waste, etc. can be added to increase the sustainability of the production process [11–14]. Thanks to the large amount of entrapped air - ranging from 60% to 85% by volume - the volume of the final product is up to five times that of the raw materials used in the production process. Adequate strength and dimensional stability are obtained through autoclaving at high temperature and pressure, with the formation of a crystalline binder, called tobermorite [15].

Thanks to the presence of small air voids (in the range of $0.1 - 1$ mm) uniformly distributed in the cement paste, AAC masonry blocks have many advantages in comparison with conventional concrete: lighter weight (typically from one-sixth to one-third of conventional concrete), lower transportation and building costs, excellent workability and easiness of laying, reduced construction times, remarkable acoustic and thermal insulation. Besides its low thermal conductivity (which can reach 0.08 W/(mK), or even less for lower density values, see [16]), AAC is characterized by an outstanding air-tightness, which further enhances building thermal performances, creating a comfortable living environment. Furthermore, the use of AAC, with its simple construction details, reduces energy losses due to thermal bridges at junctions [6].

The flip side of the coin is that the reduction of AAC density, which improves thermal properties and reduces structural masses (and consequently the self-weight and the seismic forces acting on the building), exerts an unfavourable effect on material mechanical strengths. This could represent a limitation when AAC blocks are used for the realization of load-bearing masonry walls, since in this case it is mandatory to find a compromise between satisfactory insulation requirements and minimum compressive strength values, according to Standard Codes [17]. For example, regardless of the type of adopted ma-

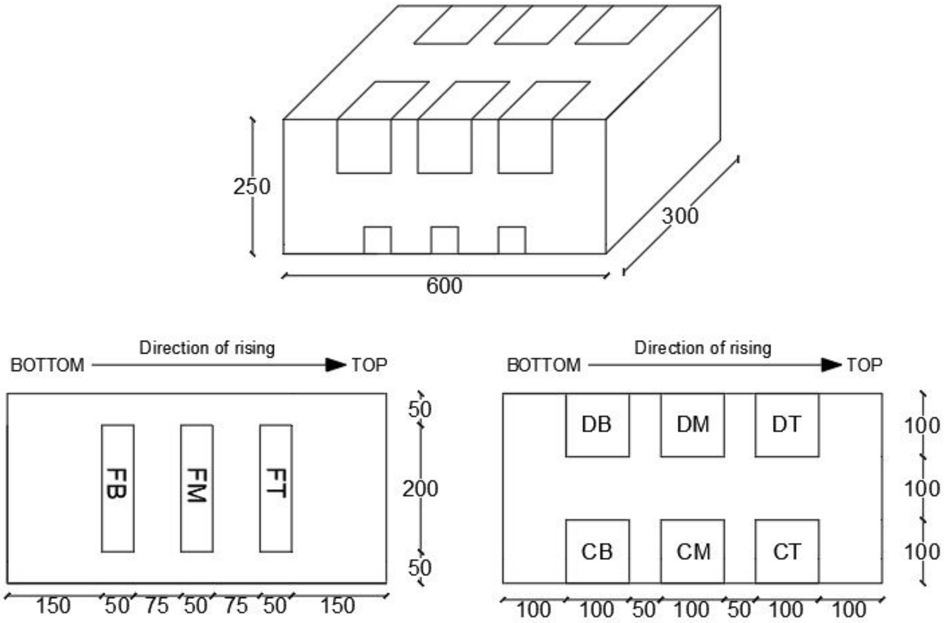

Figure 1. Sampling scheme for compression and flexural tests.

sonry units, EN 1998-1 [18] requires a minimum normalised compressive strength of 5 MPa, so to ensure adequate stability and robustness of masonry walls in seismic areas.

Even if not explicitly required by design Standards, minimum tensile strength values (and consequently minimum compressive strengths, since these two properties are strictly related to each other) should be also provided for cladding and infill panels in framed structures, to limit crack formation under static and seismic loads. It is indeed well known that one of the most common drawbacks in using AAC for the realization of cladding and infills is related to its limited fracture toughness and to its brittleness, which can reduce in some cases the durability of masonry panels, causing the appearance of premature and excessive damages [19, 20].

Aim of this work is to provide a further insight on the relation between density and mechanical properties of AAC. Despite the large number of research works on this topic, a well-established relation between compressive strength and density has not yet been found, since available experimental data are referred to different raw materials in the admixture and to different autoclaving conditions (e.g., [3, 21–24]). On this point, another critical aspect is that temperature, pressure and curing time values are often not specified, despite their marked influence on the formation process of a stable form of tobermorite. A further complication relies on the fact that compressive strength is also dependent from the moisture content at time of testing, as well as from the possible treatments undergone by the specimen to smooth its surfaces (i.e. use of sandpaper, or of a water grinding machine). To better clarify these aspects, an experimental campaign is presented on AAC specimens characterized by four different densities and four different moisture contents. The main mechanical properties, i.e. compressive and flexural tensile strengths, and the fracture energy, were determined according to relevant Standards [25–27]. The best-known relationships between these properties and the material density, as taken from the literature [23, 24, 28], were then checked against the collected data.

2. Experimental program

2.1. Preparation of AAC specimens

All the specimens were cut from commercially available AAC masonry blocks with nominal dimensions equal to 600 × 250 × 300 mm. The blocks were manufactured at the production plant starting from the following raw materials: sand with high silica content, cement, lime, water, gypsum, and aluminium powder as expanding agent. The blocks were autoclaved for 11 hours, at a temperature of 180 ° C and a pressure of 12 bars. Four different types of commercial blocks were investigated, with nominal density equal to 300, 350, 480 and 580 kg/m^3 (respectively indicated with symbols A, EN, E, and S in Table 1).

The sampling scheme followed for compression and flexural tests is depicted in figure 1. As can be seen, 6 cubes with 100 mm side and three 50 × 50 × 200 mm prisms were cut from the bottom, middle and top part of each block (with respect to the direction of rising), by using a diamond blade cutter and a hacksaw for AAC. Three of these six cubes were used

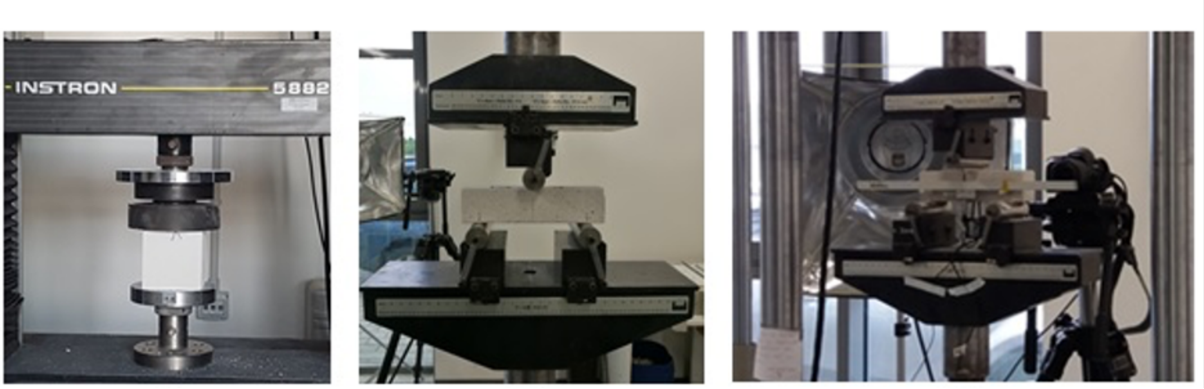

Figure 2. Test setup for the determination of: (a) compressive strength; (b) flexural tensile strength; (c) fracture energy.

for the determination of the oven-dry density (DB, DM and DT), while the remaining three were tested in compression (CB, CM, CT), according to [25, 29]. Prismatic samples were instead tested in flexure (FB, FM, FT) according to [26]. For each examined density, the sampling was repeated on six blocks (so having a total of 144 cubes and 72 prisms). According to the adopted Standards, before the tests, specimens were cured at laboratory conditions until the attainment of a moisture content equal to (6 ± 2) %.

In order to investigate the effect of moisture content on mechanical strengths, additional samples (108 cubes and 54 prisms) were realized from 18 AAC blocks with nominal density of 350 kg/m^3. These specimens were subjected to different curing conditions so to achieve a moisture content respectively equal to (0 ± 2) %, (15 ± 2) % and an "upper limit" equal to the moisture content of the samples at their delivery to the laboratory (approximately ranging from 20 to 30%).

Before conducting the tests, flatness and parallelism requirements were checked; in some cases, it was necessary to smooth sample surfaces with sandpaper.

Regarding fracture energy determination, the only available Standard for AAC is represented by RILEM Recommendations [28], which suggests to carry out wedge-splitting tests. These tests are quite complex to be performed and require a completely different setup with respect to flexural tests. On the contrary, for standard concrete, fracture energy is usually determined by means of three-point bending tests on notched specimens. Previous works (i.e. [22]) proved that this test method can be extended also to AAC, providing results in accordance with those of wedge-splitting tests. For this reason, in this work fracture energy tests were carried out on notched prismatic samples having the same geometry as those tested in flexure, following the Japanese Code [27]. It was decided to extract only one prismatic specimen from the middle of each block, together with two cubes for the determination of the corresponding oven-dry density and compressive strength. Three blocks were tested for each considered density and moisture content (also in this case, the latter was varied only for those blocks with a nominal density of 350 kg/m^3).

2.2. Determination of oven-dry density

As already stated, three twin cubes extracted from each block (DB, DM and DT according to Figure 1) were used for the determination of the oven-dry density. To this aim, the specimens were dried in a ventilated oven at the temperature of (105 ± 5) ° C until a constant mass was reached. The oven-dry bulk density was then calculated as the oven-dried mass divided by the volume. The moisture content was determined as the ratio between the loss of mass during drying and the corresponding oven-dry mass.

2.3. Compression tests

According to [25], compression strength was calculated as the average of the results obtained on three standard cubes with an edge length of 100 mm, cut from the top, middle and bottom part of each block. Compression tests were performed by using an Instron 5882 press working under loading control (Figure 2a), with a loading rate of 0.05 MPa/s, as suggested for masonry elements with an expected compressive strength lower than 10 MPa. Loading was applied perpendicular to the direction of rise.

2.4. Flexural tests

AAC modulus of rupture (tensile strength in bending, so-called MOR) was obtained from prismatic samples subjected to three-point bending over a net span of 150 mm. An Instron 8862 press was used to the scope, with a loading rate of 10 N/s (Figure 2b). Flexural tensile strength was determined as [26]:

$$f_{ct} = \frac{1.5\,Fl}{b_{fr}\,h_{fr}^2} \tag{1}$$

where F is the failure load, l is the net span, b_{fr} and h_{fr} are the specimen dimensions in correspondence of the cracked section.

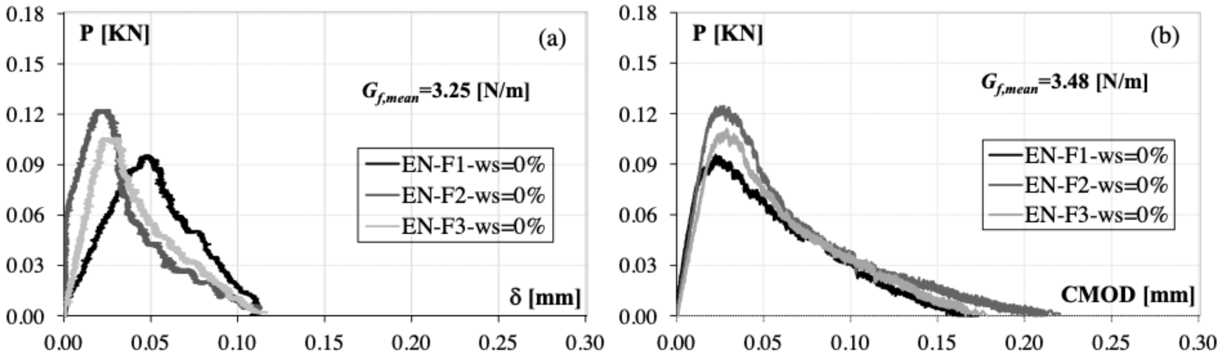

FIGURE 3. Evaluation of the average fracture energy for specimens with nominal density of 350 kg/m^3 and moisture content ws of (0 ± 2) % by considering: a) the load P -deflection δ curve; b) the load P-CMOD curve, according to [27].

Density class	Thermal conductivity (W/(mK))	Nominal density (kg/m^3)	Oven-dry density (kg/m^3)	Compressive strength (MPa)	Flexural tensile strength (MPa)
A	0.07	300 ± 50	295 (0.007)	1.93 (0.04)	0.65 (0.13)
EN	0.08	350 ± 50	346 (0.008)	2.56 (0.03)	0.77 (0.08)
E	0.11	480 ± 50	506 (0.002)	3.94 (0.08)	1.13 (0.05)
S	0.13	580 ± 50	588 (0.005)	5.49 (0.08)	1.44 (0.05)

TABLE 1. Properties of AAC specimens for different density classes, with (6 ± 2) % moisture content.

2.5. FRACTURE ENERGY TESTS

The test setup for the determination of fracture energy was similar to that adopted for flexural tests (Figure 2c). However, in this case, the specimens were notched at their mid-length (with a notch depth equal to 0.3 times the beam depth) and the tests were performed under Crack Mouth Opening Displacement (CMOD) control, with a loading rate of 0.01 mm/min. The specimens were also instrumented with a Linear Variable Displacement Transducer (LVDT) for the measurement of midspan deflection. Fracture energy Gf was calculated as [27]:

$$G_f = \frac{0.75\,W_0 + W_1}{A_{lig}} \tag{2}$$

W_0 being the area below load-CMOD curve up to specimen failure, W_1 the work done by the specimen deadweight and by that of the loading jig, and A_{lig} the area of the broken ligament. The applicability of this relation (which was originally developed for standard concrete) to AAC was preliminary checked by comparing the so obtained fracture energy with that calculated as the total work of fracture given by the area under the complete load-midspan deflection curve, divided by the ligament area [30]. The deadweight of the specimen and of the loading arrangement was taken into account also in this case. As an example, fracture energy deduced from the load-displacement curve (where the midspan deflection was that measured by the LVDT) and that calculated from the load-CMOD curve according to the Japanese Standard [27] is reported in figure 3 for three prismatic samples with nominal density of 350 kg/m^3 (class EN), and a moisture content of (0 ± 2) %.

3. RESULTS AND DISCUSSION

3.1. OVEN-DRY DENSITY

For the four density classes considered in this study, the average oven-dry density was found to be equal to 295, 346, 506 and 588 kg/m^3, with a Coefficient of Variation (COV) - reported in brackets in the table - below 0.01. These densities were almost coincident with the nominal values provided by the manufacturer, as can be seen in table 1. The declared nominal values of thermal conductivity are also reported in the table for each density class.

4. COMPRESSIVE STRENGTH

The average cube compressive strength is summarized in table 1 for all the considered density classes, for a predefined moisture content equal to (6 ± 2) %. As can be seen from Figure 4a, compressive strength increased with density due to the corresponding reduction in material porosity, but the relation between the two variables was found to be non-linear.

The experimental relation between compressive strength and density was checked against some well-known analytical expressions available in the literature. As can be seen, experimental data laid within the range suggested by RILEM Recommended Practice [28], except for the lower density values. In this case, experimental compressive strengths were higher

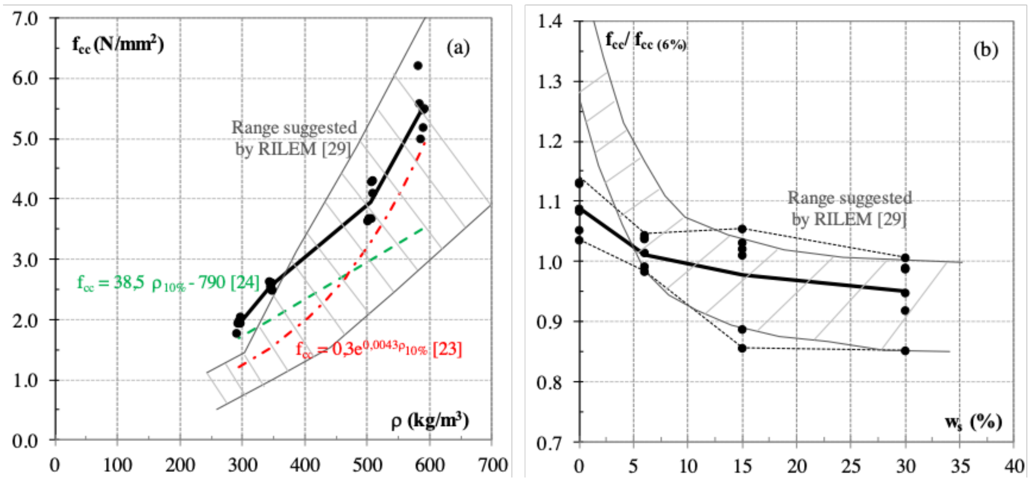

FIGURE 4. Comparison between experimental data and analytical relations available in the literature: a) cube compressive strength f_{cc} vs. density ρ; b) dimensionless cube compressive strength $f_{cc}/f_{cc\,(6\,\%)}$ vs. moisture content w_s.

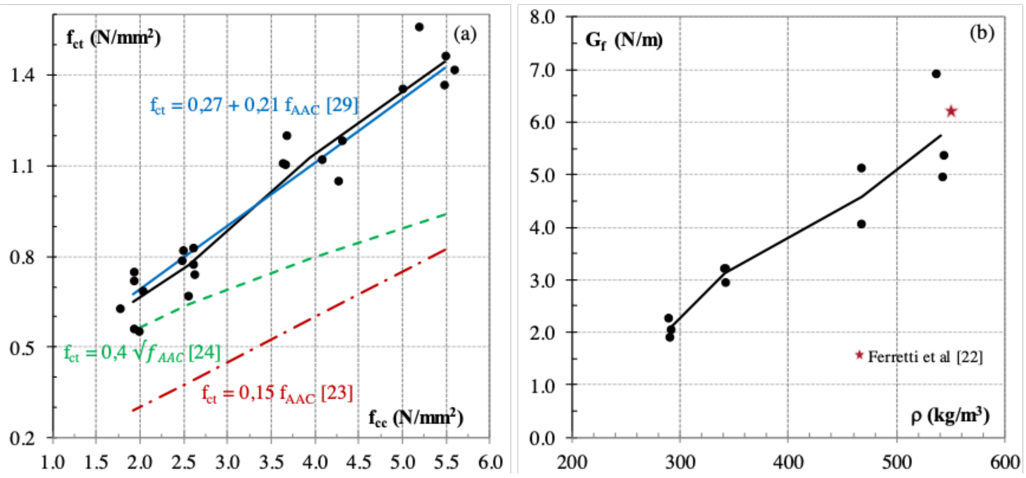

FIGURE 5. (a) Comparison between experimental data and analytical relations available in the literature in terms of flexural tensile strength f_{ct} vs. cube compressive strength f_{cc}; (b) experimental relation between fracture energy G_f and density ρ, for a moisture content of (6 ± 2) %..

than the predicted ones. In the same graph, the relations proposed by Argudo [24] and by Chen et al. [23] were also plotted. In these relations, which were obtained from the best-fitting of experimental data collected by the Authors, the compressive strength is expressed as a function of the bulk density corresponding to a moisture content of 10% ($\rho_{10\,\%}$), by assuming that the ratio $\rho_{10\,\%}/\rho_{dry}$ is equal to 1.1. The comparison between the experimental data collected in this study and the two considered analytical relations shows that a clear relation between compressive strength and density has not yet been found for AAC.

Figure 4b highlights the influence of moisture content at time of testing on the dimensionless compressive strength. It can be seen that the maximum strength was found at the end of the drying process. Even if standard Codes allow to perform compressive tests on dried specimens (by introducing a correction factor on the so obtained strength), the actual moisture content normally reached by AAC blocks in one or two years in external constructions is about $4-6\,\%$ [30]; for this reason, it seems more reasonable to provide the compressive strength value corresponding to that condition. In addition, the compressive strength of specimens tested in dry conditions may be influenced by the required thermal treatment. As can be seen in Figure 4b, experimental normalized strength at dried condition was found to be significantly lower than that suggested by RILEM Recommended Practice [28], while experimental values for other moisture contents fell inside the proposed range.

4.1. FLEXURAL TENSILE STRENGTH AND FRACTURE ENERGY

Experimental values of flexural tensile strength coming from three-point bending tests are summarized in Table 1. As for ordinary concrete, flexural tensile strength is generally expressed as a function of concrete compressive strength, instead of density. As can be seen in Figure 5a, the relation suggested by

RILEM [28] was found to well fit the experimental data collected in the performed experimental campaign, while the semi-empirical equations suggested more recently by Argudo [24] and by Chen et al. [23] had a significantly lower precision, especially for higher compressive strengths. This is a further evidence of the limits of semi-empirical relations available in the literature, which suffer the dependency of AAC mechanical properties from the raw materials adopted in the production process, the autoclaving conditions and the moisture content of the specimens at time of testing, and consequently they could hardly be generalized. A possible strategy to overcome these limitations could be the formulation of different relationships associated to distinct production processes, and to fix a predefined value of moisture to be reached before testing.

Even if tensile strength is the main parameter governing crack formation, it can be useful also to know the fracture energy, since it affects crack propagation within the material. When masonry behaviour is analysed through finite element analyses, the knowledge of fracture energy is necessary for the calibration of a proper block cohesive law. However, the dependency of fracture energy with material density has been little studied so far. A possible relation based on the data collected in this experimental program is shown in Figure 5b. This relation well fit also the average of the data collected by Ferretti et al. [22] in a previous experimental work, on a different AAC production with a density of about 550 kg/m^3. However, a further validation with other experimental programs is required.

5. Conclusions

To reduce thermal losses in buildings, an increasing attention is being paid to the reduction of CMUs thermal conductivity and, consequently, of their density. However, minimum mechanical properties should be guaranteed also for lower density blocks, so to ensure adequate structural performances and the compliance with durability requirements (i.e. limiting crack formation in infills and claddings).

This work focuses on the mechanical characterization of AAC blocks belonging to four density classes. Based on the obtained experimental results and their comparison with some semi-empirical relations available in the literature (calibrated on other AAC productions), the following conclusions can be drawn:

- an almost linear relation can be inferred between thermal conductivity and density, as well as between fracture properties (fracture energy) and density, while the relation between compressive strength and density seems to have an exponential form;
- the relation between MOR and compressive strength is almost linear;
- significant variations may be obtained in compressive strength for a given density value, mainly due to different production processes and material curing;
- eco-mechanical indexes, which are often used as synthetic indicators of environmental and mechanical performances for concrete (see, e.g. [4]), are hardly applicable in the considered case, unless modifying the definition of the reference environmental data (which are typically related to the production process, i.e., global warming potential and embodied energy, and are consequently quite similar for the four density classes). On the contrary, the major advantages of low density blocks are related to energy savings during the use phase of the building life cycle, which should be somehow taken into account.

Acknowledgements

This work is part of a research founded by Ekoru s.r.l., within PON national project n. F/090017/00/X36, CUP B18I17000450008. Authors gratefully thank Dr. F. Talento, Arch. A. Riva and Dr. L. Bergamonti for their valuable help.

References

[1] Uygunoğlu T and Keçebaş. LCC analysis for energy-saving in residential buildings with different types of construction masonry blocks. *Energy and Buildings* **43**(9):2077-2085, 2011.`https://doi.org/10.1016/j.enbuild.2011.04.011`.

[2] L. De Boeck, S. Verbeke, A. Audenaert, et al. Improving the energy performance of residential buildings: A literature review. *Renewable and Sustainable Energy Reviews* **52**:960-75, 2015. `https://doi.org/10.1016/j.rser.2015.07.037`.

[3] F. Pacheco-Torgal, P. B. Lourenço, J. A. Labrincha. Eco-efficient masonry bricks and blocks - Design, Properties and Durability, *Oxford: Woodhead Publishing*, 2015.

[4] D. Ferretti D, B. Gherri, E. Michelini. IOP Conference Series: Materials Science and Engineering, *IOP Publishing*, **442**:12011, 2018.

[5] A. Kyriakidis, A. Michael, R. Illampas. Parametric Numerical Assessment of the Energy Efficiency and the Environmental Impact of an Innovative Masonry Construction Component. *Journal of Sustainable Architecture and Civil Engineering* **16**(3), 2016. `https://doi.org/10.5755/j01.sace.16.3.16174`.

[6] C. Fudge. Designing with AAC to achieve sustainable houses. *Management*, **9**:1-11, 2011. `http://gazobeton.org/sites/default/files/sites/all/uploads/designing_with_acc_to_achieve_sustainable_houses.pdf`.

[7] A. Artino, G. Evola, G. Margani, et al. Seismic and Energy Retrofit of Apartment Buildings through Autoclaved Aerated Concrete (AAC) Blocks Infill Walls. *Sustainability* **11**(14), 2019. `https://doi.org/10.3390/su11143939`.

[8] A. M. Basil, C. Sam-Amobi, C. C. Ugwu, et al. Combating global warming/climate change via reduction of CO2 emission of buildings. *IOP Conference Series: Materials Science and Engineering* **640**(1), 2019. `https://doi.org/10.1088/1757-899x/640/1/012016`.

[9] A. Ahmed. Sustainable Construction Using Autoclaved Aerated Concrete (Aircrete) Blocks. *Research & Development in Material Science* **1**(4), 2017. `https://doi.org/10.31031/rdms.2017.01.000518`.

[10] A. Raj, A. C. Borsaikia, U. S. Dixit. Manufacturing of Autoclaved Aerated Concrete (AAC): Present Status and Future Trends. Advances in Simulation, Product Design and Development. *Lecture Notes on Multidisciplinary Industrial Engineering*, p. 825-33, 2019.`https://doi.org/10.1007/978-981-32-9487-5_69`.

[11] Y. Song, C. Guo, J. Qian, et al. Effect of the Ca-to-Si ratio on the properties of autoclaved aerated concrete containing coal fly ash from circulating fluidized bed combustion boiler *Construction and Building Materials* **83**:136-42, 2015. `https://doi.org/10.1016/j.conbuildmat.2015.02.077`.

[12] W. Wongkeo, P. Thongsanitgarn, K. Pimraksa, et al. Compressive strength, flexural strength and thermal conductivity of autoclaved concrete block made using bottom ash as cement replacement materials. *Materials & Design* **35**:434-9, 2012. `https://doi.org/10.1016/j.matdes.2011.08.046`.

[13] P. Walczak, J. Malolepszy, M. Reben, et al. Utilization of Waste Glass in Autoclaved Aerated Concrete. *Procedia Engineering* **122**:302-9, 2015. `https://doi.org/10.1016/j.proeng.2015.10.040`.

[14] H. El-Didamony, A. A. Amer, M. S. Mohammed, et al. Fabrication and properties of autoclaved aerated concrete containing agriculture and industrial solid wastes. *Journal of Building Engineering* **22**:528-38, 2019. `https://doi.org/10.1016/j.jobe.2019.01.023`.

[15] N. Narayanan, K. Ramamurth. Structure and properties of aerated concrete: a review. *Cement & Concrete Composites* **2**2:321-9, 2000. `https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.474.5811&rep=rep1&type=pdf`.

[16] B. Straube, H. Walther. AAC with low thermal conductivity. *Cement Wapno Beton.* 78-80. `http://cementwapnobeton.pl/pdf/2011/2011_Special/Straube.pdf`.

[17] A. Penna, M. Mandirola, M. Rota, et al. Experimental assessment of the in-plane lateral capacity of autoclaved aerated concrete (AAC) masonry walls with flat-truss bed-joint reinforcement. *Construction and Building Materials* **82**:155-66, 2015. `https://doi.org/10.1016/j.conbuildmat.2015.02.057`.

[18] EN 1998-1:2013. Eurocode 8 - Design of structures for earthquake resistance, 2013.

[19] R. R. Milanesi, P. Morandi, G. Magenes. Local effects on RC frames induced by AAC masonry infills through FEM simulation of in-plane tests. *Bulletin of Earthquake Engineering* **16**(9):4053-80, 2018. `https://doi.org/10.1007/s10518-018-0353-5`.

[20] R. Cerioni, N. Pongiluppi, D. Ferretti, et al. Damage assessment of autoclaved aerated concrete buildings: some Italian case studies. *International Journal of Masonry Research and Innovation* **5**(1), 2020. `https://doi.org/10.1504/ijmri.2020.10024371`.

[21] Y. Song, B. Li, E.-H. Yang, et al. Feasibility study on utilization of municipal solid waste incineration bottom ash as aerating agent for the production of autoclaved aerated concrete. *Cement and Concrete Composites* **56**:51-8, 2015. `https://doi.org/10.1016/j.cemconcomp.2014.11.006`.

[22] D. Ferretti, E. Michelini, G. Rosati. Cracking in autoclaved aerated concrete: Experimental investigation and XFEM modeling. *Cement and Concrete Research* **67**:156-67, 2015. `https://doi.org/10.1016/j.cemconres.2014.09.005`.

[23] Y. Chen, M. Peng, Y. Zhang, et al. Mechanical Properties of Autoclaved Aerated Concrete with Different Densities. *Advances in Civil Engineering Materials* **2**(1):441-52, 2013. `https://doi.org/10.1520/acem20130063`.

[24] J. Argudo. Evaluation and syntesis of experimental data for Autoclaved Aerated Concrete Ph.D. Thesis, University of Texas at Austin, 2003.

[25] EN 772-1:2015. Methods of test for masonry units - Part 1: Determination of compressive strength, 2015.

[26] EN 1351:1997. Determination of flexural strength of autoclaved aerated concrete, 1997.

[27] JCI-S-001-2003. Method of test for fracture energy of concrete by use of notched beam, 2003.

[28] F. H. Wittman. Autoclaved Aerated Concrete- Properties Testing and Design (RILEM Recommended Practice). *RILEM technical committees*, 1993.

[29] EN 772-13:2000. Methods of test for masonry units - Determination of net and gross dry density of masonry units (except for natural stone), 2000.

[30] R. G. Mathey, W. J. JR. Rossiter. Review of Autoclaved Aerated Concrete Products. NBSIR 87-3670. *National Bureau of Standards*, 1988.