Faustino, J.; Silva, E.; Pinto, J.; Soares, E.; Cunha, V.M.C.F.; Soares, S. (2015) Lightweight concrete masonry units based on processed granulate of corn cob as aggregate. *Mater. Construcc.* 65 [318], e055 http://dx.doi.org/10.3989/mc.2015.04514.

Lightweight concrete masonry units based on processed granulate of corn cob as aggregate

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Abstract:

A research work was performed in order to assess the potential application of processed granulate of corn cob (PCC) as an alternative lightweight aggregate for the manufacturing process of lightweight concrete masonry units (CMU). Therefore, CMU-PCC were prepared in a factory using a typical lightweight concrete mixture for non-structural purposes. Additionally, lightweight concrete masonry units based on a currently applied lightweight aggregate such as expanded clay (CMU-EC) were also manufactured. An experimental work allowed achieving a set of results that suggest that the proposed building product presents interesting material properties within the masonry wall context. Therefore, this unit is promising for both interior and exterior applications. This conclusion is even more relevant considering that corn cob is an agricultural waste product.

Resumen:

En este trabajo de investigación se evaluó la posible aplicación de granulado procesado de la espiga de mijo como un agregado ligero alternativo en el proceso de fabricación de unidades de mampostería de hormigón ligero. Con esta finalidad, se prepararon en una fábrica diversas unidades de mampostería no estructural con granulado procesado de la espiga de mijo. Además, se fabricaran unidades de mampostería estándar de peso ligero basado en agregados de arcilla expandida. Este trabajo experimental permitió lograr un conjunto de resultados que sugieren que el producto de construcción propuesto presenta interesantes propiedades materiales en el contexto de la pared de mampostería. Por lo tanto, esta solución es prometedora tanto para aplicaciones interiores y exteriores. Esta conclusión es aún más relevante teniendo en cuenta que la espiga de mijo es un producto de desecho agrícola.

Keywords: Concrete; Brick; Organic raw material; Waste treatment; Compressive strength

1. Introduction

Finding alternative environmentally friendly building solutions has been a goal of the technical and scientific communities. These solutions tend to be more sustainable and affordable. Using raw, organic, local and renewable materials complemented with the application of low technology processes may contribute to achieve this type of solutions because they require less consumption of energy and good quality water, and also they result in only a small amount of CO_2 emission to the atmosphere.

Traditional building techniques may be a source of inspiration for alternative environmentally friendly building solutions taking into account that they encompass the above requirements. Rammed earth, adobe, tabique, stone masonry and timber construction are some examples of traditional building techniques which are generally applied worldwide.

Several products and building solutions based on organic raw materials have been proposed. For instance, wood and cork are two well-known building materials of this type which are traditionally applied. Considering the sustainability inherent to these two organic raw materials, several alternative wood and cork engineered products have been proposed. In addition, several types of agricultural products have also been reported as possible raw organic building materials [1-6]. Some examples of these agricultural products are bagasse, cereal, straw, corn stalk, corn cob, cotton stalks, kenaf, rice husks, rice straw, sunflower hulls and stalks, banana stalks, coconut coir, bamboo, durian peel, oil palm leaves, among others. Particleboards, hardboards and fibreboards are some examples of engineered building products that may be processed using those materials and they have been mainly studied as possible alternative thermal and acoustic insulation solutions.

Among the above identified agricultural products corn cob belongs to the set which has the additional advantage of not colliding with the worldwide food stock and of being generally considered as agricultural waste. In recent years, the worldwide production of corn has increased due to the increase of the world population. In 2008, the worldwide corn production was about 791 million tons and it increased to nearly 1016 million tons in 2013 [7]. As an indicator, in 2013 the production of the twenty seven European Union countries and the USA was 117 and 353 million tons, respectively [7].

Recent research works [6,8-9] have concluded that the corn cob may have interesting material properties in terms of thermal and acoustic insulation behaviours. At the same time, granulate of corn cob has also been suggested as a possible organic lightweight aggregate of concrete for non-structural applications, and as an alternative solution to currently applied solutions such as expanded clay, particles of expanded polystyrene (EPS), particles of cork or other lignocelluloses wastes [10]. High level of water absorption of the granulate of corn cob, slow drying process and low compressive strength of the lightweight concrete produced were the main identified material limitations in [10]. Taking into account the relevance of this type of building element, several research works [11-14] have proposed alternative lightweight aggregates (i.e. volcanic slag, reservoir sediments, among other possibilities) and cement replacement materials (i.e. wood fibre waste, rice husk ash, limestone powder waste, among other possibilities) for the manufacturing of concrete masonry units.

Based on these assumptions, this research work intends to assess the potential of applying processed granulate of corn cob as an alternative solution to lightweight aggregate for the manufacturing of concrete masonry units. Covering the particles of corn cob with cement paste was the technique proposed to solve the above stated material limitations.

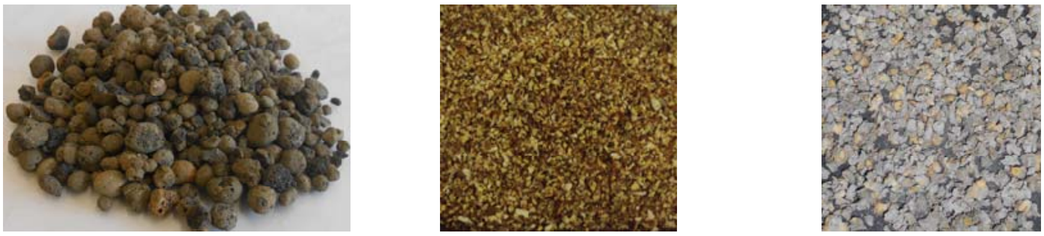
2. Experimental Research

An exhaustive experimental work was performed in order to assess some material properties of the proposed concrete masonry units with processed granulate corn cob, CMU-PCC, as well as identifying technical aspects concerning the manufacturing of a concrete masonry unit, CMU, in a common industrialized environment. In parallel, currently used CMU based on expanded clay (EC) as lightweight aggregate (CMU-EC) was also studied in the same way and as a reference.

2.1 Processed granulate of corn cob

In this research work, processed granulate of corn cob (PCC, Figure 1.c) is considered as a possible lightweight aggregate in the manufacturing process of lightweight concrete masonry units (CMU). During the PCC preparation study, expanded clay (EC, Figure 1.a) was used as a reference lightweight aggregate because it is currently applied in the context of CMU.

PGCC is based on raw corn cob particles (Figure 1.b) which are covered with a cement paste prepared with the ratio 1:1 (Portland cement 32.5 N: water). PCC was prepared in order to have a grade similar to EC. However, the shape of these two aggregates is quite different, Figure 1. EC has a spherical shape type (Figure 1.a) and PCC has a random irregular shape (Figure 1.c). The density and the water absorption coefficient of the PCC have been experimentally assessed and the respective values are 454.5 kg/m^3 and 57.9%. This density seems acceptable because it is within the density range of the expanded clay lightweight aggregates (i.e. 60 – 850 kg/m^3), [8]. On the other hand, raw corn cob particles are covered with cement paste resulting in a waterproofing improvement of the aggregate.



a) b) c)

Figure 1: Lightweight aggregates considered: a) Expanded clay (EC); b) Granulate of corn cob (GCC); c) Processed granulate of corn cob (PCC)

2.2 Concrete masonry unit manufacturing

Medium sand (MS; 0.0 – 4.0 mm), coarse sand (LS; 0.8 – 3.0 mm), gravel (G; 2.0 – 6.0 mm), Portland cement 32.5 N (C), lightweight aggregate (LWA) and water (W) are the constituents considered in this research for the manufacturing of lightweight concrete masonry units. Table 1 presents the amount of each constituent necessary to manufacture one CMU according to Mixtures 1 and 2, and considering a generalised LWA. Meanwhile, two different lightweight aggregates were studied: expanded clay (EC) and processed granulate of corn cob (PCC). Therefore, three cases (Cases 1, 2 and 3) were considered. Case 1 consists of manufacturing CMU according to Mixture 1 and using EC as lightweight aggregate (CMU-EC). Case 1 is to be used as a reference in this study. On the other hand, Case 2 corresponds to manufacturing CMU also according to Mixture 1 but using PCC (CMU-PCC) as lightweight aggregate instead of EC. This case intends to be a novelty in the light-weight concrete masonry units context, taking into account that an alternative organic lightweight aggregate has been considered (PCC) ,instead of an industrialized one (such as EC). At the same time, Case 3 is related to a manufacturing process scenario in which CMU is manufactured with Mixture 2 and it is also based on PCC (CMU-PCC). This last case intends to be a complement of Case 2 in which the amount of cement was slightly increased, Table 1.

Table 1: Adopted mixtures in the manufacturing process of CMU

Mixture (kg)	MS	LS	G	C	LWA	W
1	1.530	1.836	3.060	1.326	1.326	1.326
2	1.530	1.836	3.060	1.503	1.149	1.326

The CMUs were manufactured in an industrialized context, Figures 2 and 3. The constituents were mixed automatically. After this stage, the mixture was introduced in moulds and under compaction the CMUs were moulded, Figure 2.a. A set of five CMU were moulded automatically, Figure 2.b. Then, the CMU were transported to a chamber room for the curing/drying process, Figure 3.b, where the units were protected from the direct exposure of climate conditions (e.g. rain and sun) and the thermo-hygrometric conditions were the environmental ones.

a) b)

Figure 2: Manufacturing of CMU-PCC – Moulding: a) Moulding process and b) manufactured units

a) b)

Figure 3: Manufacturing of CMU-PCC – Curing/drying: a) automatic transportation and b) curing chamber

In this research work, a six hollow block was manufactured in a standard shape, Figure 4. The size of the adopted lightweight concrete masonry unit (CMU) is 500 mm × 200 mm × 200 mm (length (L) × width (W) × height (H)) with a +3/-5 mm dimensional tolerance. Fifteen CMU related to each case study were manufactured, Figures 4.

a) b) c)

Figure 4: CMU: a) Case 1 (C1), b) Case 2 (C2), and c) Case 3 (C3)

3. Results and discussion

Size, mass, bulk density, fire resistance, sound and thermal insulation behaviours, compressive strength, water penetration and absorption, linear drying shrinkage, aging sensitivity, are some material properties were assessed in order to characterize technically a CMU.

In this research work, size, mass, bulk density, water absorption due to capillarity, aging sensitivity and compressive strength were the material properties considered for the study of the proposed CMU.

3.1 Dimensions, mass and bulk density

The size, the dry mass ($m_{dry,s}$) and the bulk density (ρ) of these LWCMU were then assessed. The bulk density was quantified accordingly [15]. The average (AVG), the standard deviation (SD) and the coefficient of variation (CoV) of these measures are presented in Table 2 for the three cases analysed. None of the CMU have shown the exact dimensions indicated above including the reference one (Case 1, Table 2). Meanwhile, all of them have satisfied the dimensional tolerance. They also proved to have a uniform size.

In terms of bulk density, the reference CMU-EC (Case 1, $\rho = 1364$ kg/m^3, Table 2) are lighter than CMU-PCC (Case 2 and Case 3, $\rho = 1681$ kg/m^3 and $\rho = 1748$ kg/m^3, respectively). Taking into account that the adopted manufacturing process and mixture were similar in Case 1 and 2, the mass of the lightweight aggregates considered (EC and PCC, respectively) may be the main justification for this discrepancy. In this research work, the bulk density of PGCC was estimated in $\rho = 454.494$ kg/m^3. At the same time, the density of EC ranges between 275 and 430 kg/m^3

which is smaller than those of PCC. In addition, considering that the amount of cement was increased in Mixture 2, an increasing of the bulk density of CMU-PCC of Case 3 is also expected.

ASTM C 90-06a [16] defines three bulk density classes for concrete masonry units as follows: Lightweight – units having an average bulk density of less than 1680 kg/m^3; Medium Weight – units having an average bulk density of 1680 kg/m^3 or more, but less than 2000 kg/m^3; Normal Weight – units have an average bulk density of 2000 kg/m^3 or more. Therefore, according to ASTM C 90-06a [16] the reference CMU-EC (manufactured with Mixture 1) is clearly a lightweight concrete masonry unit. The CMU-PCC Case 2 (manufactured with Mixture 2) may be considered as medium weight concrete masonry units. On the other hand, the average bulk density obtained for CMU-PCC Case 2 (manufactured with Mixture 2) exceeds significantly the value of 1680 kg/m^3. In this case, the concrete masonry units may be characterized as medium weight. These results indicate that using PCC as an alternative lightweight aggregate in the manufacturing process of CMU may require adjustments of a typical mixture used in this context in order to ensure the production of a lightweight concrete masonry unit.

Table 2: Dimensions, dry mass and bulk density of the studied CMU

		L (mm)	W (mm)	H (mm)	$m_{dry,s}$ (kg)	ρ (kg/m^3)
Case 1	AVG	497	201	199	11.494	1364
	SD	1.19	1.03	1.16	0.716	41
	CoV (%)	0.24	0.51	0.58	6.23	3.0
Case 2	AVG	497	201	196	13.326	1681
	SD	0.74	0.68	4.09	0.757	89
	CoV (%)	0.15	0.34	2.08	5.68	5.3
Case 3	AVG	496	200	197	14.081	1748
	SD	0.62	0.49	1.57	0.778	60
	CoV (%)	0.12	0.24	0.79	5.52	3.5

3.2 Water absorption coefficient by capillarity

Five CMU specimens of each case (C1, C2 and C3) were prepared and tested in terms of water absorption due to capillarity action at the age of 44 days and following the recommendations prescribed in the Portuguese NP EN 772-11 standard [17]. The duration of this test was 14 days (i.e. 1209600 seconds). During this period of time, the CMU specimens were soaked in a 5 mm water layer. Table 3 presents the water absorption coefficient by capillarity, $C_{w,s}$, which was assessed by Expression 1.

$$C_{w,s} = \frac{m_{so,s} - m_{dry,s}}{A_s\sqrt{t_{so}}}10^6 \qquad (1)$$

Where: $C_{w,s}$ is the water absorption coefficient by capillarity (g/(m^{2}s$^{0.5}$)); $m_{so,s}$ is the mass of the CMU after immersion (g); $m_{dry,s}$ is the dry mass of the CMU (g); A_s is the area of the face of the CMU which is soaked in water (mm^2); t_{so} is the time of immersion in water (s - seconds).

Based on the water absorption coefficients by capillarity presented in Table 3 it is concluded that the CMU-PCC (CMU C2 and C3, Table 3) are more susceptible to absorb water due to capillarity than the CMU-EC (CMU C1, Table 3). In addition, this tendency is reduced by increasing the amount of cement in the mixture by increasing the cement paste which covers the organic particles. This last situation occurred for Cases 2 (CMU C2, prepared according Mixture 1, Tables 1 and 3) and 3 (CMU C3, prepared according Mixture 2, Tables 1 and 3) in which the respective coefficient decreased from Cw,s=7.7 g/(m^{2}s$^{0.5}$) to 7.4 g/(m^{2}s$^{0.5}$), in terms of average values, in Table 3.

The obtained value of coefficient of variation (CoV) of the water absorption coefficient by capillarity of the different studied cases is small, which means that there was an acceptable specimen variation and these experimental results may be considered consistent.

Table 3: Water absorption coefficient by capillarity ($C_{w,s}$) of the CMU

CMU	A_s (mm^2)	$m_{dry,s}$ (g)	$m_{so,s}$ (g)	$C_{w,s}$ (g/(m^{2}s$^{0.5}$))			
					AVG	SD	CoV (%)
C1.1	99495	12491	13078	5.364	4.7	0.4	9.1
C1.2	100394	11013	11521	4.601			
C1.3	99696	12285	12780	4.514			
C1.4	99897	11511	12022	4.651			
C1.5	100596	11443	11909	4.212			
C2.1	100394	12669	13516	7.671	7.7	0.3	3.6
C2.2	99400	12788	13626	7.665			
C2.3	99897	14640	15535	8.146			
C2.4	99897	14607	15464	7.800			
C2.5	100098	12632	13445	7.385			
C3.1	99200	13956	14780	7.553	7.4	0.1	1.7
C3.2	99200	15486	16299	7.452			
C3.3	99200	13684	14503	7.507			
C3.4	99897	14106	14902	7.245			
C3.5	99897	13353	14160	7.345			

All the tested CMU kept their material integrity after being in contact with water during 14 days. This aspect is very important in terms of the suitability of the CMU as building materials. In fact, some building tasks may be compromised if the CMU are vulnerable to water. Exterior application, block laying, plastering and placing the units near the ground may be some of these building tasks.

3.3 Aging sensitivity

A twenty-four hour cycle of aggressive thermo-hygrometric conditions was experimentally simulated [18-19]. The aggressive thermo-hygrometric conditions of the cycle corresponds to having the specimen in the climate testing chamber device at a constant temperature of 60 ºC during a period of time of 7 hours (first stage) followed by a second period of time of 1 hour in which the samples are soaked in water at the normal temperature of the laboratory of 22 ºC approximately (second stage), and finalizing by having the specimens placed again in the climate testing chamber cell device at the constant temperature of -15 ºC during an additional period of time of 16 hours (third stage). These extreme temperatures (60 ºC and -15 ºC), the dramatic change in temperature and the alternate dried/wet/frozen conditions allow simulating experimentally an accelerated aging process of the material.

The aging sensitivity of the CMU under study was assessed by testing the material during ten consecutive cycles of the described thermo-hygrometric conditions and following the suggested by [18-19]. Two intact LWCMU specimens of each case (C1, C2 and C3) were tested. The aging effect signals of the samples were visually monitored at the end of each cycle. Figure 5 presents the CMU after being tested (C1`, C2`and C3`). It is concluded that there was no expressive degradation of the tested materials. In fact, the tested CMU kept their integrity after being under such environmental aggressiveness. This technical aspect is relevant considering exterior applications. The tested specimens only suffered minor degradation, such as a slight change of colour (e.g. a brownish tendency) and a certain erosion of the edges of the specimens, Figure 5.

a) b) c)

Figure 5: Aged LWCMU: a) C1`, b) C2`and C3`

3.4 Compressive strength

Partition walls seem to be the main building domain of application of CMU. Therefore, lightness, material integrity, adequate durability, good thermal and acoustic insulation ability, affordable and sustainable, are some expected material properties. CMU is a non-structural element. However, it is important that this type of masonry unit presents a certain compressive strength. For instance, it has to be able to support the weight of the underlying portion of the wall. Additionally, an adequate compressive strength also indicates that the CMU presents an acceptable material integrity and therefore it can be shipped, stored and applied in the building site. For instance, BS EN 771-3:2011 [20] indicates the range of the compressive strength of aggregate concrete masonry units (dense and lightweight aggregates) from 2.9 MPa to 10.4 MPa.

In order to evaluate the compressive behaviour of the CMU (based on EC and PCC aggregates), in particular the CMU-PCC, five CMU samples of each case were prepared and tested in terms of uniaxial compression test. Specimens were tested at the age of 50 days because of logistic aspects specifically concerned with this research work. This test was performed according to NP EN 772-1 [21]. A 300 kN load bearing capacity servo-hydraulic actuator was used. The test was carried out in force closed-loop displacement control with a load displacement rate of 1.2 mm/minute.

In Figure 6, the stress vs strain curves of the CMU tested under uniaxial compression are presented. In terms of compression, it is undoubtful that CMU-EC (C1) is stronger than CMU-PCC (C2 and C3). However, all the tested CMU seem to have a similar behaviour in compression. An approximate initial straight-line portion of the diagram followed by a well-defined Yield Point are two aspects that characterize the stress vs strain curves of the specimens.

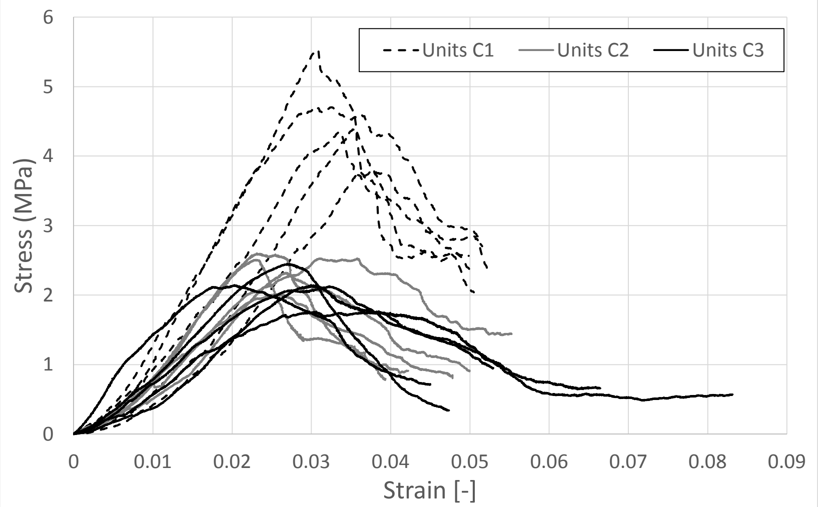


Figure 6: Compressive behaviour of the tested CMU (aged 50 days)

Additionally, the AVG, the SD and the CoV of the ultimate compressive strength ($fc_{max.}$) of the CMU tested are presented in Table 4. Two aged CMU specimens of each case (C1´, C2`and C3`) were also tested in compression. The respective estimated ultimate compressive strength is also presented in Table 4. Complementarily, the failure mode under compression faced by the tested CMU is shown in Figure 7.

The CMU-EC (C1) showed high compressive strength than CMU-PCC (Cases C2 and C3), Figure 7 and Table 4. In fact, in terms of average, the compressive strength of the reference CMU (CMU-EC, C1) is 2.14 and 1.90 times higher than the compressive strength of the proposed CMU-PCC C2 and C3, respectively. The fact that an organic product was used as aggregate may justify this compressive strength discrepancy. At the same time, the compressive strength showed by the CMU-PCC is lower than 2.9 MPa which is the minimum compressive strength admissible by [29]. On the other hand, the obtained compressive strength of CMU-PCC may still be acceptable in the context of CMU. For instance, in a 3 m height wall built with CMU-PCC, the masonry units placed at the first layer (critical ones) will be under an approximate 1.9 kN compressive force (FCd) corresponding to the dead load related to the weight of the overlying wall, Figure 8. On the other hand, the obtained experimental ultimate compressive force (F_{CRd}) for CMU-PCC related to Case 2 was 84.5 kN approximately which is significantly higher than 1.9 kN. Therefore, the proposed CMU-PCC may have an acceptable mechanical behaviour in the context of lightweight concrete masonry units for non-structural purposes. This material achievement is even more interesting considering that an agricultural waste product is proposed as a lightweight aggregate. The scatter of the results is highlighted by the CoV. The verified dispersion may be acceptable taking into account the obtained small values of the CoV and considering that an organic raw material was employed.


a) b) c)

Figure 7: Compressive failure modes of the LWCMU samples: a) C1, b) C2 and c) C3

In Table 4, the fact that an approximate 12% mechanical behaviour improvement of CMU-PCC achieved by increasing the ratio of C:LWA (in terms of weight) from 1 (Mixture 1 in Table 1) to 1.308 (Mixture 2 in Table 1) is also featured. This technical aspect is in accordance with the expected results in the lightweight concrete for non-structural purposes domain.

Table 4: Compressive strength ($fc_{max.}$) of the tested CMU

	C1	C1`	C2	C2`	C3	C3`
AVG (MPa)	4.55	3.75	2.13	2.22	2.39	2.61
SD (MPa)	0.64	0.29	0.24	0.20	0.24	0.94
CoV (%)	14.08	7.79	11.36	8.97	9.93	35.94

In order to complement the aging sensitivity analysis done in the previous section of this paper, the specimens that were tested under the aggressive environmental conditions were then also tested in terms of uniaxial compression test (C1`, C2` and C3`, Table 4). Comparing the ultimate compressive strength of the intact CMU specimens (C1, C2 and C3, Figure 6 and Table 4) with the respective one of the aged CMU specimens (C1`, C2`and C3`, Table 4), it is noticed again that both CMU-EC and CMU-PCC shown an adequate durability. In fact, the compressive behaviour of the CMU-PCC was not affected significantly during the aging test because there was no reduction of the compressive strength. In contrast, the CMU-EC was slightly affected after being tested under repeated cycles of aggressive environmental conditions because there was a reduction of its compressive strength from 4.55 MPa to 3.75 MPa (C1 and C1`, Table 4). This fact may indicate that the material has faced a certain level of degradation after being tested.

In addition, the CMU-PCC (C2 and C3, Figure 7) specimens tested under uniaxial compression showed failure modes similar to the expected one of a regular conventional lightweight concrete masonry unit such as CMU-EC (C1, Figure 7). This experimental analogy is another interesting output that enhances the practicability of the proposed technical solution of manufacturing lightweight concrete masonry units with processed granulate of corn cob as an aggregate.

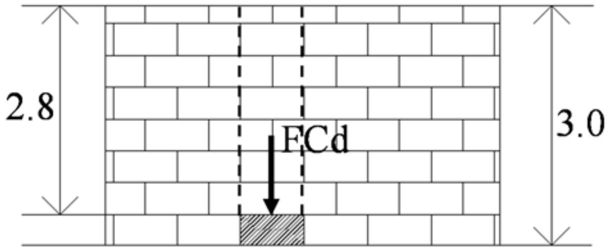


Figure 8: Dead load acting on a critical LWCMU (FCd), (m)

4. Conclusions

Lightweight concrete masonry units based on processed granulate of corn cob as aggregate (CMU-PCC) were proposed in this research work. The proposed CMU-PCC was manufactured using a current mixture and applying common technology.

It was possible to manufacture standard shape and size CMU-PCC. They were able to keep their shape and size during the drying process which is a very technical achievement. The assessed bulk density of the CMU-PCC was in the limit of acceptance in terms of lightweight concrete masonry unit (i.e. 1680 kg/m^3).

The fact that granulate corn cob was covered with cement paste tends to reduce the water absorption of the particles and also to improve the adherence between concrete and aggregate. Despite these advantages, CMU-PCC have shown a higher water absorption due to capillarity than a typical CMU-EC. On the other hand, both materials kept their integrity after being in permanent direct contact with water during 14 consecutive days. At the same time, both materials, in particular CMU-PCC, have also shown an adequate durability because after being tested under several cycles of aggressive thermo-hygrometric conditions (extreme temperature and humidity level variations) there was no indication of relevant material deterioration. Thus, the proposed product may be adequate for both interior and exterior building applications. After testing CMU-PCC and CMU-EC under compression, it was noticed that there was a significant discrepancy in terms of compressive capacity of these two types of materials. In fact, the compressive strength of CMU-EC is approximately two times higher than the respective strength of CMU-PCC. Therefore, it is necessary to conduct additional research work in order to improve the material properties of the CMU-PCC. The evaluation of the corn cob – Portland cement compatibility is a technical aspect that should be further studied.

Acknowledgements

The authors would like to thank the companies Betão do Marão Lda and Ediqual Lda for the execution of the specimens and realization of the experimental tests, respectively.

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