Thermal performance of sawdust and lime-mud concrete masonry units.

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HIGHLIGHTS

- Enhanced concrete using by-products from the forestry and paper pulp industries.
- Sawdust concrete masonry walls had better thermal resistance than ordinary walls.
- The use of sawdust as a fine-aggregate replacement reduces compressive strengths.
- Lime mud incorporated as a cement substitute counteracts reductions in strength.

Keywords:

Concrete masonry units, Industrial by-products, Cement replacement, fine aggregate replacement, Thermal properties, Mechanical properties.

ABSTRACT

Over the last three decades, a growing interest in the properties of thermal envelopes and their enhancement has led to the development of new sustainable materials. However, Concrete Masonry Units (CMUs), that continue to be widely used in the thermal envelopes of buildings, as yet are manufactured with negligible thermal properties and with an unsustainable approach. For this reason, this research aims to reuse some by-products for the development of CMUs with better thermal properties. In addition to the reference concrete, one set of blocks was manufactured with 5% sawdust in substitution of fine aggregate and another set of blocks with the same fine aggregates replacement together with 15% lime mud in substitution of cement. The physical, mechanical, and thermal performance of the CMUs were evaluated. Results show that the addition of sawdust in CMUs improve the thermal properties. Whereas, the addition of lime mud partially counteracts the decrease in strength caused by incorporating the sawdust.

1 Introduction

Currently, there is growing interest in developing new sustainable construction materials with better thermal properties for the thermal envelopes of building. However, Concrete Masonry Units (CMUs), that continue to be widely used in the thermal envelopes of buildings, have not evolved, since they are still manufactured with negligible thermal properties and with an unsustainable approach. For this reason, this research seeks to reuse some waste materials as by-products from the timber and paper mill industries for the development of ecofriendly CMUs with better thermal properties for the construction sector.

Waste materials obtained from manufacturing processes have become one of the main environmental concerns worldwide. It is noteworthy that during 2014, if we consider all economic and household activities, total waste production of the EU-28 member states amounted to 2500 million tons [1]. Besides, the poor energy efficiency of most buildings is a further cause of energy poverty. For instance, the residential sector represents 27% of the world's energy consumption and 17% of CO_2 emissions [2]. In this regard, the European Commission (EC) has issued certain Directives [3,4]: on the one hand, establishing strict requirements for waste reduction, management, and recycling that promote moves towards a circular economy. On the other hand, the EC seeks to accelerate the cost-effective renovation of existing buildings. Therefore, the reuse of those waste materials as by-products is tenable for the development of materials with better thermal properties for the construction sector.

Concrete Masonry Units (CMUs) are widely used, especially in developing countries, as part of the building façade components. They present many advantages such as, economy, durability, great flexibility of plan form, and spatial composition. Furthermore, the construction of masonry walls can fulfill diverse roles including structure, sound insulation, and fire protection [5]. There is a growing interest in finding ways that will partially substitute some of their components such as cement or aggregates for other by-products. Several studies [6-15] have been conducted on this subject, producing an environmentally friendly CMUs while maintaining an acceptable level of compressive strength. All the above research agrees that the incorporation of by-products in the mix reduces manufacturing costs and minimizes the environmental impact of the extraction of the raw materials.

Recent efforts [16-21] have been conducted along similar lines, but they have been focused on one of CMUs weaknesses, i.e. thermal properties. The minimum values specified in the standards required for high efficiency buildings are not usually met by single-width CMU walls. They usually need to be integrated into thermal insulation layers. The aim of these research is to improve the thermal properties of CMUs through the use of by-products, e.g. crumb rubber, bottom ash, hemp fibers, hurds, fly ash, sewage sludge ash and textile effluent sludge, as part of their components. However, the challenge of these research has been to meet the mechanical strength requirements, since in general, the optimization in the thermal properties is given by an increase of porosity in the concrete. Whereas, a high resistance requires that the concrete be as solid as possible [22,23].

Annually, large amounts of sawdust and lime mud are obtained as by-products from the forestry and paper pulp industries and are widely available in several countries. While the former results from sawing timber for the manufacture of furniture and wooden products, the latter is obtained during the conversion of wood into pure cellulose fibers through the kraft process. It is a solid waste generated in a causticization reaction in the alkali recycling process of the paper manufacturing industry.

Depending largely on the average width of the saw, the thickness of the sawn timber and the technology of the sawing process, between 10% and 13% of each log is reduced to fine sawdust particles [24]. Their physical and chemical properties may vary notably according to the species of tree, the geographical location, the sawing technique and, even, the particle size [25-27]. Sawdust is mainly reused for particleboard manufacture, biofuel and animal mulching [28-30].

Previous studies [26,31,32] have assessed the effect of incorporating sawdust in CMUs. Adebakin [26] evaluated the density of blocks with a mix ratio of 1:8 (one part of binder to eight part of sand). Production of blocks was made by partial replacement of sand with a varying proportion (10, 20, 30 and 40%) of sawdust. The results obtained shows that the addition of sawdust reduced the unit weight of the block and this effect was more notary as the proportion was higher. Ogundipe [31] examined the use of this by-product for concrete blocks in load and non-load bearing walls. These were produced from the nominal mixes 1:1:2, 1:1.5:3 and 1:2:4, and the W/C ratio was 0.6. The nominal mixes 1:1:2 and 1:1.5:3 were found to have a compressive strength of 18.33 Mpa and 10 Mpa at 28 days, which satisfied the requirements of the ASTM C-39 for load and non-load bearing walls, respectively. On the contrary, mix 1:2:4 did not satisfy the minimum requirement for non-load-bearing. Turgut et al. [32] manufactured brick by replacing limestone powder waste with sawdust, in proportions ranging from 10-30% by weight. Their results showed that the addition of sawdust increases the porosity, thus decreasing its thermal conductivity. The reduction in the thermal conductivity value of brick sample was lower at 30% replacement, about 38.9%, as compared with control sample.

Lime mud is basically composed of calcium carbonate ($CaCO_3$) and has an estimated waste production of 0.5 m^3 per ton of pulp [33]. The main paper producer worldwide, China, produced in excess of 10 million tons in 2011 [34] and production had continued to grow annually. Like sawdust, the quality of this by-product varies notably because of the different origins of the cellulose fibers and type of paper [35,36]. In Spain and until the most recent economic crisis, lime mud was reused in the construction sector as an additive material for cement. As demand for cement has decreased, paper companies have lobbied to dispose of their waste materials in landfill sites.

There is little research on the addition of lime mud to mortars [37,38] and concrete mixes [39], while its suitability for CMUs has not been tested. Eroðlu et al. [37] partially replaced (5-30% by weight) of cement by lime mud, finding that the density was reduced as the lime mud content increased, except for the sample with the lowest replacement (5%), which increase was about 3.5%, as compared with control sample. Modoro et al. [38] tested at compression mortars that replaced in different amounts (0, 10, 20 and 30%) of cement with lime mud. The result showed that the compressive strength of the three samples at 28 days increased by 8.4% as compared with control mortar. In a previous study by the authors [39], the thermal conductivity of concrete manufactured by partial replacement of cement with a varying proportion (5, 10, and 15%) of lime mud was not influenced in a positive or negative way by the addition of this by-product. Concrete at replacement levels of 15% lime mud showed a thermal conductivity of 1.12 W/m.K, the same as the reference sample. Other authors [40,41] have also evaluated its use in cement production as an addition to the clinker. They found that the mortars mixed with this type of cement developed satisfactory mechanical strength and did not reveal signs of deterioration or durability weaknesses [41]. Another lines of research has focused on its use as a calcined material to manufacture a new kind of calcium-rich material for bricks, as a substitute for ordinary lime, for production in autoclaves and as a soil ameliorant agent [34,42-45].

This research aims to improve the thermal properties of CMUs through the incorporation of sawdust as a fine aggregate replacement and lime mud as a cement replacement. Although the use of sawdust in CMUs has been previously studied in combination with waste paper, limestone dust, glass powder, and rice husk ash [24,32,46-48], blending it with lime mud has received little attention. Previous studies to date have focused on these by-products and their effects on physical and mechanical properties, while the analysis of thermal properties has hardly progressed at all. In this study, our aim is to compensate the negative influence of sawdust on compressive strength by adding lime mud, while maintaining its positive influence with regard to density and thermal properties. So, three types of CMUs were cast for that purpose. In addition to the initial reference concrete mix, 5% of the fine aggregate by volume was substituted for sawdust in the second mix and in the third one, in addition to the fine aggregate replacement of the second type, a binary combination was also adopted with 15% of the cement by volume substituted for lime mud. The mechanical properties were assessed though compressive strength tests at 14, 28, and 90 days. Density, water absorption, and capillary suction tests were conducted to determine the physical properties. The thermal resistance, thermal conductivity, thermal transmittance (U-value), heat flux, and convective heat-transfer coefficient were evaluated with the hot box method 28 days after manufacturing the walls. A comparison between the results obtained and the requirements of the current standards [49-51] is also discussed. Finally, the expenses involved in the production of CMUs with and without by-products were studied by cost analysis.

2 Materials

The cement type used in this study consisted of blended Portland cement CEM II/A-M (V-L) 42.5 R with a density of 3.05 t/m^3 and a composition of fly ash and limestone of 6-20% as per the EN 197-1 standard [51]. Crushed natural-limestone sand with density of 2.71 t/m^3 and size of 0-4 mm was used as fine aggregate, whereas crushed natural-limestone with density of 2.70 t/m^3 and size of 2-6 mm was used as a coarse aggregate. The sawdust used in this research was obtained from the sawing of Radiata pine wood into standard sizes for the production of packaging. Its density is of 0.57 t/m^3 with a size of 0-2 mm. The lime mud was produced as a by-product from the recycling process in paper production using Radiata pine wood as raw pulp. Its density was 0.83 t/m^3 and its size was between 0.4-50 μm. Table 1 shows the chemical analysis and mineral composition of a sample of lime mud. The Loss Of Ignition (LOI) of lime mud is mainly carbon dioxide, with a minor presence of organic matter from cellulosic fibers. Sawdust was used in partial replacement of the fine fraction while lime mud, was incorporated to reduce the cement amount. Both by-products were added without pretreatment. The grading particle size was obtained after sieving in accordance with the test in standard EN 933-1 [51] for natural aggregates and sawdust, and laser diffraction techniques for lime mud (see Fig.1). A more detail information about the physical and chemical properties of the sawdust and lime mud under study can be found in a previous study [39].

Table 1

Chemical and mineral composition of the lime mud.

Chemical composition	Percentage mass (wt.%)
SiO_2	0.03
Al_2O_3	0.01
Fe_2O_3	0.09
MnO	0.01
MgO	0.19
CaO	50.31
Na_2O	2.83
K_2O	0.17
TiO_2	0.01
P_2O_5	0.04
SO_3	1.48
LOI	46.10
Mineral composition	**Percentage mass (wt.%)**
Calcite	>90
Calcium hydroxide	1-3
Organic matter	<7

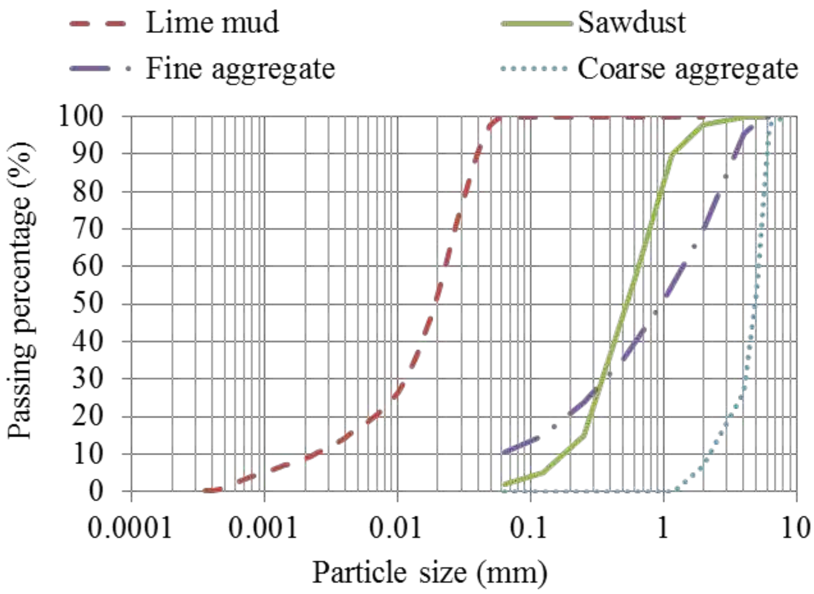

Fig.1. Grading curve of fine aggregate, coarse aggregate, sawdust, and lime mud.

2.1 Concrete mix design

Three types of two-core CMUs were manufactured, all of the same size: 390 mm x 190 mm x 190 mm. These sizes were chosen and correspond to the most widely used blocks for façades in Spain. In one type of CMU 5% of the fine aggregate was substituted (by volume) by sawdust; in another type, 5% and 15% of the fine aggregate and cement were substituted (by volume) by sawdust and lime mud, respectively. As a reference, the series of conventional CMUs involved no substitution. The designations of these 3 types of CMUs were MS, MSLM and MREF, respectively. For each type, 90 blocks were manufactured, amounting to 270 CMUs. The assumed cement and sand substitutions were based on a previous study of the first two authors [39]. In both cases, the sawdust and lime mud dosages have been adopted on the compromise between the thermal properties and the mechanical ones. On the one hand, a low sawdust percentage, 5%, was considered sufficient for improving the insulation of the CMUs without reducing drastically its strength. On the other hand, the addition of lime mud up to a 15% counteracts the negative effect of the sawdust on the mechanical properties.

The mixtures were designed to have no-slump according to the manufacturing requirements for CMUs. The w/b ratio was set at 0.4 for mixes MREF and MS and 0.38 for MSML. Both w/b ratios were low to reduce the cost of cement and the amount of water in the mix and thus obtain better results of strength. A water reducing admixture was added during the stirring stage, even though a no-slump mixes is required, to enhance the workability of all the concrete mixtures needed in the molding process, since the mix was design with a low w/c ratio. The amount of plasticizer was 1%, by weight of cement or binder. Analysis of the mix water showed no compounds that could be harmful to the concrete (pH of 7.81, sulfate content <20 mg/L and a hardness of <14 ºf). The mix design is presented in Table 2.

Table 2

Mix design per 1 m^3.

Mix code	CEM (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	SD (kg/m^3)	SD fraction (Vol. %)	LM (kg/m^3)	LM fraction (Vol. %)	W (kg/m^3)	SP (kg/m^3)
MREF	180	1900	500	-	-	-	-	72	1.80
MS	180	1805	500	19.98	5	-	-	72	1.80
MSLM	153	1805	500	19.98	5	7.35	15	72	1.61

CEM = Cement, FA = Fine aggregates, CA = Coarse aggregates, SD = Sawdust, LM= Lime mud, W = Water, SP = Super plasticizer.

The CMUs were manufactured in a local precast company, using a Giro P-750 concrete mixer and a Quadra V concrete block machine (see Fig. 2). The mixing and placement procedures were similar to the standard ones. After mixing the aggregates, the cement and the by-products were added in two successive stages. Then, the water and the water reducer admixture were gradually dosed. Once prepared, the mixture was passed along a conveyor belt to the previously selected molds where it was vibrated and compacted to produce 6 CMUs every 30 s. The manufacturing process of each series was performed within a period of approximately 7 min. Wet CMUs were finally air-dried at room temperature between 20 and 22.5 °C and at a relative humidity in excess of 50%, until the day of the test.

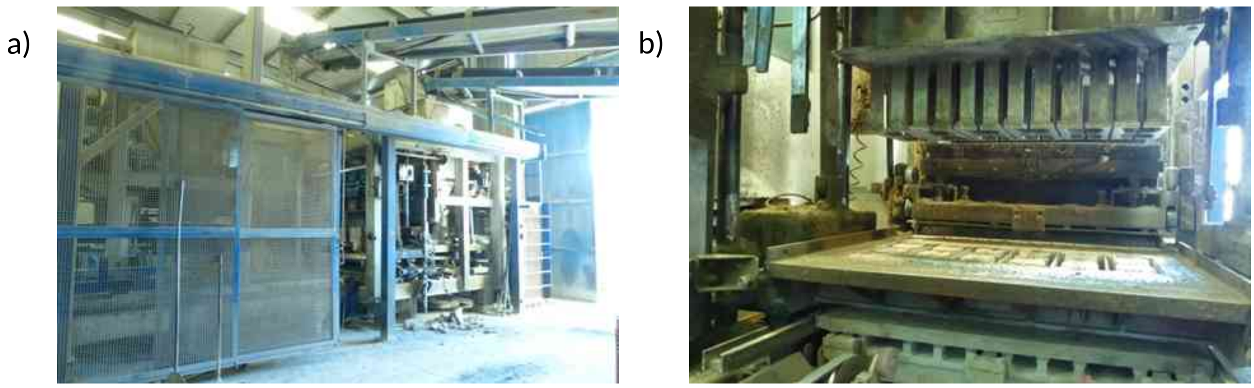

Fig.2. a) Concrete block machine and b) molds.

3 Test procedure

3.1 Density and absorption

Oven-dry density (ρ) and absorption were measured with 6 representative portions of CMUs after 28 days of curing in accordance with ASTM 140-11[49]. The mass of each sample was determined after immersion in water (W_i) at a temperature of 20 °C for 24 h. The samples were weighed while suspended from a metal wire and completely submerged in water (W_s). Subsequently, the specimens were removed from the water and allowed to drain for 60 s over a coarse wire mesh, all visible surface water was wiped away with a damp cloth, and the samples were individually weighed. Following their immersion in water, they were dried in a ventilated oven at 100 °C for no less than 24 h, until two successive weighings at 2 h intervals showed an incremental loss no greater than 0.2% of the previously determined weight of the specimen (W_d). The density and absorption of the CMUs was calculated with Eq. 1, 2 and 3.

$$\rho = W_d / (W \text{¿¿} s - W \text{¿¿} i) . 1000 \text{¿¿} \quad (1)$$

$$Absorption, (Kg/m^3) = (W \text{¿¿} s - W_d) / (W_s - W \text{¿¿} i) . 1000 \text{¿¿} \quad (2)$$

$$Absorption, \% = \text{¿¿} \quad (3)$$

3.2 Capillary suction

The capillary suction (C) of 6 whole blocks of each family after 28 days of manufacturing was determined according to EN 772-11 [51]. The CMUs were dried in an oven at 70 ºC till a constant mass was achieved, after which the specimens were left to cool down to room temperature. Subsequently, their gross area (A) and their dry mass (m) were calculated. The CMUs were then placed on supports in a tray in such way that they were submerged in water to a depth of only 5 mm ± 1 mm. A time-measuring device was activated and the water level remained constant throughout the test, adding water if necessary. After 10 min (t) the specimens were removed, any surface water was wiped away with a damp cloth, and they were weighed to obtain their saturated mass (M). The capillary suction coefficient by capillarity of each type of block was obtained with Eq. 4.

$$C = (M - m) / (A . t) . 10^6 \quad (4)$$

3.3 Compressive strength

The compressive strength test of 6 concrete blocks of each family was performed at 14, 28 and 90 days following the EN 772-1 specifications [51]. Before the test, the surface faces of each specimen to which the load would eventually be applied were capped with a cement/sand mortar. The compression load was applied axially to the capped face of each sample measuring 390 mm x 190 mm at a uniform rate of 0.05 N/mm^2/min until failure. The compressive strength was expressed in terms of the maximum load divided by the gross area of the CMU that had previously been obtained.

3.4 Thermal properties

3 walls measuring 1190 mm x 190 mm x 1000 mm (Length x Width x Height) were raised (see Fig. 3), each with 15 concrete blocks of each series. A commercial mortar formulated with cement, aerial lime, siliceous aggregates, and additives, with a thermal conductivity of 0.7 W/m.K, compliant with the specifications of standard EN 998-1 [51], was used for the mortar joints with an approximate thickness of 10 mm.

a)9 b)9 c)

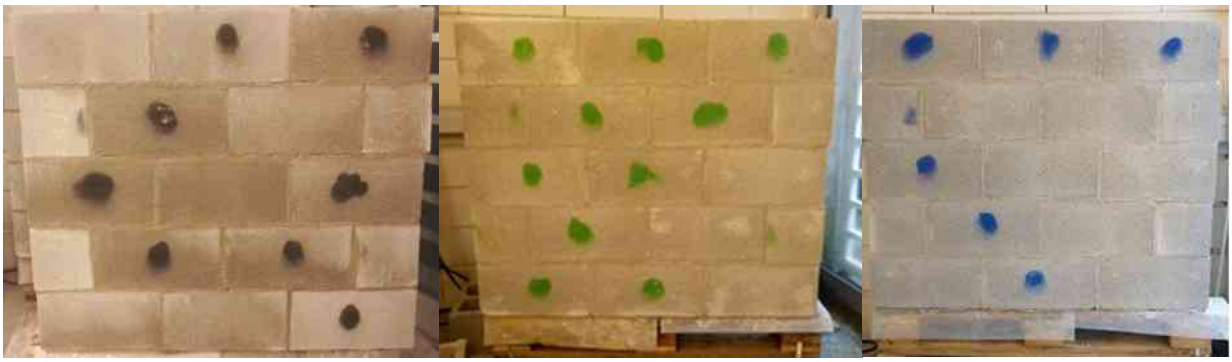

Fig. 3. Built walls: a) MREF wall; b) MS Wall; and, c) MSLM wall.

Measurements of the thermal resistance, the thermal conductivity, the heat-transfer coefficient, the heat flux, and the convective heat-transfer coefficient of the walls were performed with a guarded hot-box device called Thermo3 thermal cell, designed and calibrated according to standard EN ISO

8990 [51]. The apparatus usually consists of 2 isolated chambers, one with a temperature-controlled cold chamber and the other with a hot enclosure regulated in temperature or flow (see Fig. 4). The cold chamber makes it possible to simulate climatic conditions similar to those that may arise outside the building. In this chamber the temperature can be regulated between 5 °C to -10 °C. The hot chamber permits a simulation of the indoor temperature conditions of the building and its temperature can be regulated between 10 °C and 30 °C.

a)9 b)

Fig. 4. a) Specimen preparation for thermal conductivity test; and, b) Hot box.

The faces of the wall which are not in contact with the chambers, were sealed using wood fiber insulation (see Fig.4a), in order to limit thermal exchanges of the wall. The test sample was placed between both chambers. The cold and the hot chambers were each equipped with 12 digital temperature probes, 4 distributed throughout both chambers and 4 on each side of the wall, as shown in Fig. 5.

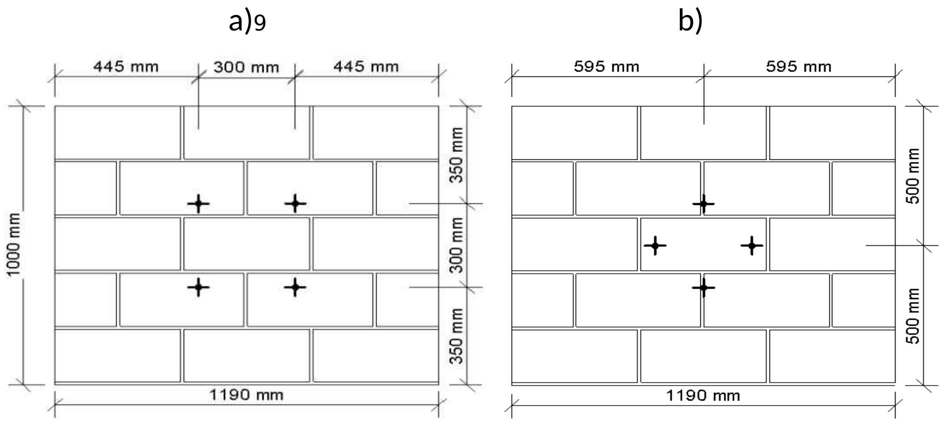

Fig. 5. Position of the temperature probes in contact with the wall: a) hot chamber; and, b) cold chamber.

The test began at a constant temperature on all the walls. Constant temperatures were maintained on both the hot side (inside) at 25 °C and on the cold side (outside) at 5 °C. When the steady state was reached, the temperature gradient could be evaluated, as specified in EN ISO-8990 [51] (minimum 20 ºC). The test was conducted over 24 h and the time of measurement in the steady state was approximately 18 h. On the basis of these measurements, the heat transfer properties of the specimen were calculated. The thermal resistance of the wall could be calculated according to Eq. 5:

$$R = A.\Delta T/\varphi_P = A.(¿ - Tn)/\varphi_P \quad (5)$$

Where: $R$is the thermal resistance, (m².K/W); $A$is the surface of the wall to be tested, (m^2); ΔT is the difference in temperature between the faces of the wall, (ºC); φ_p *is the*heat flow through the wall, (W); ¿ is the temperature of the face of the wall on the hot side, (ºC); and, Tn *is*the temperature of the face of the wall on the cold side, (s).

Similarly, the coefficient of thermal conductivity, a measure of the rate at which heat (energy) passes perpendicularly through a unit area for a temperature difference of one degree, was assessed by Eq. 6.

$$\lambda = e/R \quad (6)$$

Where: λ *represents* thermal conductivity, (W m/k); e is the wall thickness (m); and, R *is* the thermal resistance, (m² K/W).

The heat-transfer coefficient (U-value) is the parameter usually used to limit energy demand through the building façade, which is defined as follows (see Eq. 7):

$$U-value=1/R_T=1/(R_{si}+R+R_{so}) \quad (7)$$

Where: R_{si} and R_{so} are the inner and outer surface resistances, respectively, (m^2.K/W); R is the surface-to-surface thermal resistance, (m^2.K/W); and, R_T is the air-to-air thermal resistance, (m^2 K/W). In the case of horizontal heat flux the standard [51] provides R_{si} = 0.13 m^2.K/W and R_{so} = 0.04 m^2.K/W, as input parameters.

The heat flux can be calculated as follows (see Eq. 8):

$$q=\varphi_P/A \quad (8)$$

Where: q is the heat flux, (W/m^2); φ_p *is the* heat flow through the wall, (W); and, A is the wall surface to be tested, (m^2).

Equation 9 is used to calculate the convective heat-transfer coefficient of the two faces in contact with the chambers.

$$h=\varphi_P/(A.\Delta Tr) \quad (9)$$

Where: h *is* the convective heat-transfer coefficient, (W.m^2/k); ΔTr *is* the difference in temperature between the surrounding fluid area and the solid surface, (ºC); φ_p *is the* heat flow through the wall, (W); and, A *is* the wall surface to be tested, (m^2).

4 Results and discussion

4.1 Density

The average densities of each type of CMU are shown in Table 3. It was found that the greatest reduction in density (6.9%) occurred when the sawdust (5% of total aggregate fines by volume) was incorporated in the concrete mix. This reduction is attributed to the lower density of the sawdust

(0.57 t/m^3), compared to the fine aggregate (2.71 t/m^3) and to an increase in porosity, which could arise due to weaker interaction between the sawdust and the matrix [54]. In contrast, the same effect was observed in the MSLM samples, but to a lesser extent, due to partial substitution of the cement for lime mud, where the reduction in density was 3.4%, in comparison with the density of the reference CMUs. This result suggests that the incorporation of lime mud moderately counteracts the effect of the sawdust.

Table 3

Density, absorption, capillary suction and compressive strength (at 14, 28 and 90 days) values.

Code	Density (kg/m^3)	Absorption (%)	Absorption (kg/m^3)	Capillary suction [g/(m^{2}s)]	Compressive strength (MPa)		
					14 days	28 days	90 days
MREF	2030	6.20	126.5	3.7	5.4	6.7	7.2
MS	1890	10.92	209.8	4.3	3.1	4.4	4.8
MSLM	1960	7.97	159.2	4.1	3.9	5.8	6.2

The definition of a dense aggregate concrete block in EN 127771-3 [51] is any block with an oven-dry density between 1700 and 2400 kg/m^3. Comparing these values with the results, the three types of CMUs are qualified as dense aggregate concrete block. In addition, this range is typical of conventional CMU values. Nevertheless, the oven-dry density requirement for a normal, medium weight, and lightweight block per ASTM C129 [49] is: greater than 2000 kg/m^3, 1680 to 2000 kg/m^3 and lower than 1680 kg/m^3, respectively. Thus, the MREF samples according to this standard are qualified as normal blocks and, the other two samples, as medium weight blocks.

The density of CMUs is an important parameter to determine since a reduction in its weight will provide working comfort and ease of handling and will influence the dead load that the structure can finally support [18] and, therefore, the sizes of the beams, columns and foundations, which will in turn affect the final construction budget. A reduction in the density of the CMUs, as will be assessed in following subsections, would optimize its thermal behavior [55,56]. However, density is closely related to compressive strength; the lower the density of a concrete component the lower its strength [57]. Therefore, this study evaluates the positive influence of lime mud additions to ensure a suitable mechanical behavior.

4.2 Absorption

This property can be an indicator of the compaction level of the concrete mix and of the open porosity in the block. From the results shown in Table 3, an increase in water absorption on samples MS and MSLM of 65.9% and 25.9%, respectively, was observed compared to the MREF, due to the high absorption of sawdust [58]. However, the lime mud in the MSLM samples somewhat counteracted the negative effect of the sawdust. Comparing the values obtained for density and absorption, they were, as expected, found to be inversely correlated. With a decrease in density, the water absorption of the CMUs increased and vice-versa.

Although no specific limit on the absorption value of CMUs is found in the Spanish standard, the ASTM C90 standard [49] specifies maximum water absorption values for CMUs of 208, 240 and 288 kg/m^3 for normal weight, medium weight and lightweight blocks, respectively. Comparing the absorption results obtained with the requirements of this standard, the absorption values were acceptable for the three types of blocks, and within the range established in the standard.

4.3 Capillary suction

Capillary suction plays an important role in the transportation and redistribution of water after it comes into contact with the surface of the block. It depends on the porosity and the degree of connection between the internal pores of the concrete.

The results reveal that capillary absorption increased by 16.2% for CMUs containing 5% sawdust, MS (see Table 3). This increase was expected owing to the water absorption of the sawdust. Moreover, the MSLM specimens also presented an increase; however, it was not as pronounced, at around 10.8%. Thus, a slightly beneficial effect in capillary suction was noticeable in the lime mud concrete. This increase could be attributed to fewer connections between the pores that also improve the compressive strength. These results confirm the data on water absorption presented above. Moreover, the maximum capillary suction value for load-bearing CMUs according to the requirements of the Spanish Building Technical Code (CTE) [59] is limited to 5 [g/(m^2s)]. All the results are lower than the permitted maximums in the Spanish standard. The three types of blocks may therefore be used outdoors, with exposed faces in humid conditions. This test is not part of the ASTM standard for the assessment of CMU performance, so it is not required.

4.4 Compressive strength

The results of the compression test, in terms of averages, at 14, 28, and 90 days of ages are shown in Table 3. Based on experimental evidence, the compressive strength of sample MS had decreased by 34.3% at 28 days compared to sample MREF.

The decreased strength of sample MSLM was lower, at approximately 13.4%. It is evident that the use of lime mud has a positive effect on compressive strength [61]. Previous research has also proven that lime mud in partial replacement of cement will improve the compressive strength of concrete mixes [62,63]. This increased strength is due to a chemical reaction between the nano-$CaCO_3$ and the cement, which accelerates the reaction rate of tricalcium aluminate (C_3A) to form a carboaluminate complex, thereby increasing the total hydration products and the strength [64]. Additionally, there is also a reaction with the tricalcium silicate (C_3S), which reduces setting time and increases resistance at early ages [65].

The minimum 28-day standardized strength requirement for load-bearing CMU according to the Spanish CTE [50] is 5.0 MPa. However, this standard also accepts 4.0 MPa for load-bearing and 3 MPa for non-load-bearing concrete, but the compressive stress will have to be limited at the ultimate limit state to 75% of the masonry design strength, otherwise specific compressive strength studies will have to be performed. The standardized strength is equivalent to the compressive strength of a 100 mm x 100 mm (Width x Height) air dried specimen, the parts converted into equivalent compressive strength corresponding to an air-dried specimen, according to the CTE [50]. The strength was multiplied by a form factor, which in this case is 1.12, due to the size of the pieces. The standardized strengths at 28 days of the three types of CMUs are shown in Fig. 6. Note that both samples MREF and MSLM can be classified as load-bearing concrete masonry. However, additional studies would be necessary for the MS samples, were they ever used in load-bearing walls.

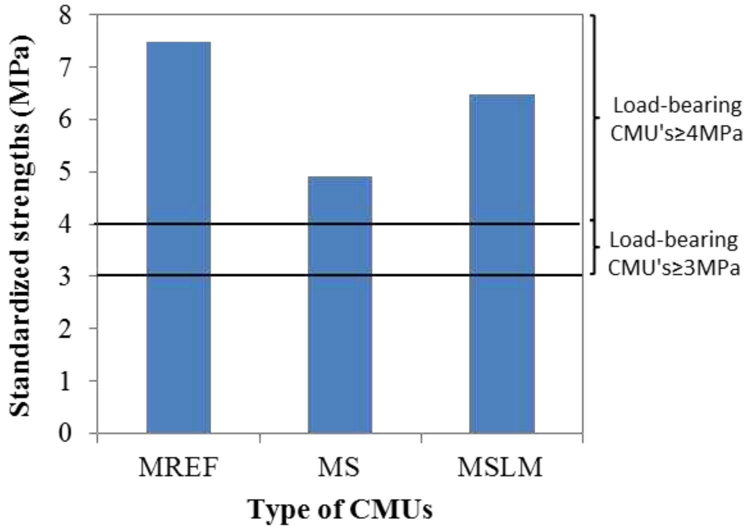

Fig. 6. Standardized compressive strength for CMUs at 28 days and CTE requirements.

While the ASTM C129 and ASTM C90 [49] standards establish a more restrictive criterion, the 28-day strength requirements were set at 4.1 MPa and 13.1 MPa for non-load-bearing and for load-bearing CMUs, respectively. The compressive strength results (see Table 3) for all types of CMUs at 28 days only satisfy the minimum requirements for non-load-bearing structures in those standards. As expected, the CMUs of lower density were observed to have lower compressive strengths.

4.5 Thermal properties

The thermal behavior of CMUs is directly related to both the presence of air voids within the concrete and the components of the concrete. The lower the thermal conductivity of inclusions that substitute the conventional components, the greater the insulation efficiency of the wall [66,67].

The results of the thermal properties of the three masonry walls are shown in Table 4 and the wall temperatures and heat flux stabilization over 24 h are shown in Fig. 7, Fig. 8 and Fig. 9.

Table 4

Thermal properties of the masonry walls.

Designation		MREF wall			MS wall			MSLM wall		
		Average	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.
Guard air temperature:	°C	23.7	23.6	23.9	23.9	23.8	24.0	23.7	23.6	23.8
Warm air temperature:	°C	22.8	22.1	22.2	22.5	22.5	22.6	22.3	22.2	22.3
Warm wall temperature:	°C	19.2	17.6	19.3	19.6	18.4	20.7	19.4	19.1	19.9
Cold air temperature:	°C	5.0	4.5	5.4	5.0	4.6	5.4	5.0	4.5	5.45
Cold wall temperature:	°C	8.1	7.8	9.1	8.1	7.8	16.0	8.3	7.9	9.1
Heat flow:	W	26.1	25.0	32.7	23.3	19.3	24.9	24.2	20.8	26.1
Thermal resistance:	m² K/W	0.27			0.32			0.30		
Thermal conductivity:	W/m.K	0.699			0.601			0.643		
U-value:	W/ m².K	2.26			2.05			2.10		
Heat flux:	W/m²	40.73			36.42			37.75		
Convective heat transfer coefficient (Hot chamber):	W/ m².K	13.53			12.50			13.14		
Convective heat transfer coefficient (Cold chamber):	W/ m².K	13.21			11.74			11.51		

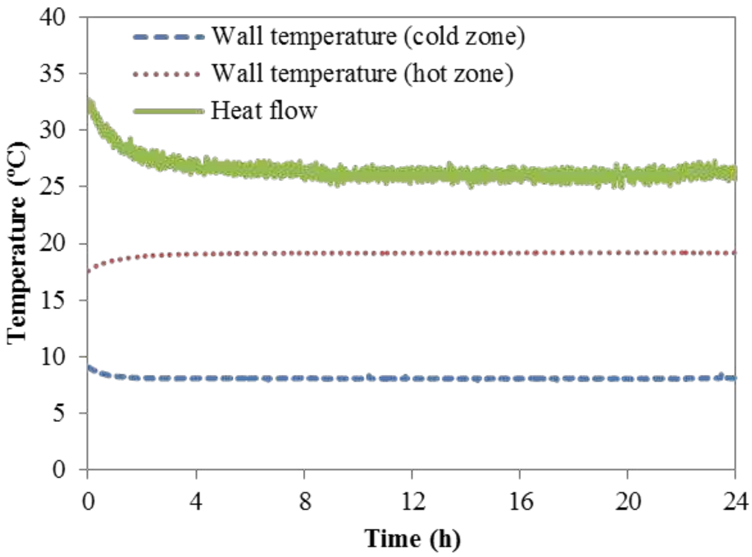

Fig. 7. Measurement of heat flux and temperatures (cold and hot zones) from the MREF wall.

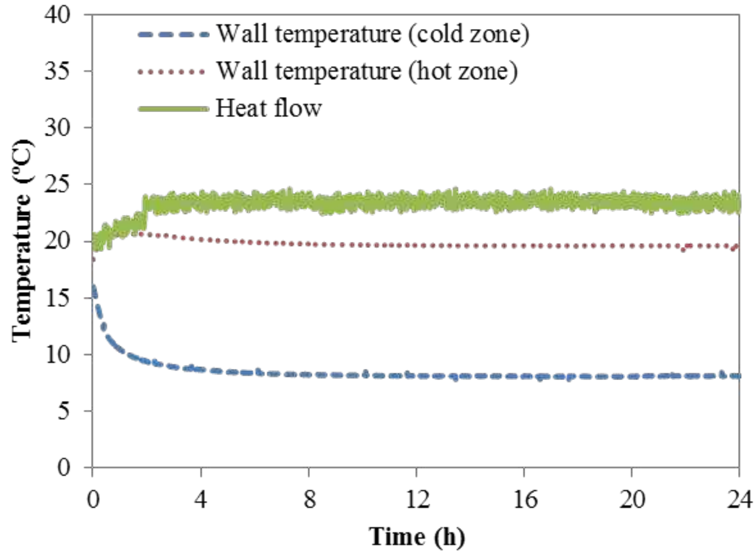

Fig. 8. Measurement of heat flux and temperatures (cold and hot zones) from the MS wall.

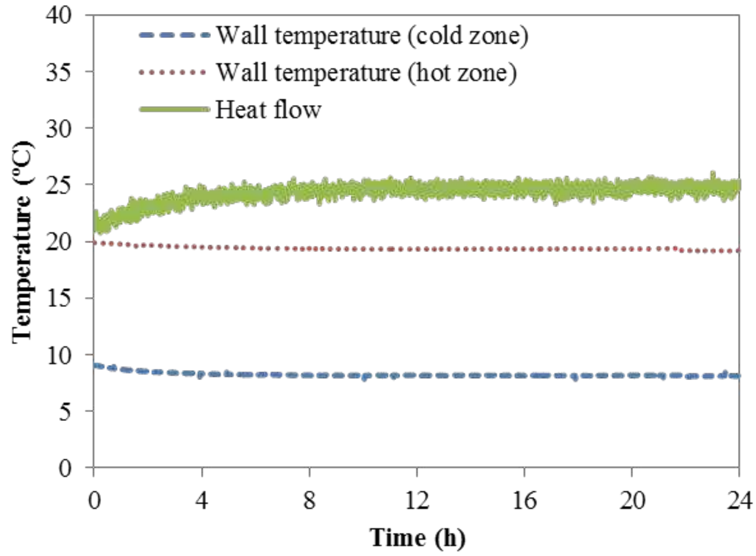

Fig. 9. Measurement of heat flux and temperatures (cold and hot zones) from the MSLM wall.

Comparing the results of the three types of masonry walls, it was found that the incorporation of 5% sawdust improved the thermal resistance values by 18.5% compared to the reference wall, while the combination of 5% sawdust and 15% lime mud improved the same values by 11.1%. This increase in thermal resistance improves the values of thermal conductivity and the transfer coefficient. A decrease in the heat flux was noted of 10.6% in the MS wall and of 7.3% in the MSLM wall.

These improvements in thermal properties are due to sawdust particles that restrain the thermal flow. The thermal conductivity of the (Radiata pine) sawdust is approximately 0.13 W/m.K [68] that is less than the thermal conductivity of the fine limestone within the range of 1-3 W/m.K [69]. Another factor to consider in the increase of voids is the weaker interaction between the sawdust and the matrix than between the fine limestone and the matrix [54], leading to an increase in occluded air. The thermal conductivity of the air is less than that of the concrete [57]. Therefore, the air-gaps oppose the heat transfer through the CMUs, which improves the thermal resistance of the wall [56]. In contrast, improvements in thermal properties are lower for CMUs with a combination of sawdust and lime mud, confirming the variations in thermal conductivity with the density of the tested CMUs [70]. Note that, even though the reduction in density improves the thermal conductivity of the blocks, this behavior reduces the thermal mass of the material, which is needed in climates where summer temperatures are high and there is a large thermal amplitude.

ACI Committee 122 [68] suggests practical thermal conductivity design values for structural concrete blocks with limestone as one of their components, which range from 0.95 W/m.K for a concrete density of 1763 kg/m^3 to 1.44 W/m.K for a density of 2083 kg/m^3. These thermal conductivity values are higher than those obtained in this research.

Although no particular thermal resistance limit value is specified in the current standards, CMUs do have to comply with the U-value stipulated for façades. In Spain, thermal regulations impose maximum U-values for external walls that are between 0.94 and 0.57 W/m^2.K, depending on the climatic area of the location. The results for U-values are between 2.26 and 2.05 W/m^2.K. Therefore, these walls will require extra insulation layers to satisfy the legislation. Therefore, these walls will require extra insulation layers to satisfy the legislation. Nevertheless, this improvement in thermal properties could lead to possible reductions in insulation thickness and thereby increase the available floor area.

The U-value of a typical CMU façade of a house located in the climatic zone of Bilbao where the CTE requires a maximum U-value of 0.730 W/m^2.K, was calculated by varying the thermal conductivity of the CMU and the thickness of the insulation. The façade components from the exterior to the interior consisted of stucco, CMU, stone wool insulation, and gypsum wallboard. Material thicknesses and thermal conductivity as well as the U-value results of 4 façades are shown in Table 5. As observed, a reduction in the insulation thickness of approximately 10 mm can be obtained and complies with the required maximum, where MS or MSLM blocks are used.

Table 5

U-values of three types of façades with the CMUs under study.

	Case 1 MREF		Case 2 MS		Case 3 MSLM		Case 4 MREF	
Materials	λ (W/m.K)	e (m)	λ (W/m.K)	e (m)	λ (W/m.K)	e (m)	λ (W/m.K)	e (m)
Stucco	0.570	0.015	0.570	0.015	0.570	0.015	0.570	0.015
CMU	0.699	0.190	0.601	0.190	0.640	0.190	0.699	0.190
Stone wool insulation	0.035	0.030	0.035	0.030	0.035	0.030	0.035	0.040
Gypsum wallboard	0.400	0.015	0.400	0.015	0.400	0.015	0.400	0.015
U-value (W/m^2.K)	0.734		0.715		0.726		0.610	
	Non-compliant		Compliant		Compliant		Compliant	

4.6 Economic benefits

The expenses involved in the production of CMUs with and without by-products were studied by cost analysis. Materials prices and daily production amounts are the overall of data collected from different providers and the staff of different precast companies, respectively, from Spain. Table 6 summarizes the unit prices of the primary components for the manufactured of CMUs and Table 7 shows the proportion of materials for each mix and the cost of materials for the three types of CMUs. The value of sawdust was set at 35.00 €/Ton, while the lime mud that would otherwise have been dumped at a landfill site was cost free (0.00 €/Ton).

Table 6

Unit price of materials used for the manufacture of the CMUs.

Materials	Price (€)	Market Unit	Volume (m^3)	Unit price per 1 m^3(€)

CEM	95.00	Ton	0.328	289.75
CA	11.00	Ton	0.370	29.70
FA	12.00	Ton	0.369	32.52
SP	0.95	Kg	0.001	995.60
W	1.23	m^3	1.000	1.23
SD	35.00	Ton	1.754	19.95
LM	0.00	Ton	1.000	0.00

CEM = Cement; CA = Coarse aggregates; FA = Fine aggregates; SP = Super Plasticizer; W = Water; SD = Sawdust; LM= Lime mud.

Table 7

Cost of MREF, MS and MSLM materials per 1m^3.

Materials	MREF			MS			MSLM		
	Required volume (m^3)	Unit Price per 1 m^3	Amount (€)	Required volume (m^3)	Unit price per 1 m^3	Amount (€)	Required volume (m^3)	Unit price per 1 m^3	Amount (€)
CEM	0.059	289.75	17.10	0.059	289.75	17.58	0.050	289.75	14.54
CA	0.185	29.70	5.50	0.185	29.70	6.11	0.185	29.70	5.50
FA	0.701	32.52	22.80	0.666	32.52	23.20	0.666	32.52	21.66
SP	0.002	995.60	1.71	0.002	995.60	1.76	0.002	995.60	1.71
W	0.072	1.23	0.09	0.072	1.23	0.09	0.072	1.23	0.09
SD	-	-	-	0.035	17.85	0.67	0.035	19.95	0.70
LM	-	-	-	-	-	-	0.009	0.00	0.00
Total cost of production per 1m^{3}:			47.20			46.76			44.19

CEM = Cement; CA = Coarse aggregates; FA = Fine aggregates; SP = Super Plasticizer; W = Water; SD = Sawdust; LM= Lime mud.

Based on these results, we can affirm that savings per cubic meter of concrete of € 0.44 may be achieved, which is a percentage saving of approximately 1% for the MS samples. There again, for the MSLM samples, the savings per cubic meter of concrete were € 3.01, which is a percentage saving of 6.4%. In this last case, the economic saving is higher, due to the substitution of the cement which is the most expensive component of the mix. Although these percentages are low, the annual savings can be significant if one of these two types of CMUs were manufactured.

A precast company can produce on average 6,000 CMUs over an 8 h workday, which allows us to estimate the savings with regard to the annual cost of materials. A total of 1,482,000 units would be manufactured each year, requiring an amount of 8,233.33 m^3 of concrete. Thus, the materials for the manufacture of typical CMUs would cost a factory € 388,613, although the costs of manufacturing the MS and the MSLM samples would be € 384,991 and €363,831, respectively. A company could therefore achieve a reduction in the cost of materials of approximately either € 3,600 or € 24,700 per year through the production of CMUs with either sawdust or with the combination of both by-products, respectively.

Likewise, for European countries where there is an important production of wood and paper, such as: Sweden, Finland, Germany and Italy and therefore, large quantities of sawdust and lime mud are generated, the economic benefits would be similar to those obtained, since the prices of construction materials in European countries are similar. While other countries such us United States of America, Brazil, Canada, China, Japan, and Russia which also have an significant generation of those by-products will obtain a lower economic benefits, since the price of cement and aggregates is lower, except for Canada and Brazil, which would have a greater economic benefits since, the opposite happens, the price of cement is higher.

A further economic aspect to consider is the savings associated with the disposal of the lime mud at landfill sites [71]. The cost of landfill is around of € 105.60 per ton. In the case of MSLM, a total of 60.52 tons of lime mud would be used. Thus, the cost savings on landfill would be at least € 6,300 per year. Note that the highest economic benefits would ensue from the manufacture of MSLM, as even though sawdust is a by-product, it already has commercial outlets.

On the other hand, a further expense would be found in the cost related to the storage of the by-products in the CMUs production facility, e.g. there would be necessary to buy and install two silos, which nowadays cost approximately 20,000 euros, being the initial inversion of 40,000 euros. Thus, two years would be needed to amortize the initial expenses of facilities for the storage of the by-products.

5 Conclusions

The results of the physical, mechanical and thermal properties of three types of Concrete Masonry Units (CMUs) have been presented in this paper: one type manufactured with 5% of the fine aggregate by volume substituted for sawdust; a second type, with 5% of the fine aggregate by volume substituted by sawdust and 15% of the cement by volume substituted for lime mud; and, a third type with no by-products that served as the reference specimen. Based on the experimental results obtained in the study, the following conclusions can be drawn:

1. The results of the thermal test show that it is possible to optimize the thermal behavior of the CMUs, with the incorporation of sawdust. This improvement is attributed to the increase of voids in the CMUs and the low density of the sawdust, which in turn decreased the density of the units. Therefore, the proportional relationship that exists between the density and the thermal properties of the materials is confirmed.

2. As expected, the partial replacement of the limestone by sawdust resulted in a decrease in the compressive strength of the CMUs, however, this decrease could be partially counteract, with the addition of lime mud and still get an improvement in thermal properties, although not as pronounced, as obtained when only the sawdust was added. This confirmed the inverse relationship that exists between mechanical resistance and thermal properties.

3. The results of compressive strength and capillary suction of the three types of CMUs, met the requirements established in the Spanish regulations for load-bearing CMUs.

4. The incorporation of by-products could lead to a reduction in the costs of the materials for the manufacture of the CMUs and in turn could slightly reduce the total budget of the project, due to the savings in the insulating material of the façade.

5. Sawdust and lime mud have the potential to be used in the production of greener and more economical CMUs. However, the tests presented in this paper constitute the first step in research on sawdust concretes and sawdust and lime-mud combinations for use as components in the

manufacture of CMUs. Further tests such as fire resistance will be needed before these new concrete masonry units may be used as construction materials.

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