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Case study

Coating mortars with improved physical properties, economic cost, and carbon footprint

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ABSTRACT

In recent years there has been renewed interest in innovative solutions for coating mortars. Previous research has clarified the importance of substituting a percentage of cement by other binders, and thus focused on a good balance between structural and thermal properties. However, the effect on the economic cost and the carbon footprint is yet to be fully understood. In this context, the present study aimed at investigating the role of hydraulic lime as a partial substitute for cement and expanded perlite in the structural and thermal properties of mortars while considering the economic cost and the carbon footprint as fundamental variables. We employed a combination of laboratory tests and theoretical calculations to clarify the optimal balance between all considered variables. The findings showed that thermal conductivity can be reduced up to 87.25% and density up to 78.94% if compared with a standard mortar; on the contrary, mechanical properties are compromised yet sufficient for rendering purposes. The final product is affordable, and its carbon footprint is remarkably lower than other alternatives. We concluded that these mortars can deliver optimal properties for rendering purposes, except for the mechanical resistance, which demands further research. In turn, our findings provide evidence for devising feasible options to maintain or repair buildings on a constrained budget, as in the case of social dwellings.

1. Introduction

The building industry accounts for approximately for 36% of the final energy use and 36% of the CO_2 emissions at a global scale, 11% of which resulted from the manufacturing of buildings materials, among which cement is included [44]. The life cycle of a building is a complex process that includes the design, construction, operation, end-of-life, and reuse phases, all of which require considerable amounts of energy. Traditionally, the energy consumption of a building was solely associated to the operation stage, but recent international standards, such as the EN:15978 ([24]), have emphasized the necessity for the assessment of the building's carbon footprint from a wide perspective. Emerging terms such as "*from cradle to grave*" stress the importance of utilizing not only highly insulating materials that limit the energy losses of the building during it operation stage, but also those having a low-embodied energy and therefore a low-carbon footprint.

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In this context, naturally available materials have emerged as a feasible option since they do not require heavy industrial processing. Moreover, their chemical composition allows for combinations with a good balance between thermal conductivity and environmental impact. The economic factor also plays a crucial role, as the construction industry has one of the lowest capital investments, and lags behind other sectors in terms of labor productivity [15], therefore needing to resort to cheap and low-technology solutions.

Mortar is commonly used in the construction industry for two main purposes: structural, whose main function is to join structural elements, such as ceramic bricks, and coating purposes, when they are rendered on a firm support. Its components are a binder (cement and/or lime), a fine aggregate (usually sand), and water; the proportion of the binders, its fabrication, and its main properties are governed by construction standards. A typical coating mortar has a density of $1900 + 50$ kg/m^3 (*UNE-EN 1015–11:2020 Métodos de Ensayo de Los Morteros Para Alb.*, n.d.), and a thermal conductivity of $0.8 + 0.1$ W/(mK) (*B*S EN 1745:2020. *Masonry and Masonry Products. Methods for Determining Thermal Properties*, 2020). Its compressive strength is categorized into three categories: CS I, between 0.4 and 2.5 MPa; CS II, between 1.5 and 5 MPa; CS III, between 3.5 and 7.5 MPa; CS IV, equal to or above 6 Mpa [46]. This standard also includes two ranges of thermal conductivity for plastering and rendering mortars: T1, equal or less than 0.1 W/(mK); T2, equal or less than 0.2 W/(mK).

Being usually employed as a finishing material for exterior coating, a good balance between mechanical and thermal properties remain essential. Also, all its components are economical, and may be mixed on-site at ambient conditions without the need of specialized equipment or industrial processing, making them a feasible option for projects with a constrained budget, such as social dwellings.

Recent research has focused on finding an optimal balance between the mechanical and thermal properties of coating mortars, while containing its economic cost and its carbon footprint. The main problem is that cement is the main responsible for the mechanical strength of mortars, but also for its high thermal conductivity; In addition, it requires a considerable amount of energy to produce. Cement reduces both the porous volume and pore size of the final product, thus limiting air entraining [63]. On the contrary, partial substitution of the content of cement by other mineral products, such as silica fume and fly ash, may result in lower conductivity, around 0.792 W/m°C, but also lower compressive strength [20]. Moreover, cement-based materials have a high embedded energy; massive industrial production of this material is responsible for the depletion of natural resources, such as conventional aggregates [56], and its production is accounted for around 6% of the CO_2 emissions worldwide [56]. With regard to mechanical properties, cement does not combine well with other traditional materials due to the low permeability and rigidity of those [63,66]. The equilibrium between thermal and mechanical properties is a much-debated issue, and some authors argue that the former should be as relevant as the latter [18].

Taken together, these studies support the notion that mortar is an economical and widely available coating material with two main drawbacks: Its high thermal conductivity and carbon footprint, which can be mainly attributed to the cement content. Being the reduction of CO_2 emissions one of the main objectives of the construction industry [60], finding a sustainable alternative to cement remains one of its main challenges. We should not also forget that these alternatives should be equally economical and with a low carbon footprint.

To solve these problems recent research has mainly focused on developing mortars with low economical cost and environmental impact [1,61] while balancing thermal and mechanical properties [71]. With this respect, two main approaches can be mentioned: First, the partial substitution of cement by other natural binders; second, the substitution of conventional fine aggregates (sand), by natural lightweight aggregates.

Regarding the first strategy, natural hydraulic lime has shown promising results as a partial substitute for the cement, in combination with other recycled materials for coating of building facades, because it is a natural material produced at a much lower temperature than cement (around 1000 °C instead of 1450 °C) [31], therefore having much less embodied energy. Much on the current literature pays attention to their chemical, mechanical, and thermal properties.

When lime is used as a partial replacement of cement, mortars have shown higher drying shrinkage [31] and better plasticity, which results in a better workability [32], optimized cement hydration and lower water retention [3], as well as better adherence to other materials [65]. Mortars with natural hydrated lime and cement have also considerably lower thermal conductivity, around 0.15 W/(m·K), and its addition has also resulted in a lower content of gel pores, with 46% higher capacity of removing air pollutants when compared with standard cement mortars [31]. With regard to the balance between mechanical and thermal properties, Gulbe et al. [35] concluded that partial replacement of lime by cement results in a higher compressive strength (1,5 MPa for the base case without cement; 4,9 MPa for the products with a replacement rate of 10%) and slightly higher apparent density; this study concluded that not only cement, but also pozzolan additives should be used in lime mortars [35]. Another study clarified that partial replacement of lime by cement can result in higher strength at early age but only if cement content is less than 25% [73]. Findings on the opposite direction were presented by Damene et al.; if 75% of cement is replaced by hydraulic lime the density of the mortars can be reduced from 1810 kg/m^3 to 1422 kg/m^3 but, at the same time, compressive strength is reduced by 80% and thermal conductivity by 69% [18].

Focusing specifically on the maintenance, restoration, and reparation of extant buildings, previous studies have shown that traditional mixed cement-lime mortars have good mechanical and hydraulic properties [35] and can find application in restoration works [73] and rehabilitation of facades when combined with innovative techniques, such as Arduino [26]; besides, their thermal and mechanical properties are also satisfactory when combined with innovative materials, such clay-silica aggregate, although their price is nearly similar to traditional materials [54].

The second technique consists of incorporating lightweight aggregates (LWA) to the mixture in substitution for the sand. Recent studies have concluded that this strategy results in better thermal and acoustic properties in cement-lime mortars [31,48,66]. This is mainly due to the lower density of the final product, which is strongly related to lower thermal conductivity [55,81]. Moreover, the dead loads of the structure may be reduced, with a consequent decrease in cost, and an increase in the efficiency of the building as a whole [17,31]. Studies conducted by Sengul et al. [70] and Wu et al. [78] agree in the fact that LWA, such as perlite, cenospheres, and diatomite reduce thermal conductivity and density of cement-lime mortars, but also compromise their compressive strength [70,78]. Using a more complex approach, other authors have explored the effects of employing recycled water as mixing water for the aggregates [57] and the solidification process of electroplating sludges in combination with porous aggregates [51].

Among the vast variety of LWA that can find application in concrete and mortars, the expanded perlite (EP) stands out from others, such as expanded glass and exfoliated vermiculite, not only because of its low density [36], but also because of its microstructure. Due to the microporous structure, EP has excellent thermal properties when added to mortar and concrete [16,19,21,50,67,70,75]. Besides, it is not harmful for health, it is fire-resistant, a good acoustic insulator, has a competitive price, and does not react or leach into ground water [16,22,37,45,53,70,72,80]. Several studies have clarified some of those properties in detail. Silva et al. [74] found out that mortars with LWA, such as perlite or vermiculite, are lighter and at the same time show chemical resistance to attacks by sulfates. Other study pointed out the beneficial effects of EP on lime-cement mortars; it reduced the size of small capillaries which, in turn, increased the larger pore size and the total porosity of the mixture [34,64] In the end, the final product showed better sound absorption and thermal conductivity [65].

Additionally, other studies have also explored a wider range of application of mortars incorporating recycled or innovative materials, including the fabrication of structural cement blocks [10] and the production of structural concrete with improved properties [12,62]. These studies provide evidence of the importance of cement as a binding material not only for mortars themselves, but also for other construction materials for which the former is an essential constituent. Nevertheless, what is known about mortars is largely based on studies on the balance between mechanical and thermal properties; either partial replacement of cement by lime or the addition of LWA are the main techniques used by previous studies, mainly from a chemistry or material engineering perspective. There is a notable paucity on research that studies mortars from a more comprehensive perspective, also including considerations about the final cost of the product and its ecological footprint.

The aim of this paper is to find a mortar with a good balance between its thermal and mechanical properties by combining two techniques, the partial substitution of cement by lime, and the addition of EP as LWA, which will be tested in a laboratory. Additionally, this study will also consider the final cost of the product and its ecological footprint as determinant factors to apply it as a construction material in the Chilean context, where the study was conducted.

The specific research questions which drive the research are: Which combination of lime, cement, and lightweight aggregates produce a mortar with an optimal balance between its structural and thermal properties? How do these solutions affect the final cost and the environmental impact of the final product? According to the background research, it is hypothesized that if 40–50% of cement is substituted by lime, the thermal conductivity of the resulting mixture will be decreased around 60%; mechanical resistance will also be affected and it is expected to decrease; however, resulting values will comply with international standards on rendering and plaster mortars [46], which establish different categories with compressive resistance after 28 days between 0.4 and 6 MPa. These properties will be assessed against a standard cement mortar complying with the specifications per ASTM C926 [9]. We also expect that the cost of the final product and the ecological footprint will be affected, although they will not deviate much from the initial solution.

Therefore, this research can shed light on the production of lighter coating mortars with improved thermal properties, by using only natural materials, such as lime and EP. This will benefit the building industry in general, but specifically owners and stakeholders of low-income houses, as sustainable and affordable solutions for repairing and improving the facades of existing buildings will be available in the market.

2. Methodology

To answer the research questions the present study first utilized laboratory tests to clarify the influence of the percentage of lime and cement in the structural and thermal properties of the mortars. The former was set as the independent variables, and the latter as the dependent variables. A note of caution is due here since this research is framed in the Chilean context; measurements of properties and testing procedures relied on the specifications as per the Chilean Standards (NCh), whose majority build on American Standards (ASTM). Both of them are mentioned in this section where necessary.

Then, building upon the results of previous studies, we calculated the ecological footprint, expressed as kg CO_2/kg material, and the

Table 1
Properties of pozzolanic cement.

Property	Pozzolanic cement
Specific weight (gr/cm^3)	2.8
Autoclave expansion (%)	0,1
Curing start time (h:m)	02:40
Curing finish time (h:m)	03:40
Compression resistance (MPa)	
3 days	26.48
7 days	31.38
28 days	40.20
Weight loss by calcination (%)	3.0
SO_3 (%)	3.5

final cost, in Chilean pesos per kg of material. The final results were interpreted and discussed in terms of the best balance between all the aforementioned properties.

2.1. 3.1 Materials

Mortar samples were elaborated using pozzolanic cement, water, hydraulic lime, and expended perlite. The properties for all materials are detailed as follows.

The employed cement (Table 1) follows the prescriptions of the Chilean standard NCh 148:1968 [40], which is a partial adoption of the American standard ASTM C150/C150 M [5]. Regarding the water, as per Chilean standard NCh 1498:2012 [43], tap water can be used to elaborate mortars and concrete.

Two types of lime are generally used in the construction industry: air lime and hydraulic lime; their chemical composition, as well as the way in which they are obtained are different and specified by national standards for construction. In this research hydraulic lime was used; it was obtained following the requirements of the Chilean standard NCh 2256 [42], a document that is referenced to the American standard ASTM C25–17 [7], and the European Standard regarding the percentage of $Ca(OH)_2$ [76] Details of the main properties of the hydraulic lime used in this study are given in Table 4.

The expanded perlite (EP) used in this research had the following chemical composition: 65–75% of silica, 10–20% of aluminum hydroxide, 2–5% of water, and less than 1% of sodium hydroxide, potassium hydroxide and lime. It had a very low thermal conductivity, 0.05 W/(m·K) as per Chilean standard NCh 853 and an apparent density of 80 kg/m^3. Commercially available EP was purchased and then, using a set of sieves that follow the American standard ASTM C136, two granulometries, called EP6 and EP8, were produced (Table 3).

2.2. Mixing process and test samples

Five different types of mortars were elaborated for this study, each one using different proportions of cement and lime. The amount of water was adjusted for each sample so that the relation between water and conglomerates R(W/C) was kept constant; a constant amount of EP was added to all samples. In such way, R(W/C) and EP were considered as control variables.

The mixing procedure can also have an influence on the final properties of the mortars [49]; among the three available procedures, in this study the cement paste was first elaborated: First, cement and lime were dry-mixed and then, water was added; the paste was mixed using a manually operated mixer. Finally, the EP was incorporated gradually, mixing EP6 and EP8 gradations in a similar proportion (50%/50%). This mixing procedure has been found to produce a more homogeneous mortar, preserving the original granulometry of the LWA and giving a final product with lower density.

Two different types of samples were produced. The first included samples measuring 30 × 30 × 3 cms that were used for the thermal conductivity tests; the second type was used to test the mechanical strength with a size of 4×4x16 mms. All samples were prepared in a laboratory with controlled temperature (20–25 °C) and relative humidity (50%–70%). Following the aforementioned procedure, mixtures were prepared and poured into molds of two different sizes, whose inner faces were coated with release agent. Those molds were put with their longest dimension on the vertical plane on a vibrating table, whose frequency was adjusted to 50 Hz. The mixture was then poured into the molds while the table was on; a first layer of approximately one third of the volume of the mold was poured and vibrated for approximately 20–30 s, until the grout started to emerge on the surface; then the second and third layer was added repeating this process; this procedure reproduces the methodology from previous studies by the authors [29].

In previous attempts a rammer was used to compact the mixture, but this technique had to be discarded because there was a possibility that the original granulometry of the LWA would be altered by the strokes of the rammer. Once mixtures were vibrated, they were kept in their molds for 24 h; after that they were released from the molds and introduced in a curing chamber with controlled temperature (20 °C) and relative humidity (96% RH), where they were stored for 28 days.

Table 2
Physical characteristics of hydraulic lime.

Characteristics	Hydraulic lime
Fineness	
Sieve 0,63%, max	0.5
Sieve 0,160%, max	5
Sieve 0,080%, max	15
Curing time (h)	
Start	2
Finish	48
$Ca(OH)_2$ content (%)	39.2
Water retentivity % (min)	75
Compression resistance 28 days MPa (min)	2
Flexural resistance 28 days MPa (min)	0.8

Table 3
Expanded perlite.

Sieve openings (mm)	% passing (EP6)	% passing (EP8)
9.5	100	100
4.75	100	99
2.36	68	42
1.18	22	20
0.6	6	6
0.3	3	4
0.15	1	3

Table 4
Composition of the different mixtures.

		Expanded perlite (50% PP6 and 50% PP8)	Cement	Hydraulic lime	Conglomerant (Cement + lime)		Water	R (W/C)
COD	Variable	(kg /m^3)	(kg / m^3)	(kg / m^3)	(kg / m^3)	(m^3)	(l)	
M1	Lime 20% / Cem. 80%	80.0	120.0	19.3	139.3	0.05358	171.32	1.23
M2	Lime 40% / Cem 60%	80.0	90.0	38.6	128.6	0.05359	158.74	1.23
M3	Lime 60% / Cem 40%	80.0	60.0	57.9	117.9	0.05360	145.51	1.23
M4	Lime 80% / Cem 20%	80.0	30.0	77.1	107.1	0.05355	132.28	1.24
M5	Lime 100% / Cem 0%	80.0	0.0	96.4	96.4	0.05356	119.05	1.23

Note: COD: Sample code; Cem.: Cement; R (W/C): Water-cement ratio

2.3. Thermal conductivity test

Thermal conductivity was tested per Chilean standard NCh 850. Of 2008 [41], which is a partial adoption of the American standard ASTM C177–19 [8]. This procedure determines the thermal conductivity of construction material under a steady and constant heat flux between the parallel and opposite faces of the samples; twin specimens of 30×30×3 cm must be tested at once in a conductometer.

After the curing process, samples were taken out from the chamber and moved to an oven, where they were dried for 24 h at 60 °C. Finally, they were left under laboratory conditions (20 °C 50–60% RH) under which they were tested for thermal conductivity. At that point mass and dimension of the samples were measured using a precision scale with an accuracy of 0.01 g and a caliper with a precision of 0.01 mm respectively; dividing the former by the latter dry apparent density of the samples was calculated.

Twin mortars were introduced in the conductometer, and 6 thermocouples were attached to each one (12 per sample). A temperature difference was induced between the two opposite faces until the system reached a stationary state; at that point, measurements from the 6 thermocouples of each face started to be registered every 30 min; 18 measurements were taken, and the average was calculated over the 6 measuring points of each face. The thermal conductivity was calculated using the average temperature difference between the opposite faces.

2.4. Mechanical resistance tests

Two tests were conducted to clarify the mechanical properties of the mortars: Compression tests and flexural tests. Compressive strength was assessed per Chilean standard NCh 158 Of:1969 [39], which is, again, a partial adoption an American standard, the ASTM C109/C109M [6]. Samples of 40 × 40 × 16 cm were used for both tests.

The compression test was done using a Control Uniframe press calibrated with a 10 kN load ring. The press had a load surface of 1600 mm2 and applied an increasing load uniformly, between 0.98 and 1.96 MPa/s until the materials collapsed; at this point the breaking load was registered. 3 specimens were tested for each mortar and the result was the average for the three of them.

The flexural test was conducted using the same apparatus, but the procedure was different. (UNE-EN 1015–11). The specimens were laid with their longest dimension horizontally. A vertical load was gradually a using a rammer, which was lowered at a speed of 0.8 mm/m until the sample broke; then the breaking load was registered. Three specimens of each mortar were also used for this test, and the final value was the average of the three of them. The breaking load was obtained from the maximum load that the material could bear; it was also a function of the distance between the two pulleys on which the samples are laid (118.5 mm in this case), the height and the width of the samples (40 mm for both of them).

2.5. Cost

The materials were purchased directly from the suppliers, and the retail price was considered for the calculations, including all taxes and charges. It needs to be noted that some materials are sold by volume due to their low density. To express all prices in a common unit, the price per unit of volume was converted into the price per kilogram by multiplying the former by the density as per the specifications of the supplier. Those were obtained from the online repository "Especificar CDT", an open-access database of construction materials sponsored by The Chilean Ministry of Housing and Urban Planning ("[27]), with direct link to the suppliers' information. (Table 5).

2.6. Carbon footprint

The calculation of the carbon footprint of each material comprised the following steps.

The first step in this process was to obtain the data about the necessary energy to produce one unit of each construction material. There are plenty of databases that provide with this information in other countries, but this is not the case for Chile, where this kind of research is still in an early stage of development and yet not fully incorporated into the construction industry. The research project Abaco, carried out in The University of The Bio-Bio, is the first of its kind to compile an open-access database of construction materials considering their carbon footprint, which were calculated using specific information from Chile [2]. One limitation of this database is that it only includes the necessary energy for the production of the materials, but not for other stages if its life cycle, such as transport, installation, maintenance, etc.); other international standards, with application at a European level [24] offers a standardized procedure for such calculations, but they have not been applied to the Chilean context yet. The information extracted from ABACO was used to obtain the necessary amount of energy to produce one kilogram of each material in Chile; eight types were considered: Electricity, natural gas, fuel-oil, diesel, LPG, coal, coking coke, and biomass. Then, using the information from Table 4, we could know how many kilograms of each material were in one cubic meter of each type of mortar. Multiplying these numbers by the energy per kg of material allowed to know the necessary energy to produce one cubic meter of mortar (Eq. 1). The next step was to obtain the emission factors for each type of energy, that is, how many kilograms of CO_2 are emitted to produce one unit of energy; this information was obtained from the IPCC guidelines for national greenhouse gas inventories [33], which is called the emission factors. Finally, multiplying these emission factors by the energy to produce one cubic meter of material we could obtain the carbon footprint per cubic meter of material (Eq. 2). To express the final results in kg CO_2/ kg of material, the former was divided into the density of each sample (Eq. 3). This was done to deliver the results in a commonly used unit, which would allow to compare our results with similar studies. The necessary unit conversion was made where necessary.

$$Energy \quad per \quad kg \quad of \quad material \left(\frac{MJ}{kg}\right) \bullet \quad kg \quad of \quad material \quad per \quad m3 \quad of \quad mortar \quad (kg) = Energy \quad per \quad m3 \quad of \quad mortar\left(\frac{MJ}{m^3}\right) \tag{1}$$

$$Energy \quad per \quad m3 \quad of \quad mortar\left(\frac{MJ}{m^3}\right) \bullet Emissionfactor\left(\frac{kg \quad CO_2}{TJ}\right) = carbon \quad footprint \quad per \quad m^3 of \quad mortar \quad \left(\frac{kg \quad CO_2}{m^3}\right) \tag{2}$$

$$\frac{carbon \quad footprint \quad per \quad m^3 of \quad mortar \quad \left(\frac{kg \quad CO_2}{m^3}\right)}{density \quad of \quad each \quad sample\left(\frac{kg}{m^3}\right)} = \quad carbon \quad footprint \quad per \quad kg. \quad of \quad mortar \quad \left(\frac{kg \quad CO_2}{kg}\right) \tag{3}$$

3. Results

The results are organized into two main areas. The first set of data presents an overview of the tested parameters in Table 6. Then, further analysis clarifies the relation between the percentage of lime and the density, the thermal, and the structural properties; this is presented on figure 2. A note of caution is due before commenting on the results. The samples with 100% of lime (M5) did not harden properly, so their structural properties could not be tested. That left only 4 pairs of samples to be tested for thermal conductivity and structural properties.

All products had a similar apparent density, but no evidence was found for the relation between a greater percentage of lime and a lower wet density. A positive correlation was found between the reduction of thermal conductivity and a decrement of both flexural and compressive resistance. All samples were rather similar in terms of their economic cost, and carbon footprint increased along with the addition of hydraulic lime (Table 6).

Substituting cement by lime had a remarkable effect on thermal conductivity and structural strength, yet the effect on density was almost negligible (Fig. 1). Apparent density could be reduced around 30%, and wet density around 15% when 80% of the cement was substituted by lime. Thermal conductivity was reduced around 20%, and similar figures are observed for the structural properties. Flexural strength was reduced by an 80% and compressive strength by around 60%. Overall, these results indicate that the addition of

Table 5
Price of construction materials considered in the study.

Material	Packaging (Unit)	Supplier	Price per unit (CLP)	Density kg /m^3	Unitary price (CLP/kg)
Cement	Sacks of 25 kg	Cementos Bio-Bio	2806.7	–	112.3
Lime	Sacks of 25 kg	Inacesa	3168.1	–	126.7
Expanded perlite PP6	Sacks of 100 l	Petrasfos	8500	80.0	85,000
Expanded Perlite PP8	Sacks of 100 l	Petrasfos	8500	80.0	85,000
Water	Tap water per m3	ESSBIO	609	–	609

Note: CLP: Chilean peso

Table 6
Properties of the tested samples.

CODE	Variable	Apparent density (kg /m^3)	Wet density (kg /m^3)	Thermal conductivity (W/m·K)	Flexural resistance (^{MPa})	Compressive resistance (MPa)	Cost	Carbon footprint	
							(CLP/ kg)	(kg CO_2/ kg)	(kg CO_2/ m^3)
M1	Lime 20% Cem. 80%	395	956	0.124	0.20	0.99	257.25	0.1101	43.48
M2	Lime 40% Cem 60%	393	717	0.108	0.13	0.82	254.45	0.1509	59.30
M3	Lime 60% Cem 40%	391	644	0.103	0.10	0.78	253.63	0.1927	75.34
M4	Lime 80% Cem 20%	398	724	0.102	0.05	0.48	247.10	0.2293	91.26
M5	Lime 100% Cem 0%	–	–	–	–	–	244.33	0.2696 0.3974	–

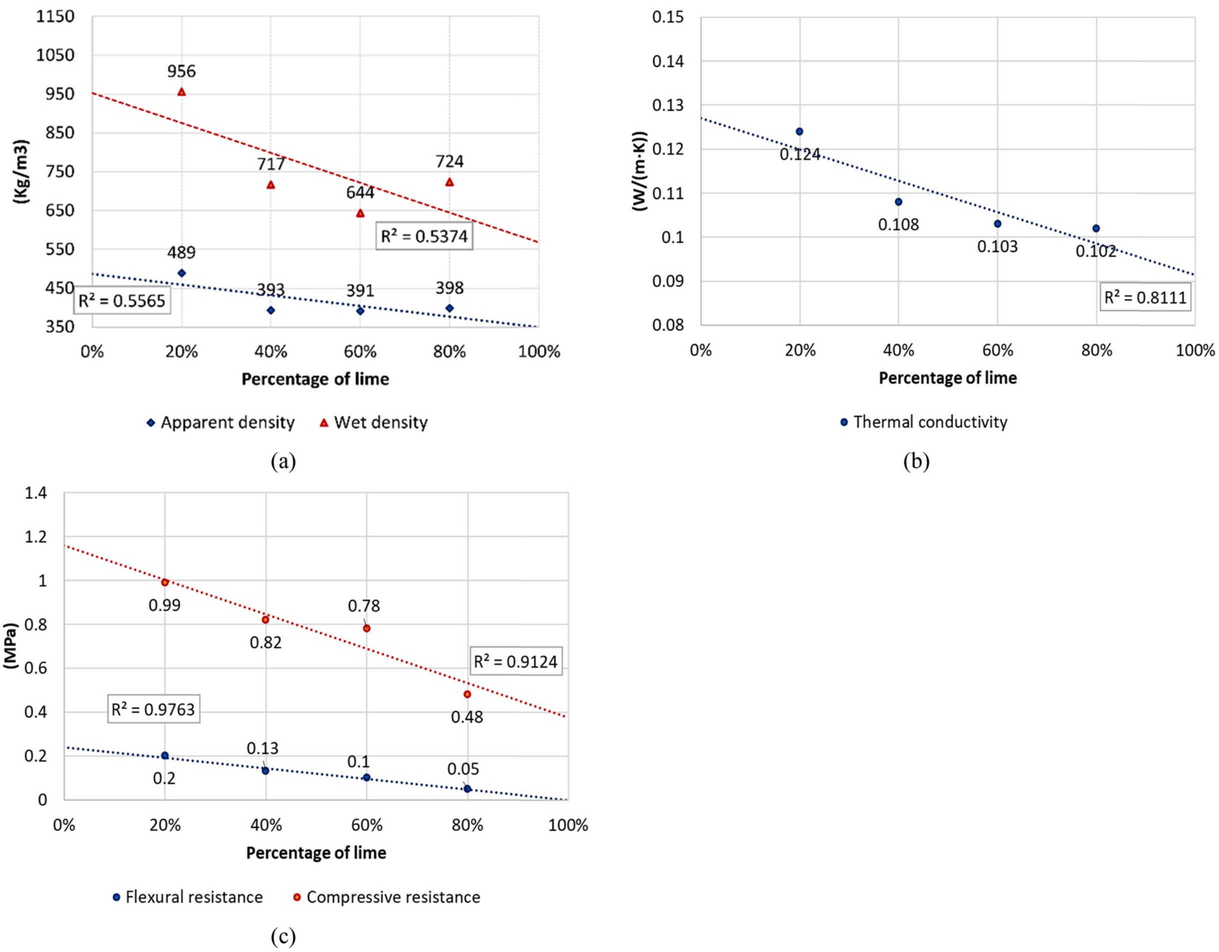

Fig. 1. Effect of the substitution of cement by lime on apparent and wet density (a); thermal conductivity (b); structural resistance (c).

lime had a positive effect on both density and thermal conductivity, although the structural properties could be compromised.

4. Discussion

This study set out to determine whether the partial substitution of cement by lime as fine aggregate, together with the addition of expanded perlite, would impact on the thermal and structural properties of mortars; additionally, the price of the final product and its carbon footprint were considered as decisive factors to assess the suitability of the final product. The lab tests confirmed that the mortars comply with the minimum requirements as per the UNE-EN 998–1:2010 standard [46]. Nevertheless, the obtained mixes could be classified in the lower tier in terms of their compressive strength (CS I). Moreover, their thermal conductivity would place them in the limit between categories T1 and T2, which are classified as low conductivity and high conductivity mortars respectively, according to UNE-EN 998–1:2010.

The obtained mixes had a remarkably low wet density, in the range of 700–1000 kg/m^3, which means that, as per the standards UNE-EN-998–2, could be classed as low-density mortars, being less dense than 1300 kg/m^3. The levels observed in this investigation are far below those observed by Issac and Jayasingh, [47], who obtained a bulk density of between 1770 and 1811 kg /m^3 with a lime to aggregate ratio of 1:3; nonetheless, this study did not use expended perlite as a fine aggregate, but three kinds of organic substances in different concentrations (2%, 4%, and 6%). Indeed, a possible explanation for this may be the total substitution of sand, which has a bulk density of around 1600 kg/m^3, with the expanded perlite, with a density of just 80 kg/m^3.

Now, the questions remains if this decrease in density was to the detriment of other properties. Our results show a quasi-linear relation between a decrease of density and a decrease of compressive resistance and thermal conductivity. These figures match those observed in earlier studies, where the compressive strength after 28 days was in the range of 0.35–1.3 MPa [47]. Another study that employed expanded vermiculite powder with a density of 1.68 gr/cm3 as a partial replacement for the fine aggregate (sand), resulted in mortars with a flexural strength between 1.20 and 6.50 MPa, and a thermal conductivity between 0.689 and 1.160 W/(m·K). Nevertheless, the density of the samples was in the range of 1400–2400 kg/m3, considerably higher than that obtained in the present study.[52]. Likewise, another study confirmed that four types of limestone aggregates were result in higher 28-day compressive strength (between 1 and 1.45 MPa) when compared with a standard sand aggregate (0.65 MPa). Scannell et al. [69]. Regarding thermal conductivity, our findings seem to be in agreement with António et al. [4], where different percentages of limestone dust and charcoal were used as a partial substitute for the cement. The thermal conductivity of the samples was between 0.1547 and 0.4971 W/(m·K); the best results were obtained with a percentage of lime dust of 9.7%, and a percentage of charcoal of 67.8%. Our results suggest that the proper combination of hydraulic lime and lightweight aggregates, such as expended perlite, may yield better results in the range of 0.1 W/(m·K), along with a low density, yet compromising mechanical properties. Another interesting finding from this study is the strong correlation between density and compressive strength (0.9158) and thermal conductivity (0.9975); our results also suggest strong correlation between these variables, always above 0.9, and in a linear fashion. Other studies [52] show agreement with our findings, with quasi-linear correlations for groups of four samples, and correlations above 0.95.

As we mentioned in the introduction, studies also considering the economic cost and the carbon footprint are scarce. In addition, they strongly depend on the country where the mortars are produced, thus comparing the cost across markets seem unfeasible. For those reasons these two variables are discussed on the light of the current state of the Chilean construction market.

Regarding the cost, one of the most commonly used databases for estimating the cost of construction materials is CYPE, a freely available online software (*Generador de Precios de La Construcción. Chile. CYPE Ingenieros, S.A.*, n.d.). In this database one kilogram of standard cement mortar for exterior coating costs 1.184 CLP; if lime is added to the mortar, the cost will be 2.708 CLP/kg. Prices for indoor coating are moderately different, 959 CLP/kg, and 2.978 CLP/kg respectively. This is the sole cost of one kilogram of material itself, without adding other indirect costs, such as labor costs or accessories. The cost of our product ranges between 257.25 and 244.33 CLP/kg, even after adding the consumption tax in Chile, which is 19%, the final price would be between 307 and 300 CLP/kg, being in this way competitive in terms of cost.

There are plenty of databases with information about carbon footprint of construction materials yet remains almost impossible to find this kind of information for Chile. Nonetheless, we can mention that a recent study by Batuecas et al. [13] obtained promising results by substituting part of the cement binder by alkaline activated materials (AAM). The carbon footprint of the base mixture was 535.80 kg CO_2/m^3. A complete substitution by AAM could reduce the carbon footprint to 129.78 kg CO_2/m^3, and partial substitution by AAM resulted in 282.54 kg CO_2/m^3. Our mixtures delivered results in the range of 43.48–91.26 thus confirming that the combination of expanded perlite and hydraulic lime can remarkably lower the environmental impact of the final product, in accordance with similar studies.

The present study was subject to a number of potential methodological weaknesses. As previously mentioned, the total substitution of cement by lime was unfeasible; the mixtures did not conglomerate, and therefore could not be tested. Moreover, despite the results for structural properties comply with the lowest category as per the current standard, it is logically arguable that these numbers may not be sufficient for exterior coating. Further work needs to be done to clarify the way to improve the structural properties while maintaining a low thermal conductivity, and a contained economic cost and carbon footprint.

5. Conclusions

This study set out to investigate the influence of two materials, namely the use of hydraulic lime as a partial substitute for the cement binder, and the addition of EP as a lightweight aggregate, on the mechanical and thermal properties of rendering mortars; density was also considered as a relevant parameter. The second aim of this study was to clarify how the carbon footprint and the cost of the final product would be affected. The most relevant findings to emerge from this research are as follows:

1. Thermal conductivity can be reduced to as low as 0.102 W/(m·K) if we substitute 80% of the cement with hydraulic lime combined with EP as a lightweight aggregate. This represents a reduction of 87.25% when compared with a standard mortar with a conductivity of 0.8 W/(m·K). Even the combination with the highest conductivity shows a reduction of 84.50% with respect to a standards mortar.

2. The different combinations of hydraulic lime and EP do noy decisively affect the apparent density of the final product, which stays in the range of approximately 400 kg/m^3 and represents a reduction of 78.94% when compared with a standard mortar; these numbers can be considered low when compared with other studies, and also have implications from the practical side, such as a better workability.
3. Mechanical properties are compromised and just barely sufficient to meet the current standards as per the UNE-EN 998–1:2010 standard [46]. They could be used as rendering mortars yet exercising extreme caution not to use them in exterior facades exposed to direct impacts or abrasion. They should be protected with some kind of hard coating. This is the main drawback of our study and surely deserves further research in the future.
4. The carbon footprint augments in parallel with the content of hydraulic lime, with values between 43.48 kg CO2/m3 and 91.26 kg CO2/m3. Nevertheless, our values are comparatively better than those from similar studies (129.78 kg CO_2/ m^3), thus it can be concluded that the combination of hydraulic lime and EP is beneficial in terms of the environmental impact of the mortars. We should also note that studies considering this parameter are still scarce, revealing a need for further research in this field.
5. The final price is not remarkably affected, rendering our products affordable and competitive when compared with similar commercial alternatives available on the market. Our prices are in the range of 257.25 CLP/kg – 247.10 CLP/kg, being roughly 73% more economical that the most affordable commercial product available on the market as per January 2022 (959 CLP/kg).
6. Considering all the positive and negative outcomes of our research, we can conclude that the mix with the best combination of all the considered properties is the M1 sample, with 20% of lime in substitution of cement as a binder, and the addition of EP as a lightweight aggregate. This is because of its mechanical properties, contained carbon footprint and cost, and acceptable thermal conductivity.

Overall, this research proves particularly innovative to consider coating mortars from both the theoretical and practical sides: Theoretical because physical properties that are decisive to assess the feasibility of mortars are considered; practical because we also include considerations about the economic cost, which is decisive when it comes to its applicability, and the carbon footprint, which connect with its environmental impact. Prior to this investigation little evidence existed on these aspects from a comprehensive approach.

Notwithstanding the methodological limitations, this study offers some insight into the production of coating mortars with improved thermal conductivity and acceptable structural properties; a proper combination of widely available materials can keep the cost low and reduce the carbon footprint mainly associated to the cement binder. We consider that our findings could be beneficial to the construction industry of emerging countries like Chile, which is deploying public resources to provide families in need with social housing. Affordable and environmentally friendly materials can help those in achieving a more sustainable housing industry.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M. Abdulkareem, J. Havukainen, J. Nuortila-Jokinen, M. Horttanainen, Environmental and economic perspective of waste-derived activators on alkali-activated mortars, J. Clean. Prod. 280 (2021), 124651, https://doi.org/10.1016/j.jclepro.2020.124651.
[2] ABACO Chile – abaco, 2019. Retrieved February 4, 2021, from http://abacochile.cl/.
[3] A.F. Angelin, R.C. Cecche Lintz, W.R. Osório, L.A. Gachet, Evaluation of efficiency factor of a self-compacting lightweight concrete with rubber and expanded clay contents, Constr. Build. Mater. 257 (2020), 119573, https://doi.org/10.1016/j.conbuildmat.2020.119573.
[4] J. António, A. António, G. Bastos, J. Almeida, A. Ant́, A. Tadeu, B. Marques, A. Marques, J. Armesto, F. Patiño, P. Patiño-Barbeito, Influence of different dosages of limestone dust and charcoal on the properties of lightweight cement composites, J. Mater. Civ. Eng. 33 (10) (2021), 04021271, https://doi.org/10.1061/(ASCE)MT.1943-5533.0003891.
[5] ASTM International, ASTM C150 / C150–41, Standard specification for Portland Cement 1941. West Conshohocken, PA. https://doi.org/10.1520/C0150_C01^{50}M–^{19}A.
[6] ASTM International, 2016. ASTM C109 / C109M - 16a. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). West Conshohocken, PA.
[7] ASTM International. ASTM C25–17, Standard Test Methods for Chemical Analysis of Limestone, Quicklime, and Hydraulic Lime 2017. West Conshohocken, PA. https://doi.org/10.1520/C0025–17.
[8] ASTM International, 2019a. ASTM C177–19. Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus. West Conshohocken, PA.
[9] ASTM International, 2019b. ASTM C926 - 19a Standard Specification for Application of Portland Cement-Based Plaster. West Conshohocken.
[10] A.R.G. Azevedo, T.M. Marvila, W. Júnior Fernandes, J. Alexandre, G.C. Xavier, E.B. Zanelato, N.A. Cerqueira, L.G. Pedroti, B.C. Mendes, Assessing the potential of sludge generated by the pulp and paper industry in assembling locking blocks, J. Build. Eng. 23 (2019) 334–340, https://doi.org/10.1016/j.jobe.2019.02.012.

[12] E. Barreto, S. dos, K.V. Stafanato, M.T. Marvila, A.R.G. de Azevedo, M. Ali, R.M.L. Pereira, S.N. Monteiro, Clay ceramic waste as pozzolan constituent in cement for structural concrete, Materials 14 (11) (2021), https://doi.org/10.3390/ma14112917.
[13] E. Batuecas, I. Ramón-Álvarez, S. Sánchez-Delgado, M. Torres-Carrasco, Carbon footprint and water use of alkali-activated and hybrid cement mortars, J. Clean. Prod. 319 (2021), 128653, https://doi.org/10.1016/j.jclepro.2021.128653.
[15] T. Bock, The future of construction automation: technological disruption and the upcoming ubiquity of robotics, Autom. Constr. 59 (2015) 113–121, https://doi.org/10.1016/j.autcon.2015.07.022.
[16] A.G. Celik, A.M. Kilic, G.O. Cakal, Expanded perlite aggregate characterization for use as a lightweight, Physicochemical Problems of Mineral Processing 49 (2) (2013) 689–700.
[17] Y.L. Chen, J.E. Chang, Y.C. Lai, M.I.M. Chou, A comprehensive study on the production of autoclaved aerated concrete: effects of silica-lime-cement composition and autoclaving conditions, Constr. Build. Mater. 153 (2017) 622–629, https://doi.org/10.1016/j.conbuildmat.2017.07.116.
[18] Z. Damene, M.S. Goual, J. Houessou, R.M. Dheilly, A. Goullieux, M. Quéneudec, The use of southern Algeria dune sand in cellular lightweight concrete manufacturing: effect of lime and aluminium content on porosity, compressive strength and thermal conductivity of elaborated materials, Eur. J. Environ. Civ. Eng. 22 (10) (2018) 1273–1289, https://doi.org/10.1080/19648189.2016.1256233.
[19] I. Demir, M. Serhat Baspinar, Effect of silica fume and expanded perlite addition on the technical properties of the fly ash-lime-gypsum mixture, Constr. Build. Mater. 22 (6) (2008) 1299–1304, https://doi.org/10.1016/j.conbuildmat.2007.01.011.
[20] R. Demirboğa, Influence of mineral admixtures on thermal conductivity and compressive strength of mortar, Energy Build. 35 (2) (2003) 189–192, https://doi.org/10.1016/S0378-7788(02)00052-X.
[21] R. Demirboğa, R. Gül, Thermal conductivity and compressive strength of expanded perlite aggregate concrete with mineral admixtures, Energy Build. 35 (11) (2003) 1155–1159.
[22] W.P. Dubé, L.L. Sparks, A.J. Slifka, Thermal conductivity of evacuated perlite at low temperatures as a function of load and load history, Constr. Build. Mater. 6 (1) (1992) 19–22, https://doi.org/10.1016/0950-0618(92)90023-R.
[24] EN 15978 2011. Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method, 1. (testimony of EN European Standards).
[26] D. Ferrández, E. Yedra, E. Atanes-Sánchez, C. Morón, Arduino based monitoring system for materials used in façade rehabilitation – experimental study with lime mortars, Case Stud. Constr. Mater. 16 (2022), e00985, https://doi.org/10.1016/j.cscm.2022.e00985.
[27] Fichas, 2021. Retrieved February 4, 2021, from http://www.especificar.cl/.
[29] V. Flores-Alés, M. Rodríguez-Romero, I. Romero-Hermida, L. Esquivias, Caracterización de morteros mixtos de cal obtenida del reciclado de fosfoyeso, Bol. De. La Soc. Esp. De. Cerámica Y. Vidr. 59 (3) (2020) 129–136, https://doi.org/10.1016/j.bsecv.2019.09.002.
[31] C. Giosuè, Q.L. Yu, M.L. Ruello, F. Tittarelli, H.J.H. Brouwers, Effect of pore structure on the performance of photocatalytic lightweight lime-based finishing mortar, Constr. Build. Mater. 171 (2018) 232–242, https://doi.org/10.1016/j.conbuildmat.2018.03.106.
[32] P.J.P. Gleize, A. Müller, H.R. Roman, Microstructural investigation of a silica fume-cement-lime mortar, Cem. Concr. Compos. 25 (2) (2003) 171–175, https://doi.org/10.1016/S0958-9465(02)00006-9.
[33] Gómez, D.R., Watterson, J.D., Americano, B.B., Ha, C., Marland, G., Matsika, E., … Treanton, K. , 2006. Directrices del IPCC de 2006 para los inventarios nacionales de gases de efecto invernadero (in Spanish). Retrieved from https://www.ipcc-nggip.iges.or.jp/public/2006gl/spanish/vol2.html.
[34] C. Guardia, D.S. Schicchi, A. Caggiano, G. Barluenga, E. Koenders, On the capillary water absorption of cement-lime mortars containing phase change materials: experiments and simulations, Build. Simul. 13 (2020) 19–31.
[35] L. Gulbe, I. Vitina, J. Setina, The influence of cement on properties of lime mortars, Procedia Eng. 172 (2017) 325–332, https://doi.org/10.1016/j.proeng.2017.02.030.
[36] L. Gündüz, Ş.O. Kalkan, A technical evaluation on the determination of thermal comfort parametric properties of different originated expanded and exfoliated aggregates, Arab. J. Geosci. 12 (4) (2019) 2017–2020, https://doi.org/10.1007/s12517-019-4301-8.
[37] M. Gürsoy, M. Karaman, Improvement of wetting properties of expanded perlite particles by an organic conformal coating, Prog. Org. Coat. 120 (January 2017) (2018) 190–197, https://doi.org/10.1016/j.porgcoat.2018.03.021.
[39] INN Instituto Nacional de Normalización. 1967. NCh 158:1967. Cementos - Ensayo de flexión y compresión de morteros de cemento. Santiago de Chile.
[40] INN Instituto Nacional de Normalización. NCh 148:1968. Cemento. Terminología, clasificación y especificaciones generales. 1968. Santiago de Chile.
[41] INN Instituto Nacional de Normalización, 1983. NCh 850:1983. Aislación térmica. Método para la determinación de la conductividad térmica en estado estacionario por el método del anillo de guarda. Santiago de Chile.
[42] INN Instituto Nacional de Normalización. NCh 2256/1 Of. 2001. Morteros - Parte 1: Requisitos generales. 2001. Santiago de Chile.
[43] INN Instituto Nacional de Normalización. NCh 1498:2012. Agua de amasado. Requisitos 2012. Santiago de Chile.
[44] International Energy Agency, 2019. Global Status Report for Buildings and Construction.
[45] B. Işıkdağ, Characterization of lightweight ferrocement panels containing expanded perlite-based mortar, Constr. Build. Mater. 81 (2015) 15–23, https://doi.org/10.1016/j.conbuildmat.2015.02.009.
[46] ISO, 2018. UNE-EN 998–1:2010. Specification for mortar for masonry - Part 1: Rendering and plastering mortar.
[47] C. Issac, S. Jayasingh, Accelerating the Hardening of Lime Mortar on Addition of Organics for Repair in Heritage Structures. RILEM Bookseries vol. 34, Springer, 2022, pp. 109–121, https://doi.org/10.1007/978-3-030-76465-4_10.
[48] A. Izaguirre, J. Lanas, J.I. Alvarez, Effect of a polypropylene fibre on the behaviour of aerial lime-based mortars, Constr. Build. Mater. 25 (2) (2011) 992–1000, https://doi.org/10.1016/j.conbuildmat.2010.06.080.
[49] M. Jedidi, O. Benjeddou, C. Soussi, Effect of expanded perlite aggregate dosage on properties of lightweight concrete, Jordan J. Civ. Eng. 9 (3) (2015) 278–291, https://doi.org/10.14525/jjce.9.3.3071.
[50] G. Jia, Z. Li, P. Liu, Q. Jing, Preparation and characterization of aerogel/expanded perlite composite as building thermal insulation material, J. Non-Cryst. Solids 482 (October 2017) (2018) 192–202, https://doi.org/10.1016/j.jnoncrysol.2017.12.047.
[51] L.F. Jochem, C.A. Casagrande, M.B. Bizinotto, D. Aponte, J.C. Rocha, Study of the solidification/stabilization process in a mortar with lightweight aggregate or recycled aggregate, J. Clean. Prod. 326 (2021), 129415, https://doi.org/10.1016/j.jclepro.2021.129415.
[52] F. Koksal, T. Nazlı, A. Benli, O. Gencel, G. Kaplan, The effects of cement type and expanded vermiculite powder on the thermo- mechanical characteristics and durability of lightweight mortars at high temperature and RSM modelling. Case Studies in Construction, Case Stud. Constr. Mater. 15 (2021), e00709, https://doi.org/10.1016/j.cscm.2021.e00709.
[53] E. Kolvari, N. Koukabi, M.M. Hosseini, Perlite: A cheap natural support for immobilization of sulfonic acid as a heterogeneous solid acid catalyst for the heterocyclic multicomponent reaction, J. Mol. Catal. A Chem. 397 (2015) 68–75, https://doi.org/10.1016/j.molcata.2014.10.026.
[54] D. Koňáková, M. Čáchová, E. Vejmelková, M. Keppert, M. Jerman, P. Bayer, R. Černý, Lime-based plasters with combined expanded clay-silica aggregate: microstructure, texture and engineering properties, Cem. Concr. Compos. 83 (2017) 374–383, https://doi.org/10.1016/j.cemconcomp.2017.08.005.
[55] J. Kurnitski, T. Kalamees, J. Palonen, L. Eskola, O. Seppänen, Potential effects of permeable and hygroscopic lightweight structures on thermal comfort and perceived IAQ in a cold climate, Indoor Air 17 (1) (2007) 37–49, https://doi.org/10.1111/j.1600-0668.2006.00447.x.
[56] P.C. Lau, D.C.L. Teo, M.A. Mannan, Mechanical, durability and microstructure properties of lightweight concrete using aggregate made from lime-treated sewage sludge and palm oil fuel ash, Constr. Build. Mater. 176 (2018) 24–34, https://doi.org/10.1016/j.conbuildmat.2018.04.179.
[57] J.-I. Lee, S.-H. Bae, J.-H. Kim, S.-J. Choi, Effect of cementitious materials on the engineering properties of lightweight aggregate mortars containing recycled water, Materials 15 (5) (2022) 1967, https://doi.org/10.3390/ma15051967.
[60] Flores-Alés Martín, Aparicio, Proposed methodology to evaluate CO_2 capture using construction and demolition waste, Minerals 9 (10) (2019) 612, https://doi.org/10.3390/min9100612.

[61] M.T. Marvila, A.R.G. Azevedo, J. Alexandre, H. Colorado, M.L. Pereira Antunes, C.M.F. Vieira, Circular economy in cementitious ceramics: replacement of hydrated lime with a stoichiometric balanced combination of clay and marble waste, Int. J. Appl. Ceram. Technol. 18 (1) (2021) 192–202, https://doi.org/10.1111/ijac.13634.

[62] M.T. Marvila, A.R.G. de Azevedo, P.R. de Matos, S.N. Monteiro, C.M.F. Vieira, Materials for production of high and ultra-high performance concrete: review and perspective of possible novel materials, Materials 14 (15) (2021), https://doi.org/10.3390/ma14154304.

[63] M.J. Mosquera, B. Silva, B. Prieto, E. Ruiz-Herrera, Addition of cement to lime-based mortars: effect on pore structure and vapor transport, Cem. Concr. Res. 36 (9) (2006) 1635–1642, https://doi.org/10.1016/j.cemconres.2004.10.041.

[64] S. Olaniyan, Pore structure as a determinant of flexibility in sustainable lime-cement mortar composites, Eur. J. Eng. Technol. Res. 6 (6) (2021) 113–122.

[65] I. Palomar, G. Barluenga, A multiscale model for pervious lime-cement mortar with perlite and cellulose fibers, Constr. Build. Mater. 160 (2018) 136–144, https://doi.org/10.1016/j.conbuildmat.2017.11.032.

[66] I. Palomar, G. Barluenga, J. Puentes, Lime-cement mortars for coating with improved thermal and acoustic performance, Constr. Build. Mater. 75 (2015) 306–314, https://doi.org/10.1016/j.conbuildmat.2014.11.012.

[67] A. Różycka, W. Pichór, Effect of perlite waste addition on the properties of autoclaved aerated concrete, Constr. Build. Mater. 120 (2016) 65–71, https://doi.org/10.1016/j.conbuildmat.2016.05.019.

[69] S. Scannell, M. Lawrence, P. Walker, Impact of aggregate type on air lime mortar properties, Energy Procedia 62 (2014) 81–90, https://doi.org/10.1016/J.EGYPRO.2014.12.369.

[70] O. Sengul, S. Azizi, F. Karaosmanoglu, M.A. Tasdemir, Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete, Energy Build. 43 (2–3) (2011) 671–676, https://doi.org/10.1016/j.enbuild.2010.11.008.

[71] P. Shafigh, I. Asadi, A.R. Akhiani, N.B. Mahyuddin, M. Hashemi, Thermal properties of cement mortar with different mix proportions, Mater. De. Constr. 70 (339) (2020) 224, https://doi.org/10.3989/mc.2020.09219.

[72] D. Shastri, H.S. Kim, A new consolidation process for expanded perlite particles, Constr. Build. Mater. 60 (2014) 1–7, https://doi.org/10.1016/j.conbuildmat.2014.02.041.

[73] B.A. Silva, A.P. Ferreira Pinto, A. Gomes, Natural hydraulic lime versus cement for blended lime mortars for restoration works, Constr. Build. Mater. 94 (2015) 346–360, https://doi.org/10.1016/j.conbuildmat.2015.06.058.

[74] L.M. Silva, R.A. Ribeiro, J.A. Labrincha, V.M. Ferreira, Role of lightweight fillers on the properties of a mixed-binder mortar, Cem. Concr. Compos. 32 (1) (2010) 19–24, https://doi.org/10.1016/j.cemconcomp.2009.07.003.

[75] I.B. Topçu, B. Işikdağ, Manufacture of high heat conductivity resistant clay bricks containing perlite, Build. Environ. 42 (10) (2007) 3540–3546, https://doi.org/10.1016/j.buildenv.2006.10.016.

[76] UNE EN 459–2:2022 Building lime - Part 2: Test methods UNE EN 459–2:2022 Building lime - Part 2: Test methods, 1 2022. (testimony of UNE).

[78] Y. Wu, J.Y. Wang, P.J.M. Monteiro, M.H. Zhang, Development of ultra-lightweight cement composites with low thermal conductivity and high specific strength for energy efficient buildings, Constr. Build. Mater. 87 (2015) 100–112, https://doi.org/10.1016/j.conbuildmat.2015.04.004.

[80] S. Yilmazer, M.B. Ozdeniz, The effect of moisture content on sound absorption of expanded perlite plates, Build. Environ. 40 (3) (2005) 311–318, https://doi.org/10.1016/j.buildenv.2004.07.004.

[81] Q.L. Yu, P. Spiesz, H.J.H. Brouwers, Ultra-lightweight concrete: conceptual design and performance evaluation, Cem. Concr. Compos. 61 (2015) 18–28, https://doi.org/10.1016/j.cemconcomp.2015.04.012.