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Review

Expanded Vermiculite: A Short Review about Its Production, Characteristics, and Effects on the Properties of Lightweight Mortars

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Abstract: Global temperatures have led to an increasing need for air conditioning systems. So, because of this fact, buildings have been improved in terms of their thermal and energy efficiency. Regarding this, the Brazilian standard ABNT NBR 15.575-4/2013 set minimum parameters for the thermal transmittance and thermal capacity of sealing elements, which allow classifying the thermal efficiency of the building. In order to comply with the requirements, the usage and study of lightweight construction materials have been in focus. An example of these materials is vermiculite. The present research reviewed articles about expanded vermiculite. The study involved the examination and comparison of various articles to analyze the properties of vermiculite and the impact of its usage on coating mortars. It was possible to verify that using vermiculite in mortars caused bad workability and a decrease in mechanical strength. However, the porosity and water absorption in mortars increased. Additionally, it reduced the specific weight and the thermal conductivity of the mortars, allowing for a better thermal insulation of the rooms. As an alternative to decreasing the negative effects of vermiculite, it is possible to use chemical admixtures, mineral additions, and mix design with a greater consumption of binder or a combination of particle sizes.

Keywords: vermiculite; fine aggregate; lightweight aggregate; coating mortar; thermal comfort

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1. Introduction

The consumption of natural resources has greatly increased in recent times. Industrial activities have led to an increase in global temperature over the years. According to a report from the Intergovernmental Panel on Climate Change [1], global temperature has increased by 0.8 °C to 1.2 °C compared to the average temperature of the 20th century.

As a consequence of this temperature increase, warmer thermal sensations have been experienced by the world population, especially in tropical areas, where temperatures are naturally higher. To mitigate heat and improve environmental comfort, cooling systems have been widely used. According to a technical note from the Energy Research Company (ERC) [2], in 2014 and 2015, higher thermal waves in relation to previous years were recorded, and because of this, the number of air conditioner sales recorded peaks in the same period. In addition, the ERC's study showed that in 2017, air conditioners were in fourth position among the devices that consumed the most energy in Brazilian homes, with this proportion increasing by 7% between the years 2005 and 2017.

In view of this temperature increase and thermal inconvenience, public policies were created to set up guidelines for improving buildings' energy efficiency, providing well-being, and providing low costs to the end consumer. As an example, in Brazil, there is a law whose number is 10.295 [3] and a technical standard NBR 15.575-4/2013 [4] that described rules to achieve the ideal requirements for thermal comfort and others. The technical standard evaluates a building's thermal performance based on the minimum parameters of thermal transmittance and thermal capacity of its wall elements, thereby categorizing its thermal efficiency using this information.

The building system has a significant impact on the thermal comfort of a house. In this regard, Lamberts [5] found that the heat transfer between a wall's surfaces and the thermal comfort of a room enclosed by them is associated with the physical properties of the wall's constituent materials (including brick masonry and coating mortar). These properties can include thermal conductivity, bulk density, and specific density. The author pointed out that the use of materials with low thermal conductivity provides a lower heat flow inside the wall, decreasing the heat exchange between the external and internal environment.

Several solutions that promote low thermal conductivity and greater thermal inertia in walls have been researched for reducing heat exchange between rooms. Some types of materials can be applied to promote this thermal insulation, such as glass, wool, rock wool, expanded polystyrene, cellular concrete, and mortars with lightweight aggregates. These materials present common characteristics such as low specific density, which, according to Stancato [6], is related to thermal conductivity and decreases as the amount of air inside the material increases, consequently reducing its specific weight.

Vermiculite belongs to this group of materials. Due to its chemical, mineralogical, and structural features, it is considered an excellent insulator, and when applied to other materials or components, it enhances their properties. It is nontoxic, noncombustible, capable of absorbing liquids, acts as a lubricant at high temperatures, and provides thermal and acoustic insulation [7]. This aggregate is already widely used in the construction industry with the aim of promoting thermal comfort; however, its use in cementitious materials is hampered by high water absorption. This fact becomes a problem because it can modify the workability of the mixes and, consequently, other properties in fresh and hardened states.

This paper aims to provide a comprehensive overview of vermiculite's significance as a construction material, particularly its thermal insulation properties when it is used in mortar mixes. This review will focus on the characteristics of lightweight aggregate and its impact on the fresh and hardened properties of mortars, as well as the thermal conductivity of coating mortars.

2. Vermiculite

Vermiculite is the geological name given to a group of hydrated laminar minerals that are aluminum-iron-magnesium silicates, resembling mica in appearance [8]. The *Encyclopedia Britannica* (2018) [9] describes vermiculite as being a clay mineral with a structure similar to montmorillonite ($(Na,Ca)_{0.3}(Al,Mg)_2Si_4O10(OH)_2.nH_2O$), with a tendency to swell in the presence of water and with a high ion exchange capacity. Vermiculite is of supergene (chemical weathering) and/or hydrothermal (water and temperature action together) origin, produced from the alteration or substitution of phlogopite, biotite, and chlorite, among other mafic micas (volcanic origin) in various types of rock [10].

This clay mineral occurs in both macroscopic and microscopic categories, the first one being formed predominantly in natural deposits, and it can be found in four rock types: (1) ultramafic and mafic; (2) gneiss and schist; (3) carbonate rocks; and (4) granitic rocks [11]. Through an experimental and bibliographical search, Bassett (1961) [11] suggests that vermiculite formation occurs predominantly via supergene processes (chemical weathering).

Schulze (2005) [12] points out vermiculite as a clay silicate with particles smaller than 2 μm and a crystalline structure formed by layers of type 2:1. (Figure 1). Interlayer minerals such as mica and biotite have potassium atoms in their constitution, but in vermiculite, the interlayer has water molecules and magnesium [13].

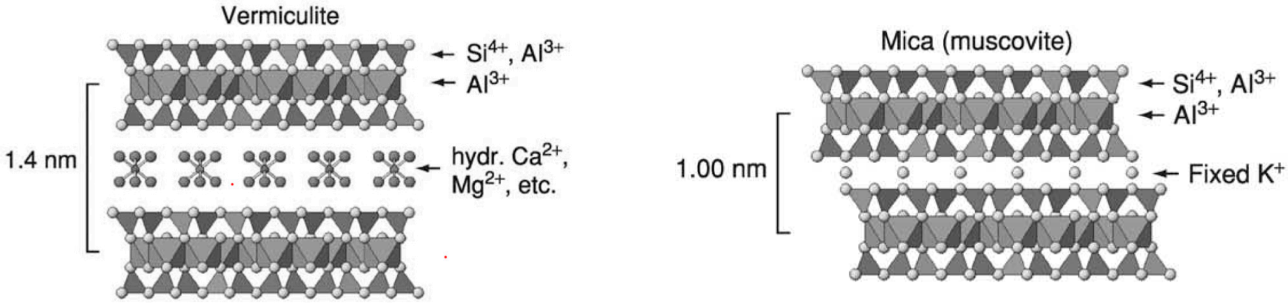


Figure 1. Molecular structure of vermiculite and mica. Font: Schulze (2005) [12].

Vermiculite presents a variety of chemical compositions because of the elements contained in the original mica formation and chemical changes during weathering and ion exchange [14]. Hindman [14] proposed a common chemical formula for vermiculites based on the analysis of over 60 vermiculites (Figure 2).

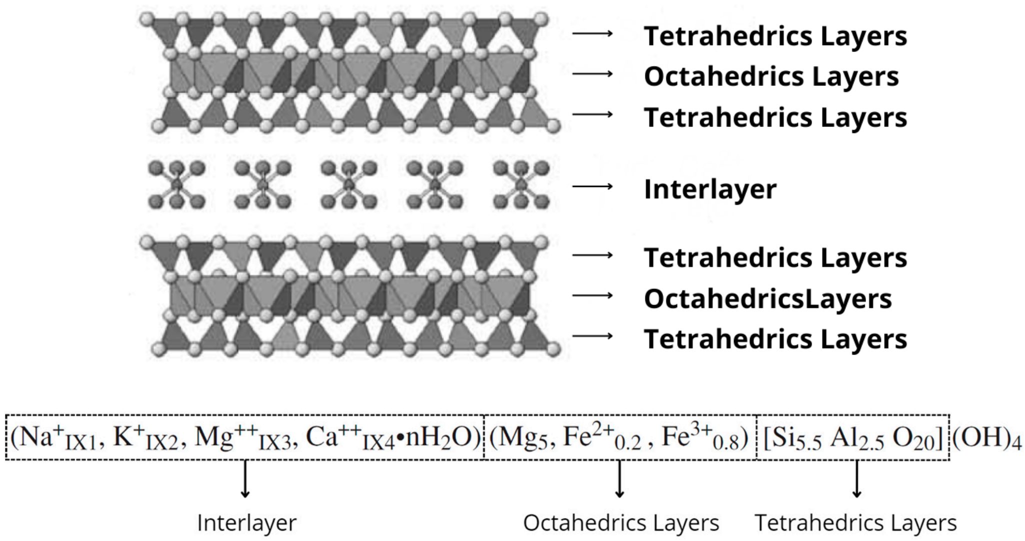


Figure 2. Chemical composition of vermiculite [12,14].

The properties of vermiculite are a function of the oxide contents. Nascimento (2008) [15] showed that there are possible variations in the constituent oxides of vermiculite and these are shown in Table 1. The presence of other minerals or higher concentrations of some oxide may cause changes in vermiculite's chemical composition, and its mineralogical origin is one of the main factors for differences in the oxide contents. Ugarte et al. (2005) [16] state that one of the forms of emergence of vermiculite is due to a change in biotite, which has a large concentration of iron oxide. Because of the high iron oxide contents, a golden-red coloration or silver coloration in vermiculite is observed, contrasting the traditional light- or dark-brown coloration [17].

Another chemical element influential in the characteristics of vermiculite is potassium; if its contents amount to greater than 1%, material expansion will be increased [18]. In fact, samples with potassium contents less than 1% have a greater presence of the mineral vermiculite and a lower expansion rate, and for values of approximately 5%, there is a reduction in the amount of the mineral vermiculite and an increase in the expansion rate [19]. Samples containing approximately 5% potassium have more than one phase/mineral constituting the flake; mica is commonly found along with vermiculite, forming an intermediate phase called hydrobiotite, which commonly has a higher expansion rate.

Table 1. Constituent elements of vermiculite [15].

Element	% By Weight
SiO_2	38.00–46.00
Al_2O_3	10.00–16.00
MgO	16.00–35.00
CaO	1.00–5.00
K_2O	1.00–6.00
Fe_2O_3	6.00–13.00
TiO_2	1.00–3.00
H_2O	8.00–16.00
Others	0.20–1.20

A higher expansion rate is due to the presence of mica minerals and/or hydrobiotite in the vermiculite flake that will be expanded. These minerals act as barriers preventing the escape of water vapor generated by heating the vermiculite flake that forces the separation of octahedral and tetrahedral layers, expanding the vermiculite [19].

Figure 3 reports the potassium (K_2O) contents and the expansion rate of vermiculites (K) from different authors, and it is observed that "Pure vermiculites" present a low potassium content and low expansion rate, but vermiculites with more than one constituent phase (polyphase samples) present a higher expansion rate. It is concluded that for vermiculite flake to have a higher expansion rate, it should present potassium contents between 3% and 5%; this range means that there are mica and/or hydrobiotite phases in the material.

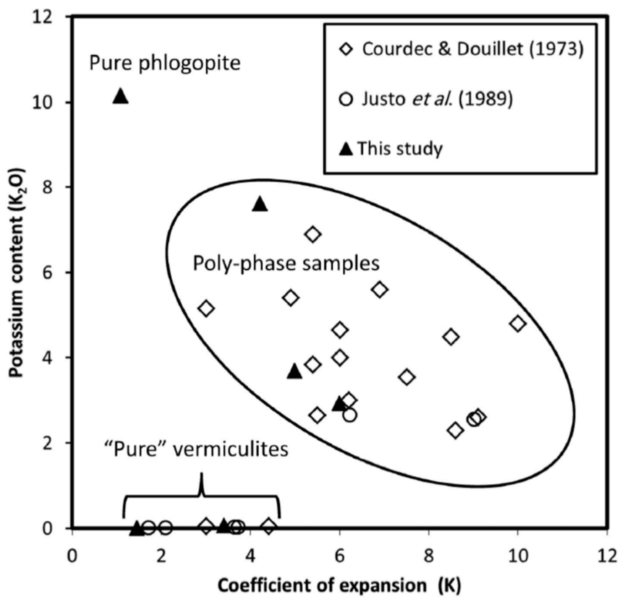


Figure 3. Relationship between potassium content and expansion rate, showing that vermiculites with more than one constituent phase (polyphase samples) show greater expansion rate in relation to "Pure" vermiculites [19].

Due to exposure, vermiculite originates from changes in the crystalline structure and atomic composition of other minerals. These changes in atoms can promote variations in the characteristics of vermiculite, such as coloration and expansion rate. These characteristics are appreciable for assessing the potential commercial use of vermiculite, especially when it is expanded, and this subject is discussed in the following topics.

2.1. Expanded Vermiculite

When expanded, vermiculite acquires characteristics that make its commercial consumption appreciable in several industry types. Some of these properties are low elasticity, low density, high surface area, porosity, high adsorption, and absorption capacity due to its negative surface charge [16]. These characteristics are obtained when vermiculite undergoes the expansion process.

The expansion procedure consists of dugging, crushing, and separation of the rock into flakes of different sizes; later, the flakes are heated in a vertical oven, and the expanded vermiculite is separated into different granulometries [20]. It is during the expansion process that vermiculite obtains characteristics such as low density and low thermal conductivity. The heating process causes a vermiculite mass loss which is due to the evaporation of water present inside, thus making the aggregate increase in volume and incorporate voids.

In order for vermiculite to reach its expanded stage, it is necessary for the material to be heated to a temperature between 800 and 1000 °C, which makes it expand by approximately 6 to 20 times its size [15,21]. The expansion temperature cannot be higher than 1000 °C because this can convert vermiculite into clinoenstatite, causing the loss of the thermal insulation property [22].

After the expansion process, vermiculite obtains different particle sizes. Table 2 [23,24] shows the coarse, medium, fine, super fine, and micron international system classification which is equivalent to the classification 1, 2, 3, 4, and 5, respectively, of the American system. The international vermiculite particle size classification system can be verified as follows:

1. In the American standard, the maximum sizes of the American diameter range are slightly smaller than the international system, and the minimum range is larger relative to the same parameter.
2. The Brazilian standard does not have maximum and minimum diameter ranges, but in relation to the particle size distribution range, it presents larger diameters for the same classification compared to the international system.

Table 2. Particle size classification of vermiculite [23,24].

System	Classification	Diameter Range (mm)		Particle Size Distribution Range
		Maximum	Minimum	
American	1	7	3.33	-
	2	3.5	1.75	-
	3	2.0	0.6	80% of the particles are greater than 0.6 mm
	4	0.85	0.212	80% of the particles are greater than 0.3 mm
	5	0.3	-	55% of the particles are greater than 0.3 mm
International	Large	8	2.8	60~70% of the particles are greater than 4.0 mm
	Medium	4	1.4	60~70% of the particles are greater than 2.0 mm
	Fine	2	0.71	60~70% of the particles are greater than 1.0 mm
	Superfine	1	0.355	60~70% of the particles are greater than 0.5 mm
	Micron	0.71	0.25	60~70% of the particles are greater than 0.25 mm
Brazilian	-	-	-	-
	Medium	-	-	55~95% of the particles are greater than 2.4 mm
	Fine	-	-	65~95% of the particles are greater than 1.2 mm
	Superfine	-	-	70~95% of the particles are greater than 0.6 mm
	Micron	-	-	80~100% of the particles are greater than 0.3 mm

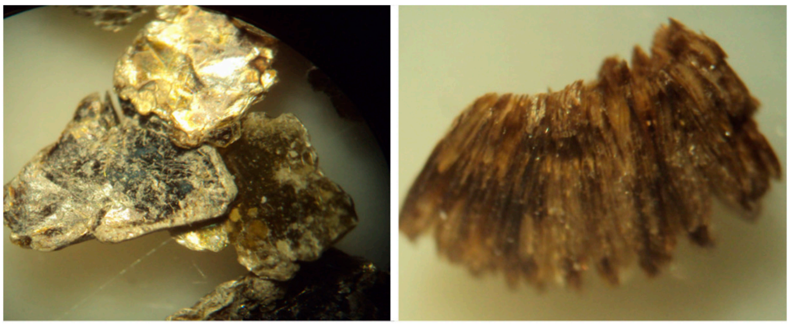
The water evaporation formed inside vermiculite is necessary for its expansion. Hillier (2013) [19] suggests that a better expansion of vermiculite happens when the mineral flake contains large particles and mica or hydrobiotite phases. Table 3 shows that samples with multiple phases, named in his study as VER-2, MK-1, and PB, had a higher expansion rate and, consequently, the generated product presented a greater reduction in the apparent weight. Samples containing mostly vermiculite and low levels of potassium, KL-2 (0.014%), and VER-18 (0.076%) presented bulk densities of 482 ± 18 kg/m^3 and 241 ± 3 kg/m^3 at 900 °C. These samples showed a considerable reduction in bulk density and this decrease occurred due to the loss of water from these vermiculites; they did not have a high expansion rate.

Table 3. Relationship between vermiculite composition and its properties when heated [19].

Predominant Composition	Sample	Average Potassium Content (%)	Bulk Density (kg/m^3)			Loss Mass (%)		Expansion (K)	
			20 °C	400 °C	900 °C	400 °C	900 °C	400 °C	900 °C
Vermiculite	KL-2	0.014	689 ± 15	644 ± 17	482 ± 18	13.8 ± 0.3	19.8 ± 0.7	1.1 ± 0.02	1.5 ± 0.05
	VER-18	0.076	818 ± 9	680 ± 14	241 ± 3	10.7 ± 0.3	19.5 ± 0.4	1.2 ± 0.03	3.4 ± 0.02
Hydrobiotite	VER-2	4.68	827 ± 21	466 ± 8	169 ± 1	9.3 ± 0.0	14.0 ± 0.4	1.7 ± 0.04	5.0 ± 0.06
	MK-1	4.63	852 ± 25	262 ± 8	145 ± 2	10.9 ± 0.3	15.2 ± 0.4	3.2 ± 0.04	6.0 ± 0.05
	PB	6.00	491 ± 9	219 ± 4	117 ± 1	5.8 ± 0.5	8.2 ± 0.7	2.2 ± 0.04	4.2 ± 0.12
Phlogopite	PHL-3	10.16	214 ± 6	225 ± 6	201 ± 3	0.5 ± 0.0	0.7 ± 0.3	0.9 ± 0.09	1.1 ± 0.09

The samples with multiple constituent phases and potassium content of approximately 5% (VER-2 (4.68%), MK (4.63%) and PB (6%)) showed apparent densities of 169 kg/m^3 (VER-2), 145 kg/m^3 (MK-1), and 117 kg/m^3 (PB), respectively, at 900 °C. Based on the loss of mass and expansion rate of these samples, it could be observed that they lost water via evaporation and had a large increase in their volume, confirming the idea that to have a great expansion, the presence of water and hydrobiotite in the flake in the vermiculite is necessary. In sample PHL-3 high levels of potassium in the flake were observed, and this fact is not enough if there is no presence of vermiculite mineral inside as water is necessary for expansion.

After the thermal process, vermiculite obtains the shape of a worm or accordion, as shown in Figure 4. In addition to appearance, Nascimento (2008) [15] and Gellert (2010) [25] point out that vermiculite, when expanded, presents changes in physical properties such as: a decrease in density (0.15–0.25 g/cm^3) and an increase in specific surface area, water absorption, thermoacoustic insulation, and fire resistance. These characteristics give vermiculite the potential to be applied in the composition of fertilizers and soil formation for horticulture, the manufacture of tires and brake pads for the automobile industry, and the elaboration of materials for thermoacoustic insulation in civil construction [16]. With a focus on its application as a material for civil construction, the properties such as low density, thermoacoustic insulation, and fire resistance are very appreciable, leading to vermiculite being used for construction. According to Ugarte et al. [16], vermiculite can be used to produce precast blocks with plaster/vermiculite mortar used in internal partitions, coating mortars, refractory bricks, blocks, and plates resistant to high temperatures, as well as in the protection of steel structures at high temperatures.



(A) **(B)**

Figure 4. Fragments of crude vermiculite (**A**) and expanded vermiculite (**B**) under a microscope [26].

2.2. Vermiculite and Other Lightweight Aggregates

In cementitious composites, vermiculite is commonly used as the inert fraction of the mixture, such as aggregate. According to Mehta and Monteiro (2014) [27], this fraction occupies about 60 to 80% of the volume of cementitious composites. Carneiro and Cincotto (1999) [28] highlight the aggregate as a fundamental part for some properties of cementitious composites, since they are responsible for water retention, reducing water consumption, maintaining workability, mitigating stresses from hardening, and reducing permeability, when they have continuous particle size distribution.

According to Ribeiro et al. (2013) [29], aggregates can be classified by how they were obtained, their bulk density, and their grain shape. Bauer (2008) [30] highlights that, considering the bulk density of aggregates, they can be divided into lightweight when this value is less than 1 kg/dm^3, medium when it is between 1 and 2 kg/dm^3, and heavy when it is higher than 2 kg/dm^3.

Lightweight aggregates are characterized by open pores and higher water absorption, which increases the porosity of cementitious composites and decreases their specific mass due to the increase in voids in the internal structure of the material. Rossignolo (2009) [31] states these aggregates influence the decrease in mechanical strength and the increase in water loss and shrinkage in cementitious composites, but using these materials benefits the thermal conductivity because the air trapped in the pores decreases the absorption and transfer of heat inside the material. Due to these characteristics, lightweight aggregates are being studied and applied in construction systems with the purpose of reducing the weight of the building and providing thermoacoustic insulation. Thus, Sousa (2010) [32] highlights the following as lightweight aggregates: expanded clay, expanded shale, expanded vermiculite, expanded perlite, pumice stone, expanded blast furnace slag, fly ash, expanded polystyrene (EPS), expanded glass, and organic aggregates.

Blast furnace slag and fly ash, despite being widely known as mineral additions, can be used as aggregates depending on their manufacturing process. Neville and Brooks (2013) [33] explain that when blast furnace slag is projected by a water spray, it acquires pellet forms with a crystalline and porous structure, meaning it can be used as lightweight aggregate. According to Mehta and Monteiro (2014) [27], when it undergoes palletization and sintering processes at temperatures between 1000 °C and 1200 °C, fly ash can be used as lightweight aggregate. Besides these materials, Bezerra (2014) [34] demonstrates EVA (ethylene vinyl acetate) as an alternative to lightweight aggregates in cementitious composites; Table 4 shows some characteristics of these aggregates.

Table 4. Characteristics of lightweight aggregates [32,34].

Aggregate	Bulk Density (kg/m^3)	Thermal Conductivity (W/m·K)
Expanded clay	966~1118	0.81
Expanded shale	450~1050	0.13~0.93
Expanded vermiculite (less than 1 mm)	125	0.04 ~0.05
Expanded vermiculite (1–2 mm)	95	
Expanded vermiculite (3–6 mm)	80	
Expanded vermiculite (3–10 mm)	65	
Expanded perlite (less than 0.9 mm)	40~50	0.05
Expanded perlite (less than 1.2 mm)	50~60	
Expanded perlite (less than 2 mm)	75~85	
Pumice stone	400~ 900	0.09~0.17

Table 4. *Cont.*

Aggregate	Bulk Density (kg/m^3)	Thermal Conductivity (W/m·K)
Expanded blast furnace granular slag (less than 6.3 mm)	1000	0.13
Expanded blast furnace granular slag (6.3–12.5 mm)	900	
Expanded blast furnace granular slag (12.5–25 mm)	800	
Fly ash (less than 5 mm)	1040	0.14
Fly ash (5–8 mm)	835	
Fly ash (8–13mm)	770	
EVA (ethylene vinyl acetate)	100~350	-
Expanded polystyrene (EPS)	12~14	0.035

2.3. Vermiculite in Civil Construction

The properties of low bulk density and low thermal conductivity make vermiculite attractive in various industrial sectors and, according to ESMA (the European Specialty Minerals Association), have applications in different areas such as: construction, automotive, horticulture, and packaging.

Such diversity in applications makes vermiculite have a good commercial appreciation, with it being exploited in several countries. According to the United States Geological Survey (USGS) (2020) [35], its world production in 2019 was 500 thousand tons, and United States, South Africa and Brazil are the largest producers, corresponding to 40%, 36%, and 12%, respectively.

In the Brazilian territory, the National Mining Agency (NMA) (BRAZIL, 2017) [36] points out that the national reserves of vermiculite in 2016 were distributed in five states: Goiás (69.75%), Paraíba (17.31%), Bahia (12.07%), Piauí (0.84%), and Pernambuco (0.03%). In the same year, the national production of processed vermiculite was concentrated in the regions of Goiás (75.8%), Paraíba (21.2%), and Pernambuco (3.0%).

While unexpanded vermiculite has very few uses, expanded vermiculite can be used in the construction industry (as aggregate for concrete and mortar), in insulation (loose fill and acoustic tiles), in horticulture (aggregate, soil modification, and carrier fertilizer), and various other domains [13].

Vermiculite exploration and application date back to the early 20th century [37]. The material was used to promote thermal insulation in buildings, being mainly used as an alternative to mineral wool for filling walls and slabs; other applications of vermiculite came in the form of the production of lightweight blocks and covers for pipes [37].

Reports about the usage of vermiculite in cementitious composites in the first decades of the 20th century are virtually nonexistent. Pence and Blount (1944) [38] in their work pointed out that the use of vermiculite as a lightweight aggregate for concrete had already been well established, thus proposing the use of this material in the production of ceramic pieces and demonstrating the possibility of producing thermal insulating ceramic blocks.

Even though vermiculite's usage in concrete is well known, the quantification of its influence on the properties of cementitious products has long remained a mystery. Because of this, Hansen (1953) [39] studied the influence of lightweight aggregates on the thermal conductivity of insulating concretes, and one of them was vermiculite. According to this research, it was shown that thermal conductivity follows a direct relationship with increasing temperature, and an inverse relationship with the vermiculite content in the mixture. This means that when there is more vermiculite in the mix, lower conductivity occurs.

Low (1984) [40] proved the influence of the size and packing of particles on thermal conductivity and the potential use of vermiculite in elements for construction. The author observed that the use of smaller particles of vermiculite provided a lower thermal conductivity than when using the same particles pressed to form a rigid element; in addition, the strength also decreased. A combination between vermiculite and binder was recommended to obtain a resistant material and low heat conduction.

Even though vermiculite presents a high capacity to be used in cementitious products, few studies focus on its influence and its peculiarities in mortars; we can highlight the research conducted by Silva et al. (2010) [41], which proposed the partial replacement of the fine conventional aggregate with vermiculite. Their study demonstrated a reduction in thermal conductivity in the mixed mortars and their mechanical performance. In view of this, some research in which vermiculite was applied in coat mortars for buildings will be presented in the following sections.

2.4. Coating Mortars with Vermiculite

In construction, coating mortar has the following functions: (a) protecting masonry and structures against the action of weathering, in the case of external coating; (b) assisting in the performance of wall systems, contributing several functions such as: thermal insulation, acoustic insulation, watertightness, fire safety, and resistance to wear and surface shaking; (c) regularizing the surface of wall elements and serving as a basis for decorative finishing, contributing to the esthetics of the building [42]. To improve the thermal properties in mortar coatings, several types of lightweight aggregates have been used, among which expanded vermiculite can be highlighted.

Lightweight aggregate usage in mortars promotes an improvement in thermoacoustic insulation properties and decreases the specific mass, which causes a reduction in mechanical properties and an increase in water absorption. To analyze the effects of vermiculite on mortars, information was compiled from several authors who studied the properties of mortars in their dry, fresh, and hardened states [7,17,41,43–45]. Table 5 shows the mortars studied by these authors, who presented mix designs with cement, lime, sand, and vermiculite, in which vermiculite was used as a partial and/or total replacement for sand.

Based on Table 5, it is noted that Silva et al. (2010) [41], Cintra et al. (2014) [7], and Gündüz and Kalkan (2019) [45] presented the mortar mixes containing a vermiculite mass corresponding to the total mass of dry materials.

Silva et al. (2010) [41] fixed the consumption of cement (12%) and lime (12%) and varied only the content of aggregates, which was formed by sand and vermiculite, in which sand was partially replaced by vermiculite in contents of 2%, 3.5%, 5%, and 10%. Similarly, Gündüz and Kalkan (2019) [45] set the cement (30%) and lime (7.2%) content and replaced sand with vermiculite at a fraction of 24%. Unlike the last two authors, Cintra et al. (2014) [7] varied the contents of all mortar components, when the amount of vermiculite changed from 40% to 34%.

Palomar et al. [43], Barros [17], and Sinhorelli [44] presented their mortar compositions' rates by uniting the volume and the consumption of each material in kg/m^3. Palomar et al. [43] presented a rate of 1:1:6 (cement/lime/aggregate) with the partial replacement of conventional aggregate with vermiculite at contents of 25% and 50%. In this study, there was a fixed consumption of cement (214 kg/m^3) and lime (68 kg/m^3), with variation only in the vermiculite content. However, the vermiculite volume increment reduced the total dry material mass which caused the cement mass to have a greater representation related to the total dry material as the use of vermiculite increased from 0% (P15V0) to 3% (P15V3) and 7% (P15V7).

Similarly, Barros [17] proposed the partial and total replacement of conventional aggregate with vermiculite in volume, using a 1:1:6 proportion with aggregate replacement levels of 25%, 50%, 75%, and 100%. However, there was an increasing variation in the binder contents with the increasing vermiculite content and this caused a significant increase in water consumption. As in Palomar et al.'s study [43], vermiculite reduced the total mass of dry material, so the cement mass had a greater representation in the mixture, going from 12.38% (B18V0) to 15.16% (B18V3); 19.55% (B18V7); 27.54% (B18V15); and 46.54% (B18V34).

Table 5. Mix designs' compositions [7,17,41,43–45].

Author (s)	Samples	Mix Ratio (Cem/Lime/Sand/Verm.)	Material Content					w/c
			Cement	Lime	Sand	Verm.	Water	
Silva et al. (2010) [41]	SV10V0	1:1:6.33:0 (weight)	12% -	12% -	76% -	0% -	- -	1.9
	SV10V2	1:1:6.17:0.16 (weight)	12% -	12% -	74% -	2% -	- -	2.25
	SV10V3.5	1:1:6.08:0.33 (weight)	12% -	12% -	72,5% -	3.5% -	- -	2.5
	SV10V5	1:1:5.92:0.42 (weight)	12% -	12% -	71% -	5% -	- -	2.8
	SV10V10	1:1:5.5:0.83 (weight)	12% -	12% -	66% -	10% -	- -	3.5
Cintra et al. (2014) [7]	CT14V40	1:0.8:0.48:1.6 (weight)	25% -	20% -	12% -	40% -	80% -	3.2
	CT14V40	1:0.75:1.4:1.7 (weight)	20% -	15% -	28% -	34% -	70% -	3.5
Palomar et al. (2015) [43]	P15V0	1:1:6 (vol.) 1:0.32:7:0 (weight)	12% 214 kg/m^3	3.81% 68 kg/m^3	84.19% 1502 kg/m^3	0% 0.00 kg/m^3	- 140 kg/m^3	0.65
	P15V3	1:1:6 (vol.) 1:0.32:5.2:0.19 (weight)	14.76% 214 kg/m^3	4.69% 68 kg/m^3	77.72% 1127 kg/m^3	2.83% 41 kg/m^3	- 270 kg/m^3	1.26
	P15V7	1:1:6 (vol.) 1:0.32:3.5:0.38 (weight)	19.19% 214 kg/m^3	6.10% 68 kg/m^3	67.35% 751 kg/m^3	7.35% 82 kg/m^3	- 300 kg/m^3	1.40
Barros (2018) [17]	B18V0	1:1:6 (vol.) 1:0.42:6.66:0 (weight)	12.38% 214.5 kg/m^3	5.16% 89.4 kg/m^3	82.46% 1428.8 kg/m^3	0% 0.00 kg/m^3	- 308.8 kg/m^3	1.44
	B18V3	1:1:6 (vol.) 1:0.42:5:0.18 (weight)	15.16% 238.6 kg/m^3	6.32% 99.5 kg/m^3	75.74% 1192.1 kg/m^3	2.78% 43.7 kg/m^3	- 377.0 kg/m^3	1.58
	B18V7	1:1:6 (vol.) 1:0.42:3.33:0.37 (weight)	19.55% 239.4 kg/m^3	8.16% 99.9 kg/m^3	65.14% 797.6 kg/m^3	7.15% 87.6 kg/m^3	- 526.8 kg/m^3	2.20
	B18V15	1:1:6 (vol.) 1:0.42:1.67:0.55 (weight)	27.54% 246.4 kg/m^3	11.48% 102.7 kg/m^3	45.86% 410.4 kg/m^3	15.12% 135.3 kg/m^3	- 652.9 kg/m^3	2.65
	B15V34	1:1:6 (vol.) 1:0.42:0:0.73 (weight)	46.54% 239.9 kg/m^3	19.40% 100 kg/m^3	0% 0.00 kg/m^3	34.06% 175.6 kg/m^3	- 779.7 kg/m^3	3.25
Sinhorelli (2019) [44]	S19V0	1:1:6 (vol.) 1:0.7:9.8:0 (weight)	8.70% 174 kg/m^3	6.09% 121.8 kg/m^3	85.22% 1704.9 kg/m^3	0% 0 kg/m^3	- 250.5 kg/m^3	1.44
	S19V5	1:1:6 (vol.) 1:0.7:5.85:0.38 (weight)	12.60% 179.3 kg/m^3	8.82% 125.5 kg/m^3	73.80% 1050.6 kg/m^3	4.78% 68.1 kg/m^3	- 401 kg/m^3	2.24
	S19V9	1:1:6 (vol.) 1:0.7:3.91:0.58 (weight)	16.15% 187.4 kg/m^3	11.31% 131.2 kg/m^3	63.17% 732.9 kg/m^3	9.37% 108.7 kg/m^3	- 108.7 kg/m^3	2.46
	S19V17	1:1:6 (vol.) 1:0.7:1.95:0.77 (weight)	22.63% 198.3 kg/m^3	15.84% 138.8 kg/m^3	44.11% 386.6 kg/m^3	17.42% 152.7 kg/m^3	- 524.3 kg/m^3	2.64
Gündüz e Kalkan (2019) [45]	G19V0	1:024:2.07:0 (weight)	30% -	7.2% -	62% -	0 -	- -	1.22
	G19V24	1:0.24:1.26:0.8 (weight)	30% -	7.2% -	38% -	24% -	- -	2.48

Following the same reasoning of the previous author, Sinhorelli [44] conducted a study focusing on the rheology of mortars containing vermiculite as aggregate. Mortars with volume proportions of 1:1:6 (cement/lime/aggregate) were prepared, partially replacing the conventional aggregate with vermiculite in percentages of 40%, 60% and 80%, and cement and water consumption also increased.

Thus, based on the compilation of the results from these studies, in the following sections, their mortar properties are discussed; for a better comparative analysis, graphs were prepared relating the properties under analysis to other properties and/or to vermiculite and/or cement contents in order to demonstrate the varying impact of these characteristics on the mortar properties.

2.4.1. Workability and Water Consumption

Workability is the property of mortars in a fresh state that determines the facility with which they can be mixed, transported, applied, consolidated, and finished in a homogeneous condition [42]. The adverse effects caused on mortars' workability by using lightweight aggregates are still little-discussed. Lanzón and Garcia-Ruiz [46] point out that lightweight aggregates have a porous structure with high water retention and, when they are used in mortars, it is necessary to increase water consumption to have good handling conditions.

In order to measure the workability of the mortars, Palomar et al. [43], Barros [17], and Sinhorelli [44] used a flow table and measured the flow diameter of the mortars [17,43,44]. Palomar et al. [43] produced mortars with a fixed cement and lime consumption and followed the recommendations by the UNE-EN 1015-3:2000 standard. For the samples P15V0, P15V3, and P15V7, they measured spreads of 169 mm, 175 mm, and 177 mm, respectively. On the other hand, Barros [17] and Sinhorelli [44] followed the recommendations by NBR 13.276 (ABNT, 2005) and sought to produce mortars with flow diameters close to or within the 260 $\pm$ 5 mm range. The mortars produced by these two authors showed an increasing consumption of cement, lime, and vermiculite, causing an increase in water consumption. Because they used fixed binder contents and smaller flow diameters, the samples studied by Palomar et al. [43] presented lower water consumption compared to the samples from the studies of Barros [17] and Sinhorelli [44].

As mentioned previously, to obtain minimally workable mortars that complied with the proposed technical recommendations, the authors measured increasing water consumption as the content of vermiculite and binders increased in the mixtures. Table 6 and Figure 5 relate the water consumption to the cement and vermiculite consumptions in these authors' mixtures.

Palomar et al. [43] presented the smallest variations in water consumption; this was due to the fixed value of the cement (214 kg/m^3) and lime (68 kg/m^3) consumption and to using vermiculite in small amounts: about 3% of the total dry material in the P15V3 mixture and 6% in the P15V6 mixture. Although the vermiculite contents presented a small percentage related to the total dry material, its consumption variation caused an increase in the water amount from 140 kg/m^3 (P15V0) to 270 kg/m^3 (P15V3) and 300 kg/m^3 (P15V6), representing a variation of 92% and 114%, respectively.

Table 6. Cement, vermiculite, and water consumption for mortars [17,43,44].

Author	Samples	Cement Consumption (kg/m^3)	Vermiculite Consumption (kg/m^3)	Water Consumption (kg/m^3)
Palomar (2015) [43]	P15V0	214	0	140
	P15V3	214	41	270
	P15V7	214	82	300
Barros (2018) [17]	B18V0	214.5	0	308.8
	B18V3	238.6	43.7	377
	B18V7	239.4	87.6	526.8
	B18V15	246.4	135.3	652.9
	B18V34	239.9	175.6	779.7
Sinhorelli (2019) [44]	S19V0	174	0	250.5
	S19V5	179.3	68.1	401
	S19V9	187.4	108.7	460.4
	S19V17	198.3	152.7	524.3

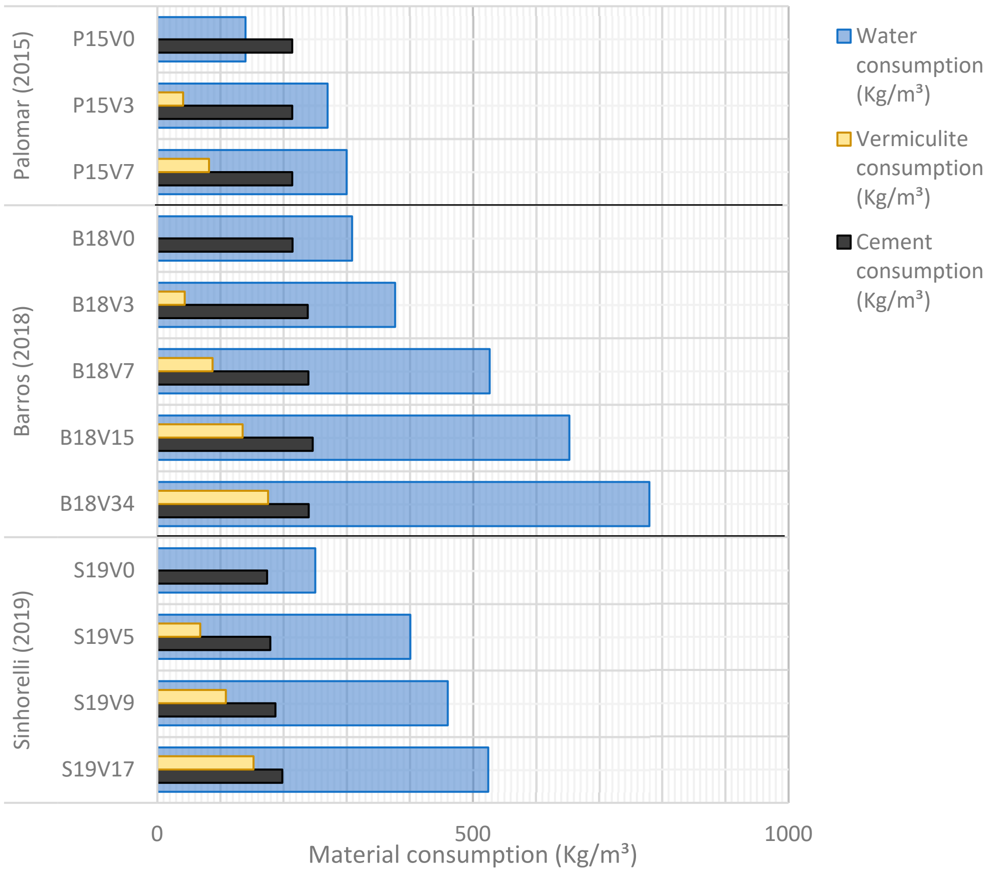


Figure 5. Correlation of water, cement, and vermiculite consumption [17,43,44].

From Barros [17] and Sinhorelli's [44] studies, it is notable that the cement consumption increased as the vermiculite content increased. The binder increasing was due to maintaining the same mortar volume. When the cement and vermiculite content in the mixes studied by Barros [17] increased, the water consumption also increased from 308.8 kg/m^3 (B18V0) to 377 kg/m^3 (B18V3), 526.8 kg/m^3 (B18V7), 652.9 kg/m^3 (B18V15), and 779.7 kg/m^3 (B18V34). These values represented increases of 22%, 70%, 111%, and 152%, respectively.

Similarly to the previous study, the mixes evaluated by Sinhorelli [44] also presented increases in the cement and vermiculite contents, but these increases occurred in smaller amounts compared to Barros´s mixes [17]. This increasing behavior in the contents of these two materials caused gradual increases in water consumption. These values increased from 250.5 kg/m^3 (S19V0) to 401 kg/m^3 (S19V5); 460.4 kg/m^3 (S19V9); and 524.3 kg/m^3 (S19V17), compared to the standard sample, and this represented increases of 60%, 83.7%, and 109%, respectively.

Another factor for Sinhorelli's [44] mortars presenting lower water consumption compared to Barros's [17] mixtures is because the mixes of the last author used vermiculite with a thinner particle size, named superfine in the Brazilian standard, instead of the fine one used by Sinhorelli (2019). This particle size distinction, according to Silva et al. (2010) [41] and Rojas-Ramírez et al (2019) [47] causes greater water absorption by the superfine vermiculite, because it presents greater surface area.

Although authors have shown important information about water consumption to keep the workability of mortars with vermiculite at ideal levels, studies about this subject are still scarce. To mitigate the effects of high-water-absorption content by the lightweight aggregate, Rossignolo [31] and Koksal et al. [48] recommend prewetting the lightweight aggregate to avoid their negative effects on the mixes.

2.4.2. Fresh Density and Incorporated Air Content

Density is a property that is intrinsically linked to the specific mass of the materials used and the air incorporated within the mixture. Cardoso [49] points out that the presence of air in the microstructure of cementitious compounds increases the volume occupied by the paste, facilitates spreading, and increases cohesion. According Struble and Jiang (2004) [50], the presence of air contents up to 25% can provide such benefits.

Silva et al. (2010) [41], Cintra et al. (2014) [7], Palomar et al. (2015) [43], Barros (2018) [17], Sinhorelli (2019) [44], and Gunduz and Kalkan (2019) [45] demonstrated that the incorporation of vermiculite in mortars causes a reduction in the fresh specific mass of these mixtures. This reduction in fresh density is due to the increase in incorporated air content caused by the addition of vermiculite. In Silva et al. (2010) [41], Cintra et al. (2014) [7], and Sinhorelli's (2019) [44] studies (Table 7 and Figure 6), the relationship between vermiculite content in the mixtures and the fresh density, incorporated air content, and mortar properties was demonstrated.

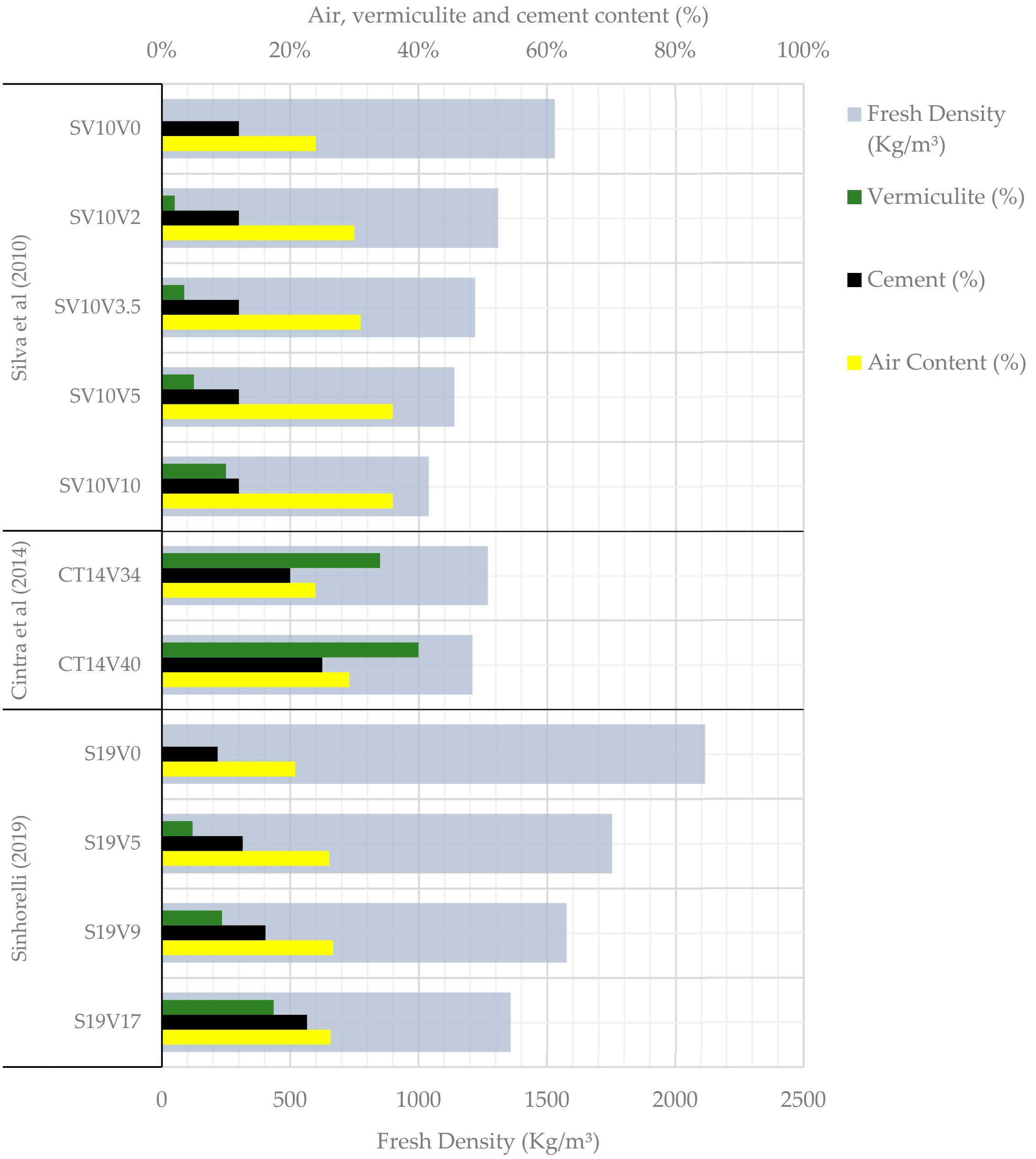


Figure 6. Correlation of the fresh density, air content, cement, and vermiculite [7,41,44].

Table 7. Fresh density, incorporated air content, cement, and vermiculite content from different authors' studies [7,41,44].

Author	Samples	Cement Content (%)	Vermiculite Content (%)	Fresh Density (kg/m^3)	Incorporated Air Content (%)
Sinhorelli (2019) [44]	S19V0	8.70%	0.00%	2115.00	20.80%
	S19V5	12.60%	5.00%	1753.20	26.10%
	S19V9	16.15%	9.00%	1576.30	26.70%
	S19V17	22.63%	17.00%	1358.90	26.30%
Cintra et al. (2014) [7]	CT14V34	20.00%	34.00%	1270.00	23.95%
	CT14V40	25.00%	40.00%	1210.00	29.23%
Silva et al. (2010) [41]	SV10V0	12.00%	0.00%	1530.00	24.00%
	SV10V2	12.00%	2.00%	1310.00	30.00%
	SV10V3.5	12.00%	3.50%	1220.00	31.00%
	SV10V5	12.00%	5.00%	1140.00	36.00%
	SV10V10	12.00%	10.00%	1040.00	36.00%

Silva et al. (2010) [41] used vermiculite in small amounts such as 2%, 3.5%, 5%, and 10%. Compared to the reference mortar, the incorporated air content in the mixtures increased from 24%, to 30%, 31%, 36%, and 36%, respectively. These increments in the incorporated air in the mortars caused their fresh density to decrease from 1530 kg/m^3 (SV10V0) to 1310 kg/m^3 (SV10V2), 1220 kg/m^3 (SV10V3.5), 1140 kg/m^3 (SV10V5), and 1040 kg/m^3 (SV10V10), respectively, compared to the reference mortar. So, the reductions were by 14.38%, 20%, 25%, and 32%, respectively.

Unlike the previous study, Cintra et al. (2014) [7] used high vermiculite contents, in the order of 34% (CT14V34) and 40% (CT14V40), and these mortars had incorporated air contents of 23.95% and 29.23%, respectively, which were lower than the values found in Silva et al.'s study (2010) [41]. The increase of approximately 6% in vermiculite content and incorporated air reduced the fresh density from 1270 kg/m^3 to 1210 kg/m^3, representing a variation of 5%. Despite the high vermiculite amount, Cintra et al. (2014) [7] presented samples with vermiculite presenting levels of incorporated air close to Silva et al.'s (2010) sample without vermiculite [41]. The reason for this behavior can be attributed to the high cement content in these mixes, which was used in proportions of 20% and 25% for samples CT14V34 and CT14V40, respectively, and also to the use of silica fume (3%) as a mineral addition, which improved the refinement of the voids.

In Sinhorelli´s (2019) [44] study, a reduction in fresh density from 2115 kg/m^3 to 1753 kg/m^3, 1576.30 kg/m^3, and 1358.90 kg/m^3 was noted, and these lower values occurred when the mixes contained vermiculite contents of 3%, 7%, 15%, and 34%, respectively. Despite the reduction in fresh density, the samples with vermiculite showed a fixed increase of approximately 6% in the air content compared to the standard sample (20%). In the other words, although the content of vermiculite increased and the specific mass gradually reduced, the incorporated air content in the samples with vermiculite showed values close to 26%. This fact can be attributed to the increasing cement and lime contents, which are materials with smaller particle sizes and that can favor void reduction.

The Brazilian standard does not set maximum and minimum limit values regarding the incorporated air content. It only specifically limits the density in the fresh state, through ABNT NBR 13.281/2005 [51], recommending the values of 2000 and 1400 kg/m^3, respectively, as maximum and minimum limits. The American standard (ASTM C270/1999) [52] recommends values for air incorporation between 12% and 18%, and BS 4887/1986 [53] works with a range between 14% and 20%. Moreover, authors such as Gomes and Neves (2002) [54] recommend 8% and 17% as the ideal incorporated air content values for mortar.

By analyzing the mentioned works, we found that increasing the vermiculite content in mortars causes increases in the incorporated air content and, consequently, a reduction in fresh density. Additionally, through the works of Cintra et al. (2014) [7] and Sinhorelli (2019) [44], it was seen that one way to mitigate this increasing incorporated air content is the usage of binders or mineral admixtures.

2.4.3. Hardened Density and Porosity

The use of vermiculite caused a reduction not only in the fresh density, but in the hardened density, due to its ability to incorporate voids, that is, the porosity. Table 8 and Figure 7 compile the results from Silva et al. (2010) [41], Palomar et al. (2015) [43], and Barros (2018) [17]. In general, an increase in mortar porosity can be seen as the vermiculite content increases, and, consequently, the hardened density decreases.

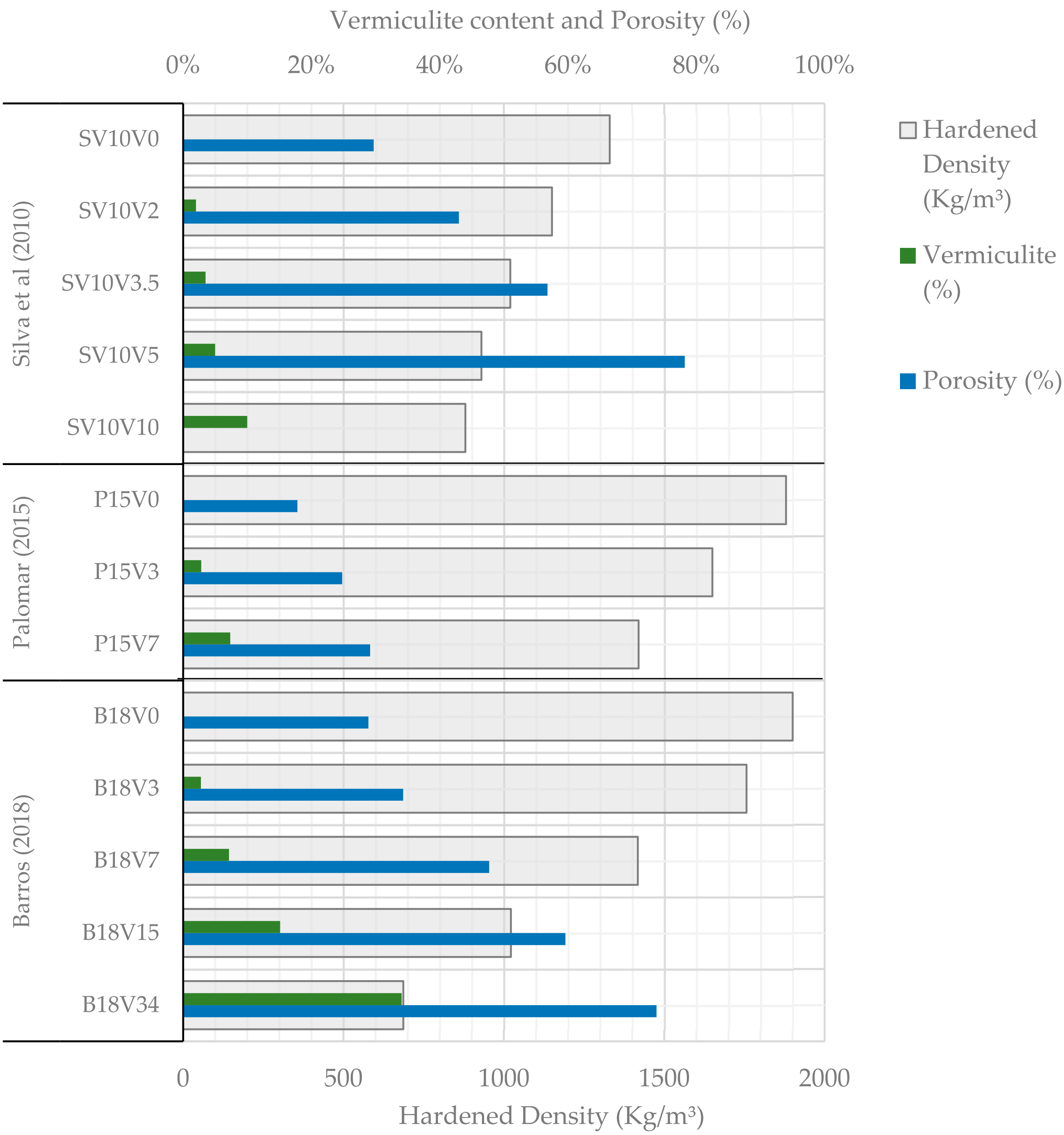


Figure 7. Correlation of the porosity, hardened density, and vermiculite content [17,41,43].

Table 8. Correlation of porosity, hardened density, and vermiculite content [17,41,43].

Author	Samples	Vermiculite Content (%)	Hardened Density (kg/m^3)	Porosity (%)
Silva et al. (2010) [41]	SV10V0	0.00%	1330.00	29.70%
	SV10V2	2.00%	1150.00	43.00%
	SV10V3.5	3.50%	1020.00	56.80%
	SV10V5	5.00%	930.00	78.20%
	SV10V10	10.00%	880.00	-
Palomar (2015) [43]	P15V0	0.00%	1880.00	17.83%
	P15V3	3.00%	1650.00	24.79%
	P15V7	7.00%	1420.00	29.16%
Barros (2018) [17]	B18V0	0.00%	1900.30	28.90%
	B18V3	3.00%	1756.70	34.30%
	B18V7	7.00%	1417.90	47.70%
	B18V15	15.00%	1022.20	59.60%
	B18V34	34.00%	686.40	73.80%

Silva et al. (2010) [41] presented lower hardened density values compared to the ones found by Palomar et al. (2015) [43] and Barros (2018) [17]. The mortars produced by Silva et al. (2010) [41] had fixed cement and lime contents of 12% each, and the vermiculite content was increased in proportions of 2%, 3.5%, 5%, and 10%. This increase in vermiculite content caused an increase in porosity, which varied from 29.70% (SV10V0) to 43% (SV10V2), 56.80% (SV10V3.5), and 78.20% (SV10V5); for the sample with 10% vermiculite incorporation (SV10V10), the author did not present porosity results. Due to the increasing porosity, the samples SV10V0, SV10V2, SV10V3.5, SV10V5, and SV10V10 showed values of hardened density of 1330 kg/m^3, 1150 kg/m^3, 1020 kg/m^3, 930 kg/m^3, and 880 kg/m^3, respectively, which corresponded to reductions in the order of 13.5%, 23.3%, 30%, and 33.8%, respectively.

In the study by Palomar et al. (2015) [43], mortars were prepared with cement and lime consumption fixed at 214 kg/m^3 and 68 kg/m^3, respectively, and vermiculite varied in content from 0 to 41 kg/m^3 (3%) and 82 kg/m^3 (7%). It can be noted that the vermiculite content in the mortars studied by Palomar et al. (2015) [43] was similar to that of Silva et al. (2010) [41]. However, the porosity measured by Palomar et al. (2015) [43] was lower, being in the order of 17.83% (P15V0), 24.79% (P15V3), and 29.16% (P15V7). This fact can be attributed to a lower water presence in these mixtures, which was perceived by comparing the w/c ratio to these mixes from the other two studies. Additionally, due to the small presence of vermiculite and relatively low w/c ratios, the mortars evaluated by Palomar et al. (2015) [43] showed higher hardened density than the other mixes studied by the authors previously cited here, but decreasing behavior could be seen as the vermiculite content increased, with the measured reductions being of the order of 12% and 24%, respectively, for samples P15V3 and P15V7.

Barros (2018) [17] presented mortars with vermiculite contents of 0%, 3%, 7%, 15%, and 34% related to the total mass of dry material. The porosity values obtained for the mixes were 28.90%, 34.30%, 47.70%, 59.60%, and 73.80%, respectively. From Table 8, the mortars studied by Barros (2018) [17] presented higher porosities than the ones studied by Palomar et al. (2015) [43]. The obtained hardened density values were close to each one, presenting for samples B18V0, B18V3, B18V7, B18V15, and B18V34 values of 1900 kg/m^3, 1756.70 kg/m^3, 1417.90 kg/m^3, 1022 kg/m^3, and 686.40 kg/m^3, respectively. This similarity in hardened density values can be justified by the increasing binder consumption in Barros' mortars [17] (2018). In other words, there was an increase in fine materials (cement and lime) as the vermiculite consumption content increased, thus mitigating the reduction in density caused by vermiculite.

From the presented studies, it is clear there is a direct relationship between porosity and vermiculite content; in other words, as vermiculite content increases, the porosity also increases. Additionally, because of this growth in porosity, there is a gradual decrease in the hardened density values of mortars. According to Koksal et al. (2020) [55], increasing the binder content in the consumption provides a lightweight aggregate consumption reduction and, consequently, also a reduction in the porosity. However, the use of vermiculite inevitably reduces the hardened density and provides an increase in mortar porosity, consequently affecting other properties such as capillarity coefficient, mechanical strength, and thermal conductivity.

2.4.4. Capillarity Coefficient

Carneiro (1993) [56] pointed out that one of the main functions of coating mortar is to be watertight, since water penetration occurs through pores and/or fissures present in the coating element. Salvador (2005) [57] explains that mortar permeability depends on the amount and type of binder used, the granulometry of the aggregate, and the characteristics of the substrate, and this property is directly proportional to the water/binder ratio and inversely proportional to the mortar strength. Baía and Sabbatini (2000) [58] confirmed that permeability not only depends on the composition and mortar design; it is necessary to have a good execution technique, good coating thickness, and final finishing. In general, capillarity depends on the porosity; the distribution, dimensions, and continuity of the pores [59]; and the materials and techniques employed in the preparation of the coating that aim to attenuate the porosity in the executed layer.

However, Silva et al. [41] explain that the permeability and porosity of mortars produced with lightweight aggregates are not directly linked to the porosity of the aggregate, but to its ability to incorporate voids in the mixture. Thus, to analyze the water permeability of mortars with vermiculite, the capillarity index of these cementitious mixes is used as a means to quantify and study this behavior. To analyze the effect of vermiculite on this property, the results from Silva et al. [41], Palomar et al. [43], Barros [17], and Sinhorelli [44] are compiled in Table 9 and Figure 8; the capillarity indexes presented were converted to a single common unit of kg/m^2·min$^{0.5}$.

Table 9. Values of capillarity index and vermiculite content from the reviewed articles [17,41,43,44].

Author	Samples	Vermiculite Content (%)	Capillarity Index (kg/m^2·min$^{0.5}$)
Silva et al. (2010) [41]	SV10V0	0.00%	0.09
	SV10V2	2.00%	0.07
	SV10V3.5	3.50%	0.07
	SV10V5	5.00%	0.06
	SV10V10	10.00%	0.05
Palomar (2015) [43]	P15V0	0.00%	0.53
	P15V3	2.83%	1.48
	P15V7	7.35%	1.30
Barros (2018) [17]	B18V0	0.00%	1.35
	B18V3	3.00%	1.20
	B18V7	7.00%	1.77
	B18V15	15.00%	2.91
	B18V34	34.00%	2.69
Sinhorelli (2019) [44]	S19V0	0.00%	1.09
	S19V5	5.00%	1.41
	S19V9	9.00%	1.28
	S19V17	17.00%	1.45

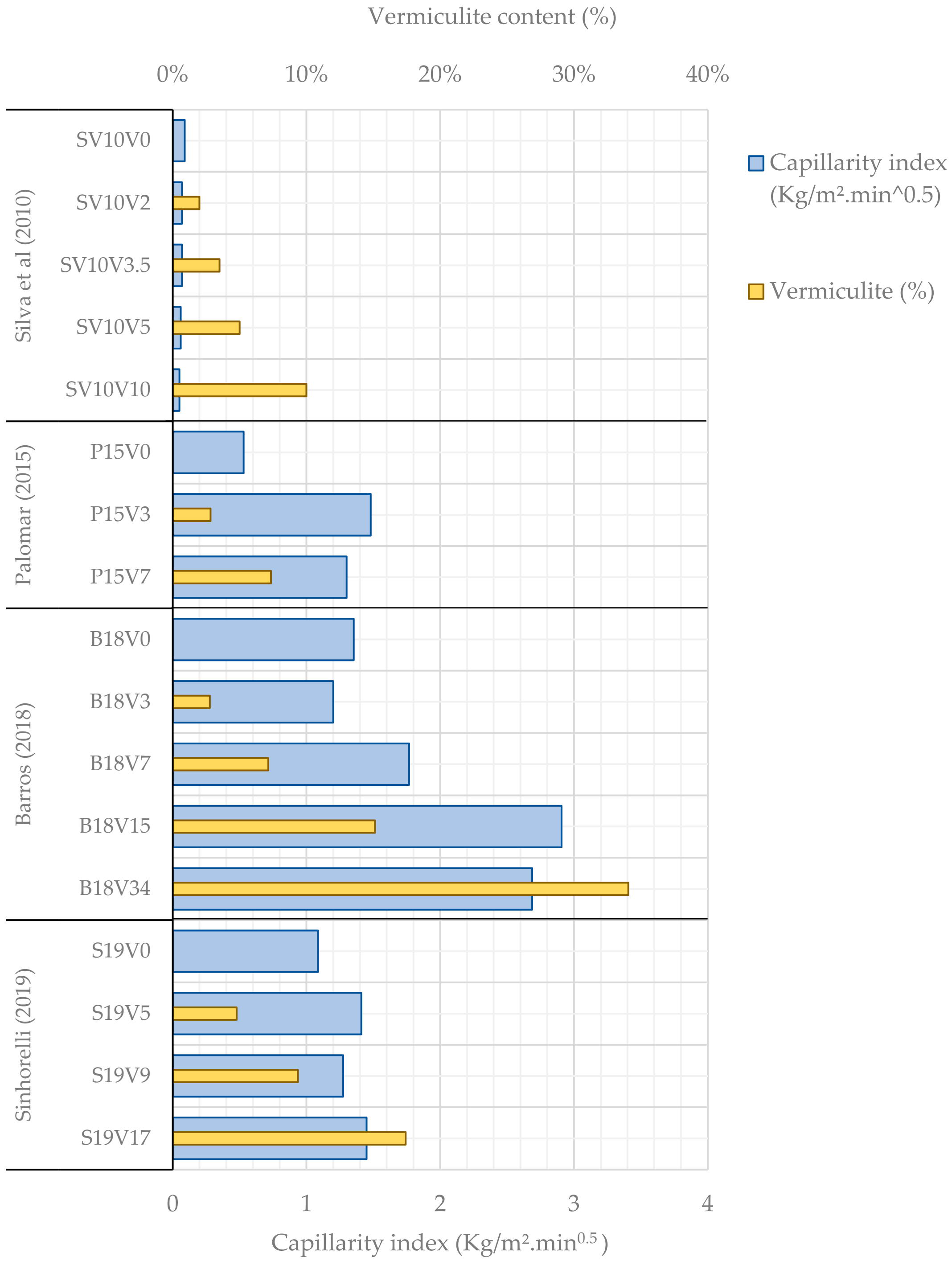


Figure 8. Correlation of the values of capillarity index and vermiculite content of the studied articles [17,41,43,44].

In a peculiar way, Silva et al. [41] showed an increasing porosity as the vermiculite content increased. However, the mortars' capillarity coefficients in this study showed a decreasing behavior and significantly low values. In this case, property values of 0.09 $kg/m^2 \cdot min^{0.5}$ (SV10V0); 0.07 $kg/m^2 \cdot min^{0.5}$ (SV10V2); 0.07 $kg/m^2 \cdot min^{0.5}$ (SV10V3.5); 0.06 $kg/m^2 \cdot min^{0.5}$ (SV10V5); and 0.05 $kg/m^2 \cdot min^{0.5}$ (SV10V10) were noted. Silva et al. [41] explained that the capillarity index decreased due to the fact that vermiculite used in the mixtures presented a very fine grain size; thus, it acted as a filler, which provided the refinement of the pores and mitigated the interconnection between them.

Different from the previous research, Palomar et al. (2015) [43], Barros (2018) [17], and Sinhorelli (2019) [44] observed that replacing conventional aggregate with vermiculite caused a noticeable increase in the capillary absorption in the mortars.

Analyzing the results obtained by Barros (2018) [17], a slight reduction in capillarity absorption was seen when up to 3% vermiculite content was used. The author believes this range is ideal to not have a large amount of absorption of water by capillarity, since for contents above 3%, the observed capillarity indexes were up to two times higher compared to the standard sample.

In the studies by Palomar et al. (2015) [43] and Sinhorelli (2019) [44], the samples P15V3 and S19V5 containing 3% and 5% vermiculite, respectively, presented an increase in capillarity compared to the reference samples. However, when the vermiculite content increased from 3% to 7% in the study by Palomar et al. (2015) [43] and from 5% to 9% in the study by Sinhorelli (2019) [44], a slight decrease in capillarity absorption was observed in the order of 12% and 9%, respectively.

With the exception of the study produced by Silva et al. [41], the other studies pointed out that the increase in capillarity absorption was due to the porosity generated by the addition of vermiculite in the mixture. In this context, Sinhorelli (2019) [44] highlighted the water/cement ratio influenced the mortar porosity, given that the use of vermiculite brings the need to increase the demand for water to make the mortar minimally workable. The evaporated water caused a greater number of voids in the internal structure of the mortar. The effect of water content can be seen by analyzing the result shown by Barros (2018) [17], where a higher water consumption in her mixes, together with vermiculite, contributed to a higher void content and capillarity index.

As an alternative way to minimize high water absorption, Koksal et al. (2015) [48] and Sinhorelli (2019) [44] demonstrated that the use of 5% silica fume or 20% metakaolin can reduce water absorption by between 20% and 30%; another alternative was demonstrated by Koksal et al. (2020) [55], when vermiculite was used in combination with waste-expanded polystyrene, it was possible to reduce water absorption as the content of waste-expanded polystyrene in the mortar increased. This fact occurred because polystyrene does not absorb water due to its polymeric and cellular microstructures with closed cells.

2.4.5. Compressive and Flexural Strength

Carasek (2010) [42] points out that one of the main characteristics of mortars should be the ability to resist impact and building deformations. Bauer et al. (2005) [60] points to Portland cement as one of the main binders to provide adhesion and strength to mortar. However, the author mentions that a high amount of cement in mortars worsens their workability and increases shrinkage and cracking by drying. The use of lime is an option to combat the adverse effect caused by excess cement. Rago and Cincotto (1999) [59] and the BPCA (2002) (Brazilian Portland Cement Association) [61] indicate that using lime in small proportions is beneficial in mixed mortars. Lime provides better workability, adherence, and resistance to deformation for the mortars. On the other hand, although lime improves the workability of mortars, it causes a decrease in the compressive strength [62]. However, Grist et al. (2013) [63] demonstrated that the use of lime and pozzolanic admixtures together provides an improvement in the mechanical properties of mortars and concretes by means of the pozzolanic reaction.

The type of aggregate has proven to be another influential factor in the mechanical properties of cementitious composites, such as lightweight aggregates. Rossignolo (2009) [31] showed that the use of expanded clay in cementitious composites promotes a reduction in mechanical properties due to an increase in the porosity of the material. To mitigate this effect, the author quotes the need to increase the binder content. In the case of mortars using vermiculite, authors such as Silva et al. (2010) [41], Cintra et al. (2014) [7], Palomar et al. (2015) [43], Barros (2018) [17], Sinhorelli (2019) [44], and Gündüz and Kalkan (2019) [45] demonstrated a compressive strength and flexural tensile strength reduction (Table 10, Figure 9, Table 11, and Figure 10) as the vermiculite content increased.

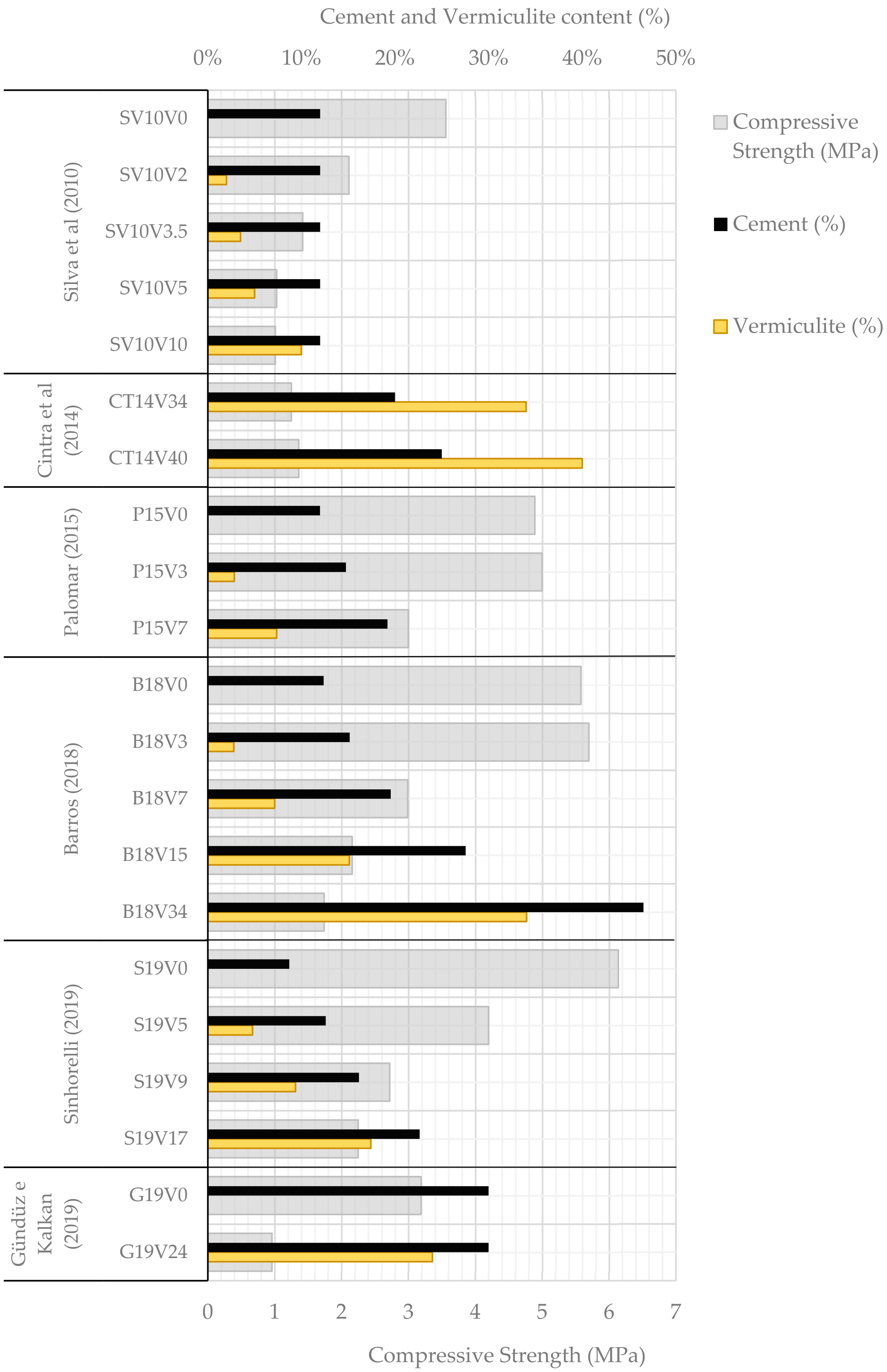


Figure 9. Correlation of the values of compressive strength and cement and vermiculite content of the studied articles [7,17,41,43–45].

Table 10. Values of compressive strength and cement and vermiculite content in the articles studied [7,17,41,43–45].

Author	Sample	Cement Content (%)	Vermiculite Content (%)	Compressive Strength (MPa)
Silva et al. (2010) [41]	SV10V0	12.00%	0.00%	3.56
	SV10V2	12.00%	2.00%	2.11
	SV10V3.5	12.00%	3.50%	1.42
	SV10V5	12.00%	5.00%	1.03
	SV10V10	12.00%	10.00%	1.01
Cintra et al. (2014) [7]	CT14V34	20.00%	34.00%	1.25
	CT14V40	25.00%	40.00%	1.36
Palomar (2015) [43]	P15V0	12.00%	0.00%	4.89
	P15V3	14.76%	2.83%	5.00
	P15V7	19.19%	7.35%	3.00
Barros (2018) [17]	B18V0	12.38%	0.00%	5.58
	B18V3	15.16%	3.00%	5.70
	B18V7	19.55%	7.00%	2.99
	B18V15	27.54%	15.00%	2.16
	B18V34	46.54%	34.00%	1.74
Sinhorelli (2019) [44]	S19V0	8.70%	0.00%	6.14
	S19V5	12.60%	5.00%	4.20
	S19V9	16.15%	9.00%	2.72
	S19V17	22.63%	17.00%	2.25
Gündüz and Kalkan (2019). [45]	G19V0	30.00%	0.00%	3.19
	G19V24	30.00%	24.00%	0.96

Table 11. Values of flexural strength and cement and vermiculite content of the studied articles [17,41,43,44].

Author	Sample	Cement Content (%)	Vermiculite Content (%)	Tensile Strength (MPa)
Silva et al. (2010) [41]	SV10V0	12.00%	0.00%	1.56
	SV10V2	12.00%	2.00%	1.14
	SV10V3.5	12.00%	3.50%	0.79
	SV10V5	12.00%	5.00%	0.55
	SV10V10	12.00%	10.00%	0.45
Palomar (2015) [43]	P15V0	12.00%	0.00%	1.59
	P15V3	14.76%	2.83%	1.57
	P15V7	19.19%	7.35%	1.74
Barros (2018) [17]	B18V0	12.38%	0.00%	1.90
	B18V3	15.16%	3.00%	1.84
	B18V7	19.55%	7.00%	1.46
	B18V15	27.54%	15.00%	1.11
	B18V34	46.54%	34.00%	0.84
Sinhorelli (2019) [44]	S19V0	8.70%	0.00%	2.54
	S19V5	12.60%	5.00%	1.86
	S19V9	16.15%	9.00%	1.50
	S19V17	22.63%	17.00%	1.18

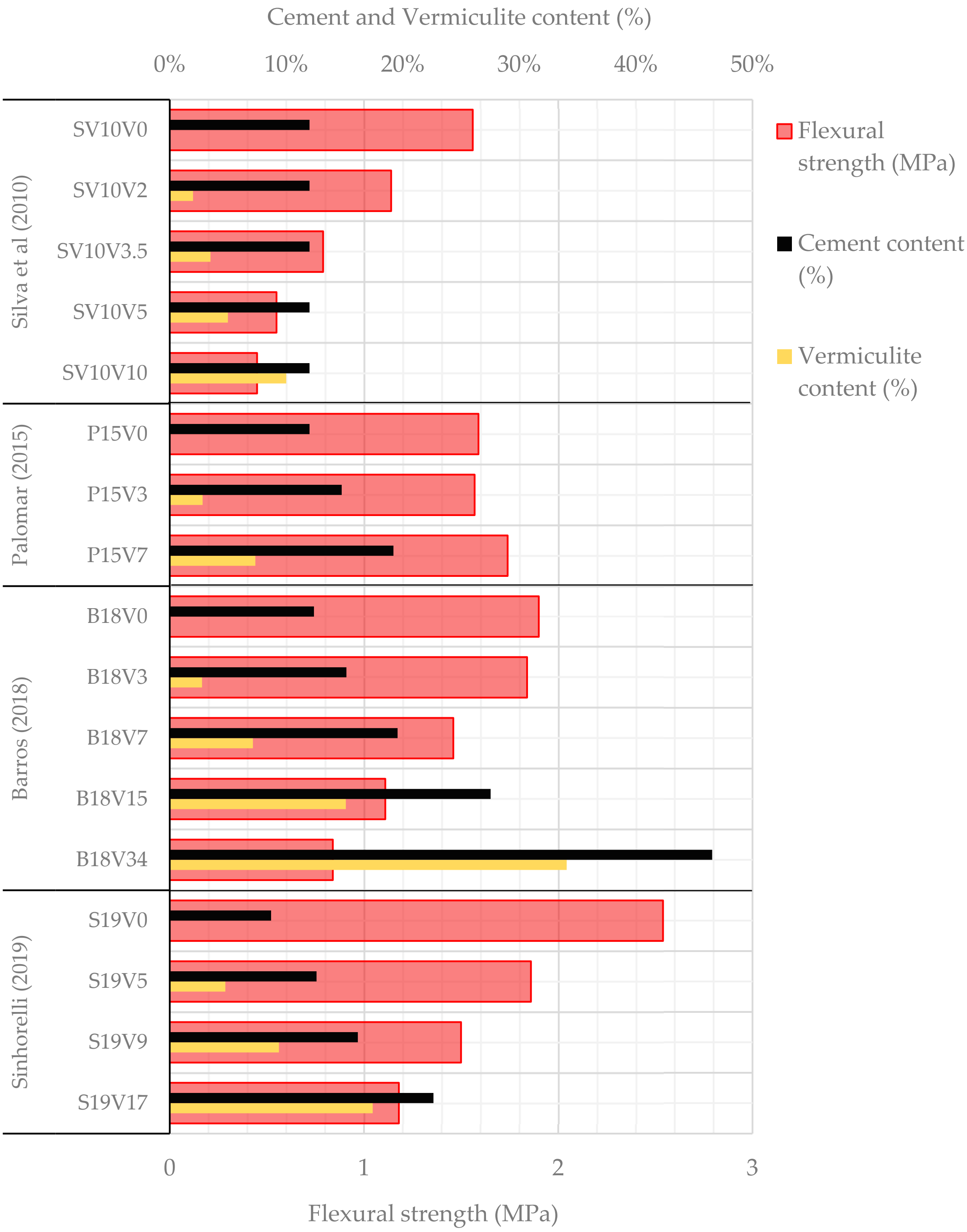


Figure 10. Correlation of the flexural strength values and cement and vermiculite content of the studied articles [17,41,43,44].

In mortars that had fixed cement contents such as in the studies by Silva et al. (2010) [41] and Gündüz and Kalkan (2019) [45], a significant decrease in compressive strength was noted. In the work by Silva et al. (2010) [41], the author fixed the cement and lime content, and varied the vermiculite content by 0%, 2%, 3.5%, 5%, and 10%. This small amount of this aggregate reduced the compressive strength from 3.56 Mpa (SV10V0) to 2.11 MPa (SV10V2); 1.42 MPa (SV10V3.5); 1.03 MPa (SV10V5); and 1.01 MPa (SV10V10), respectively, which represented decreases in the orders of 41%, 60%, 71%, and 72%, respectively.

Similarly, Gündüz and Kalkan (2019) [45] prepared mortars with a fixed cement content of 30% and a lime content of 7.20%, and varied the vermiculite content from 0%

to 24%, which caused a reduction in the compressive strength in the order of 70%. Thus, mortars with fixed cement content have a significant drop in their compressive strength as the vermiculite content increases. To mitigate this behavior, it is necessary to increase the binder content as the vermiculite content increases or use some mineral admixtures.

The mortars studied by Cintra et al. (2014) [7], Palomar et al. (2015) [43], Barros (2018) [17], and Sinhorelli (2019) [44] showed increasing cement and vermiculite contents related to the total dry material. Additionally, although vermiculite caused a decrease in compressive strength in the mortars, the increasing cement contents prevented this reduction from reaching the levels cited by Silva et al. [41] and Gündüz and Kalkan [45] in their mortars.

Although Palomar et al. [43] used a fixed cement consumption of 214 kg/m^3, the representativeness of consumption on the total dry material increased; thus, the cement content varied from 12% to 19.19%, while the vermiculite content varied from 0% to 7%. Due to the increase in cement content, the sample with 3% vermiculite (P15V3) showed no decrease in compressive strength. However, the one with 7% (P15V7) showed a reduction of nearly 39%.

Barros [17] presented samples with cement and vermiculite contents varying similarly to Palomar et al. (2015) [43], but with different cement and lime consumptions (kg/m^3). As in the study by Palomar et al. (2015) [43], the mortar studied by Barros (2018) [17] containing 3% vermiculite did not show a significant change in compressive strength; however, the increase in vermiculite content of 7%, 15%, and 34% caused reductions in the compressive strength in the order of 46%, 61%, and 69%, respectively. Comparing the studies by Palomar et al. (2015) [43] and Barros (2018) [17] to that by Silva et al. (2010) [41], for mortars with vermiculite not to present significantly low strengths, it is necessary to have a high cement consumption.

Sinhorelli [44] also showed an increasing cement consumption as the vermiculite content increased from 0% to 5%, 9%, and 17%. The vermiculite content variation in mortars caused a decrease in the compressive strength from 6.14 MPa to 4.20 MPa, 2.72 MPa, and 2.25 MPa, respectively. Comparing the results from Palomar et al. [43] and Barros [17] to those from Sinhorelli (2019) [44], it can be noted that mortars with a minimum cement consumption of 214 kg/m^3 and vermiculite content up to 3% of the total dry material did not present major changes in the compressive strength. However, mortars with a cement consumption lower than 200 kg/m^3 and/or a vermiculite content higher than 3% presented a reduction in compressive strength.

In the study by Cintra et al. [7], the samples CT14V34 with 34% vermiculite and CT14V40 with 40% vermiculite showed the following values of compressive strength: 1.25 MPa and 1.36 MPa, respectively. Analysis of these authors' article showed that, despite the increased vermiculite content, the CT14V40 sample had a higher content of binders and lower water consumption, which justifies the slightly increased compressive strength.

As with the compressive strength, vermiculite causes a negative influence on the flexural strength of mortars. The studies by Silva et al. (2010) [41], Barros (2018) [17], and Sinhorelli (2019) [44] demonstrated gradual reductions in this property as the vermiculite content increased.

In the study by Silva et al. (2010) [41], it was noted that the cement and lime content was fixed, and the vermiculite content varied from 0% to 10%. This increasing vermiculite content in the mixtures caused a reduction in the tensile strength from 1.56 MPa (SV10V0) to 0.45 MPa (SV10V10). Thus, as with compressive strength, one way to mitigate the decrease in tensile strength is by increasing the cement content of the mixtures; this is clear in the studies by Palomar et al. (2015) [43], Barros (2018) [17], and Sinhorelli (2019) [44].

The mortars of Palomar et al. (2015) [43] had a fixed cement consumption of 214 kg/m^3, but although the consumption of this binder had been fixed, its share of the total dry material increased as the vermiculite increased; as a result, the mortars of Palomar et al. (2015) [43] showed no decrease in the flexural strength.

Barros (2018) [17] and Sinhorelli (2019) [44] showed increasing cement consumption as the consumption of vermiculite increased. So, the representation of this binder of the total dry mix showed increasing behavior. In the study by Barros (2018) [17], the cement content varied from 12.38% to 46.54% and the vermiculite content varied from 0% to 34%, and even with increased cement consumption, the flexural strength of the mortars, in this study, obtained lower values ranging from 1.90 MPa (B18V0) to 0.84 MPa (B18V34). In these samples, an increase in the w/c ratio occurred along with an increase in the vermiculite content. In the research by Sinhorelli (2019) [44], the cement content varied from 8.70% to 22.63%, and the vermiculite content varied from 0% to 17%, which provided reductions in tensile strength from 2.54 MPa to 1.18 MPa.

The reduction in mechanical properties was justified by Silva et al. (2009) [41] by the capacity of vermiculite to incorporate voids, since this material is porous and thin and, thus, promotes a higher water demand, consequently generating more voids after water evaporation.

To minimize the loss of resistance, some solutions can be considered. Rossignolo (2009) [31] points out that a solution for working with a lightweight material and controlling water demand is to presaturate the aggregate, preventing it from removing water intended for cement hydration. Koksal et al. (2020) [55] showed that the combined use of vermiculite (EV) with waste-expanded polystyrene (WEPS) in the proportions of 50% EV + 50% WEPS and 75% EV + 25% WEPS in 1:3, 1:4, and 1:5 (cement: EV + WEPS) mixtures by volume provided considerable mechanical strength gains compared to mortars containing only WEPS or vermiculite. However, a well-established solution is the use of mineral admixtures, as proposed by Sinhorelli (2019) [44], Koksal et al. (2015) [48], and Soda et al. [64]. All of these authors demonstrated that the use of mineral admixtures promotes the refinement of and a reduction in pores; this occurs due to the pozzolanic effect in the mineral admixtures, which enables the additional production of C–S–H [64,65], which can bring improvements in the mechanical properties of mortars, as can be seen in Figure 11.

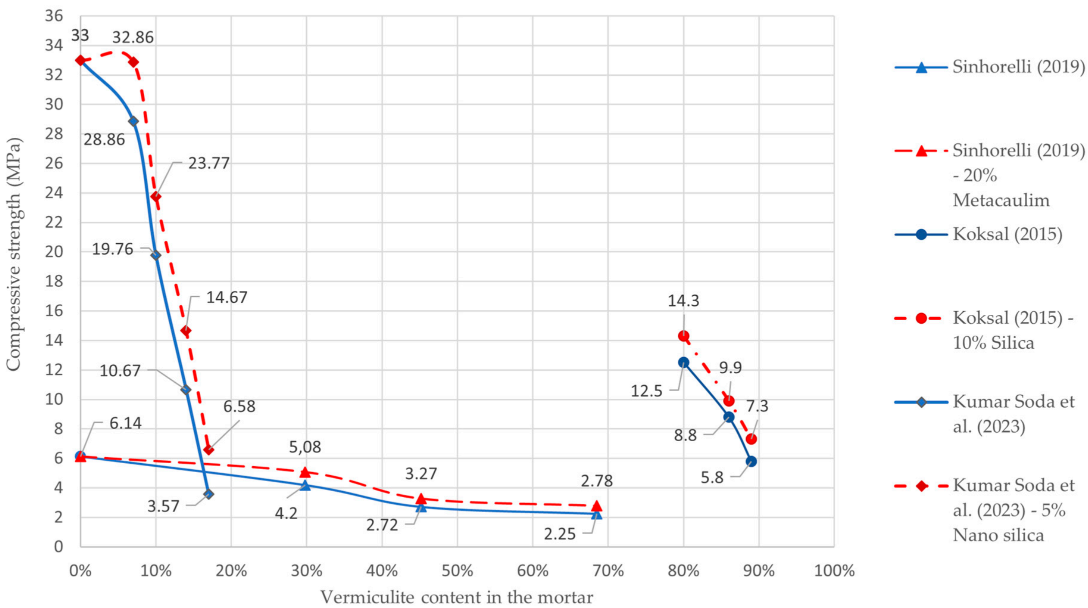


Figure 11. Correlation between vermiculite content in the mixture and compressive strength in samples with and without mineral addition [44,48,64].

Sinhorelli (2019) [44] used metakaolin (MK) in a 1:1:6 (cement/lime/aggregate) ratio mix design with 20% of MK. This amount of MK promoted an increase in the compressive strength in the range of 20% to 23%. The sample studied by Koksal et al. (2015) [48] presented higher compressive strength in mortars in a range between 12% and 25% with the use of silica fume in a proportion of 15% using ratios of 1:4, 1:6, and 1:8 (cement/aggregate). Additionally, Soda et al. [64] demonstrated that the addition of 5% nanosilica improved the compressive strength by between 14% and 84% when comparing mortars to one had the same vermiculite content.

Regarding compressive and tensile strength, the results showed that the use of vermiculite causes reductions in these properties. In general, the use of lightweight aggregates in mortars causes reductions in their mechanical properties, but according to the study by Gündüz and Kalkan (2019) [45], vermiculite causes smaller reductions compared to perlite, which is also a lightweight aggregate of mineral origin.

2.4.6. Thermal Conductivity and Thermal Transmittance

Studies on the use of thermal coating have been widely developed by the scientific community. Carneiro (1993) [56] points out that the thermal conductivity of a material is related to its density, and in a wall system, thermal insulation is guaranteed by a low thermal conductivity in the constituent elements and a guarantee of nonwetting.

The Brazilian standard NBR 15220-2 [66] specifies that common, cellular, cement-based, and gypsum mortars with vermiculite have a thermal conductivity (λ) of 1.15 W/(m·K), 0.40 W/(m·K), and 0.30 W/(m·K), respectively. In cement mortars containing vermiculite, the air present in the aggregate and in the voids formed in the hardened mixture produces low thermal conductivity and, consequently, high resistance to the heat passage [17]. Barros [17] still demonstrated that the replacement of sand with vermiculite benefited the thermal properties of mortars, as shown in Table 12.

Table 12. Thermal property of mortars with vermiculite [17].

Properties	Mix Design				
	0%	25%	50%	75%	100%
Thermal conductivity (W/m·K)	1.34	1.08	0.62	0.34	0.24
Thermal resistivity (m·K/W)	0.746	0.927	1.605	2.981	4.256
Volumetric heat capacity (MJ/m^{3}K)	2.42	2.18	1.50	1.32	1.23
Thermal diffusivity (mm^2/s)	0.57	0.50	0.42	0.26	0.19

In the research carried out by Palomar et al. (2015) [43], Koksal et al. (2015) [48], Barros (2018) [17], Sinhorelli (2019) [44], Gündüz and Kalkan (2019) [45], and Koksal et al. (2020) [55], an indirect relationship between the vermiculite content and thermal conductivity of lightweight mortars can be seen. The decrease in thermal conductivity as the vermiculite content increases is justified by the increasing porosity of the mortars caused by the addition of this lightweight aggregate.

In Figures 12–19, the results of the thermal conductivity and porosity of mortars, found by Palomar et al. (2015) [43], Koksal et al. (2015) [48], Barros (2018) [17], and Koksal et al. (2020) [55], are presented, and it is clear there is a linear correlation between increasing porosity and decreasing thermal conductivity.

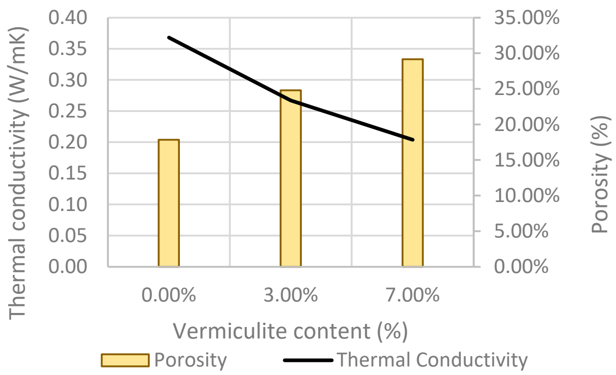


Figure 12. Correlation of vermiculite content, thermal conductivity, and porosity results from the study by Palomar et al. (2015) [43].

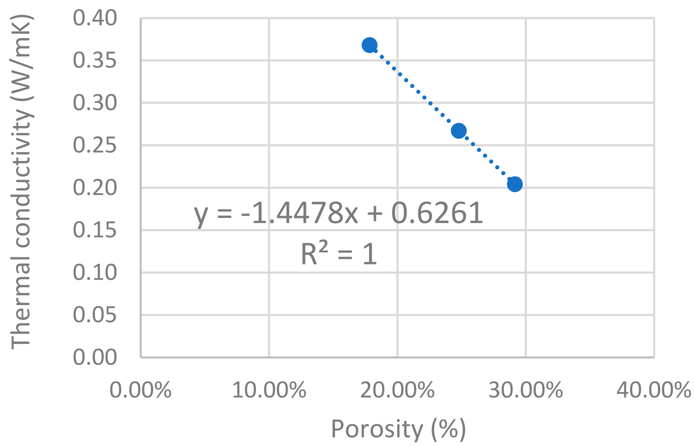


Figure 13. Correlation between thermal conductivity and porosity from the study by Palomar et al. (2015) [43].

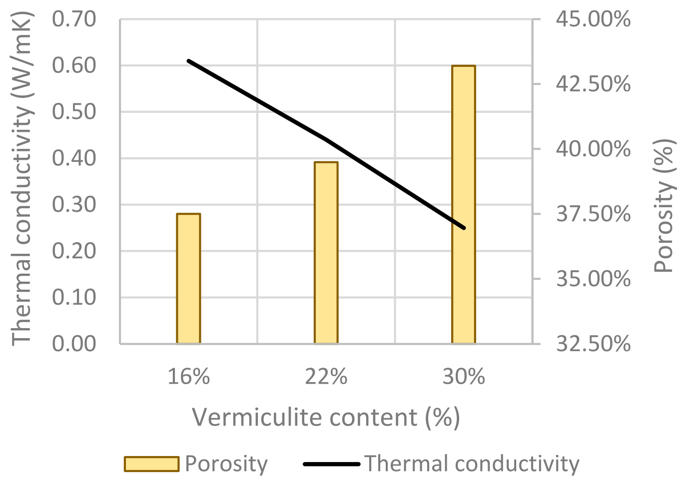


Figure 14. Correlation of vermiculite content, thermal conductivity, and porosity results from the study by Koksal et al. (2015) [48].

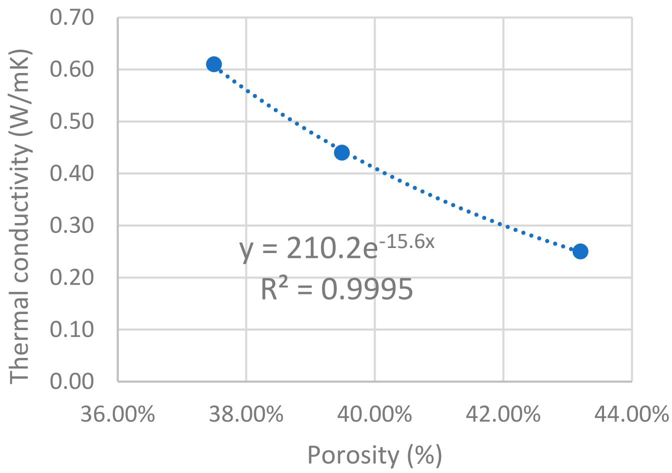


Figure 15. Relationship between thermal conductivity and porosity results from the study by Koksal et al. (2015) [48].

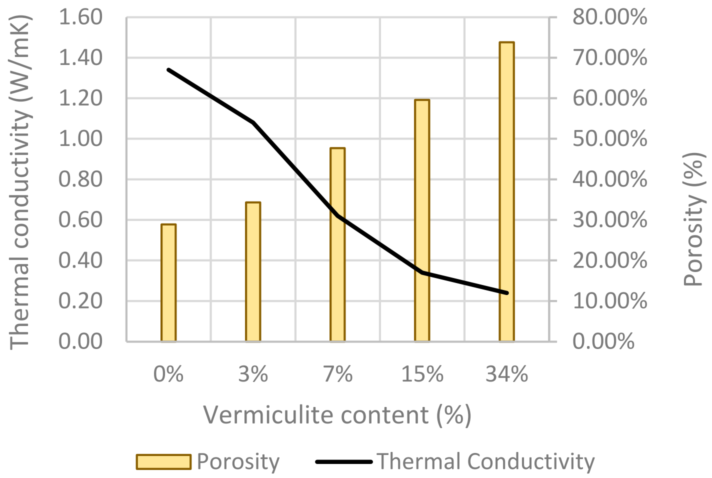


Figure 16. Correlation of vermiculite content, thermal conductivity, and porosity results from the study by Barros (2018) [17].

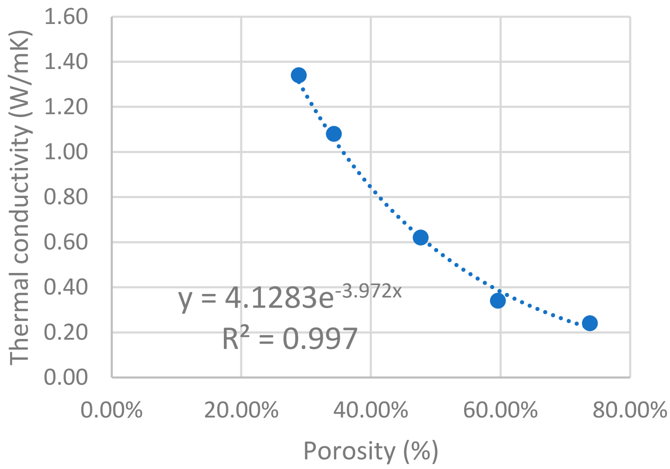


Figure 17. Thermal conductivity and porosity correlation from the study by Barros (2018) [17].

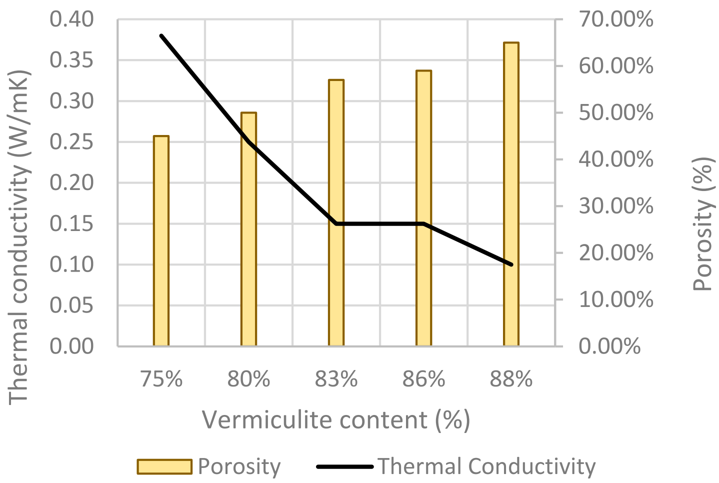


Figure 18. Correlation of vermiculite content, thermal conductivity, and porosity from the study by Koksal et al. (2020) [55].

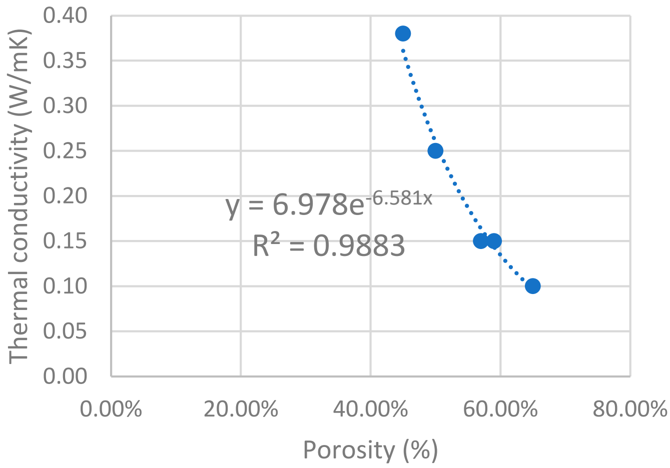


Figure 19. Thermal conductivity and porosity correlation from the study by Koksal et al. (2020) [55].

As can be seen in Figure 12, Palomar et al. (2015) [43] obtained a low thermal conductivity for the mortar without vermiculite (0.37 W/m·K); despite this, with the addition of vermiculite contents of 3% and 7%, the thermal conductivity reduced to 0.27 W/m·K and 0.20 W/m·K, respectively. This reduction had a strong correlation with the increase in porosity, as seen in Figure 13, and is defined by a first-degree function with a high coefficient of determination (R^2 = 1).

The mortars studied by Barros [17] containing vermiculite contents of 0%, 3%, 7%, 15%, and 34% reached porosity values ranging from 28.90% to 73.80%. The increase in porosity caused a reduction in the thermal conductivity from 1.34 W/m·K to 0.24 W/m·K (Figure 14). As observed by Palomar et al. [43], the results from Barros's study (2018) [17] also reached a very good correlation between porosity and thermal conductivity (Figure 15). The function that best explained this correlation between these two variables is the exponential equation, which obtained a coefficient of determination equal to 0.997.

The mortars produced by Koksal et al. (2015) [48] showed varying porosity of 37.50%, 39.49%, and 43.20% as the vermiculite content increased from 16% to 22% and 30%, respectively. This increase in the number of pores reduced the thermal conductivity from 0.61 W/m·K to 0.25 W/m·K, and the porosity and thermal conductivity values also showed a strong correlation with a coefficient of determination equal to 0.9995.

Different from the previous study, in the one by Koksal et al. (2020) [55], the mortars presented higher vermiculite contents varying from 75% to 88%, and, consequently, the porosity was also higher and varied from 45% to 65%, providing a reduction in the thermal conductivity from 0.38 W/m·K to 0.10 W/m·K.

In the previously mentioned studies, it was clear that mortars with vermiculite had higher porosity contents, which can be attributed to the porous nature and high water absorption capacity of this aggregate. Thus, as the vermiculite content increased, the porosity also showed an increasing behavior. Because of the increasing porosity, the thermal conductivity reduced in the mortars, and through the coefficients of determination (R^2), a strong correlation between the porosity and thermal conductivity was noted.

To conclude, the use of vermiculite proved to be beneficial for reducing the thermal conductivity of mortars. The thermal insulation of walls reduced the thermal transmittance and heat exchange between faces, thus contributing to a better thermal performance of the building. According to Gündüz and Kalkan (2019) [45], the use of this aggregate can contribute to reducing the thermal transmittance of the wall element (coating mortar + masonry block) by approximately 13% compared to when it is used traditional mortar.

In Table 13, it can be seen from Barros's results (2018) [17] that the use of mortars with vermiculite and low thermal conductivity enables a reduction in thermal transmittance and thermal capacity of wall systems produced with ceramic bricks or concrete blocks. It can be observed that for the thermal transmittance in the wall system with a "ceramic brick + mortar coating on both sides", there was a reduction between 2.5% and 28.5% when sand was replaced by vermiculite (in volume) contents of 25%, 50%, 75%, and 100%. For the system with a "concrete block + mortar coating on both sides", the reduction was between 2.4% and 30.6%. In the Brazilian standard ABNT NBR 15.575-4 (2013) [4], the buildings located in the midwest, southeast, south, and northeast regions must have a wall system with thermal transmittance lower than 2.5 W/m^{2}K and a thermal capacity higher than 130 kJ/m^{2}K; thus, in the system with ceramic brick, the mortars with 0%, 25%, 50%, and 75% vermiculite comply with these requirements. In the system with concrete blocks, the samples with 75% and 100% vermiculite meet the minimum requirements of the Brazilian standard (NBR 15.575-4, 2013) [4].

Table 13. Thermal mortar performance in EVSS [17].

External Vertical Sealing Systems (EVSS)	Properties	Mix Design				
		0%	25%	50%	75%	100%
-	Thermal conductivity of the coating mortar (W/m·K)	1.34	1.08	0.62	0.34	0.24
Ceramic bricks coated on both sides	Thermal transmittance (W/m^{2}K)	2.42	2.36	2.18	1.92	1.73
	Thermal capacity (kJ/m^{2}K)	177.7	167.7	139,0	131.3	127.5
Concrete blocks coated on both sides	Thermal transmittance (W/m^{2}K)	2.94	2.87	2.63	2.28	2,04
	Thermal capacity (kJ/m^{2}K)	204.9	195.1	167.2	159.8	156.1

Because of the decreasing thermal transmittance, room-heating and -cooling equipment may have diminished use. Bastos (2018) [67] showed that the use of vermiculite mortars for external and internal coating provides an energy consumption reduction to cool a room by approximately 20%, improving the building's energy efficiency.

3. Conclusions

According to this article review, the following conclusions can be made:

- Vermiculite is a mineral originating from the alteration of micaceous minerals by chemical weathering and hydrothermal action. When it is heated to temperatures close to 1000 °C, it undergoes an expansion process, that is, an increase in volume caused by water vapor formed inside the vermiculite, which causes internal stresses, separating the octahedral and tetrahedral plates that compose the vermiculite.
- When undergoing the expansion process, the volume of vermiculite increases and acquires a porous structure. Because of its expansion, there is a decrease in the density of the material to 0.15–0.25 g/cm^3. The specific surface area and the ability to be inert, absorbent, a thermoacoustic insulator, and fire-resistant increase. In addition to these characteristics, when it is expanded, it acquires different granulometry sizes, and the particle size can be classified as large, medium, fine, super fine, and micron, depending on the classification system.
- These properties make vermiculite a promising material for use in civil construction. It can be used, with little negative impact, to produce precast blocks with plaster/vermiculite mortar used in internal partitions, refractory bricks, blocks, and plates resistant to high temperatures, as well as in the protection of steel structures at high temperatures. However, when used in mortars, it can mitigate some fresh and hardened properties; however, this does not make the application of mortars with this type of aggregate unfeasible.
- In the fresh state, the lack of workability of mortars with vermiculite is noticeable due to the high water absorption of this aggregate. Due to this adverse effect, in order to make them workable, mortars with vermiculite have a higher water consumption. To improve this property, the vermiculite can be prewetted, and chemical additives or a

combination of granulometries (to have a continuous particle size distribution) can be used.

- In the hardened state, vermiculite promotes an increase in the number of pores due to the increase in water consumption. This fact causes a growth in the w/c ratio, and as a consequence of this, the mechanical strength decreases when the vermiculite content increases in the mixture. To mitigate the loss of mechanical strength, some measures can be adopted, such as working with lightweight presaturated aggregate, combining the use of vermiculite (EV) with waste-expanded polystyrene (WEPS), or adding mineral admixtures such as metakaolin or silica fume.
- Despite causing negative effects on the workability and mechanical strength, vermiculite promotes a thermal conductivity reduction in mortars by making the composite more porous. This can be seen as a viable option when aiming for thermal insulation in an environment because it can reduce the thermal transmittance of wall elements and, consequently, reduce energy consumption and improve the building's energy efficiency.

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