Macroporous Mortars for Laying and Coating

Morteros macroporosos para asentamiento y revestimiento

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Abstract
The envelope of a building is responsible for its physical protection against external agents, including humidity and temperature. Thus, the present work seeks to evaluate the effect of air entraining admixtures (AEA) in mortars for laying and coating to improve their physical and thermal performances. The AEA generates macropores, interrupting the system of canaliculi that allows the capillary absorption of water. The AEA used is based on biodegradable surfactant molecules of Linear Alkyl Benzene Sodium Sulfonate. Results compare physical tests (water absorption, capillary coefficient, specific gravity, and mechanical strength), and thermal evaluation (thermal conductivity and specific heat) from two mortars mixtures with varying levels of AEA. Scanning electron microscopy (SEM) of the pore system were also analysed. All mixtures studied presented higher workability and cohesion, reduced thermal conductivity, decreased specific heat, and a reduction in the effects of water absorption, capillary elevation and specific gravity (density). In this sense, the durability of mortars to humidity effect is potentially improved, along with several other properties. Therefore, this work seeks to contribute to the quality of built environments, as well as to promote the technological development of cement-based composites.

Keywords: air-entraining admixture; mortars; macroporous cement-based composites; capillarity; built environment.

Resumen
Los cerramientos de un edificio son responsables de su protección física contra agentes externos, incluida la humedad y la temperatura. Por lo tanto, el presente trabajo busca evaluar el efecto de los aditivos inclusores de aire (AEA) en los morteros para asentamiento y revestimiento para mejorar

sus rendimientos físicos y térmicos. Los AEA generan macroporos, interrumpiendo el sistema de canalículos que permiten la absorción capilar del agua. El AEA utilizado se basa en moléculas de un surfactante biodegradables - alquil benceno sulfonato de sodio lineal. Los resultados comparan pruebas físicas (absorción de agua, coeficiente capilar, masa específica y resistencia mecánica) y evaluación térmica (conductividad térmica y calor específico) de dos mezclas de morteros con niveles variables de AEA. También se analizó la microscopía electrónica de barrido (SEM) del sistema de poros. Todas las mezclas estudiadas presentaron mayor trabajabilidad y cohesión, reducción de la conductividad térmica, disminución del calor específico y reducción de los efectos de la absorción de agua, elevación del capilar y gravedad específica (densidad). En este sentido, la durabilidad de los morteros al efecto de la humedad es potencialmente mejorada, junto con varias otras propiedades. Por lo tanto, este trabajo busca contribuir a la calidad de los entornos construidos, así como a promover el desarrollo tecnológico de compuestos de matriz cementicia.

Palabras clave: Aditivos inclusores de aire; morteros; compuestos macroporosos de matriz cementicia; capilaridad; ambiente construido.

Introduction

Mortars are a fundamental element of the envelope system, designed to ensure proper aesthetics and guaranteeing the environmental seal (Yazigi, 2004). One of the main characteristics of mortars is its pore system, including gel pores (1-100 nm), formed within the cement hydration products; and capillary channels (diameters on the range of 100 nm - 5 µm), the space left between cement particles after the consumption or evaporation of water (Powers, 1949; Mehta & Monteiro, 2014).

This system of interconnected pores allows the inlet of water and aggressive agents. Water mainly penetrates mortars through cracks on the surface, flow (when there is a pressure gradient), and capillary absorption. When the significantly narrow capillary channels are placed into contact with the surface of a liquid, the surface tension between the two substances will act to draw the liquid up into it (Dyer, 2014). In turn, the moisture originates from several sources (Bertolini, 2014):

Construction humidity: the permanence of moisture from the curing water during construction;
Descending humidity: originated by direct contact with water from the external medium (i.e. rainwater);
Steam moisture: condensation of water vapour in the pores or surface;
Ascending moisture: absorption of water by capillarity due to direct contact of the lower parts of the masonry with water or moist soils.

Among those, ascending moisture through capillary absorption is one of the most challenging phenomena to control in masonry (Souza & Ripper, 1998). The penetration of water contributes significantly to the degradation of the envelope, to the deterioration of the quality of indoor environment, and to the occurrence of pathologies in the structure (Souza & Ripper, 1998). Some common pathological manifestations are: the corrosion of steel bars, efflorescence, freezing damage, erosion, blistering and bubbles in paints, among others (Bertolini, 2014). They generate high costs of maintenance and recovery.

One way to avoid the ascending moisture is to use waterproofing admixtures (Yazigi, 2004). These substances react with the cement during the hydration process, producing mineral compounds that block the capillary network; and thus, they significantly reduce the permeability of this network (Vedacit, 2016). Other types of admixtures for cement-based composites are acrylic polymers, which form an impermeable film; or yet water-repellent substances (hydrophobic admixtures) that prevent the penetration of water (Ramachandran, 1995).

Despite the several products available in the market, the use of waterproofing admixtures in the mortars without adequate treatment of the foundations only slows down the pathological effects of moisture. In typical situations, in which only the external face of the wall is waterproofed through impermeable paints or ceramic tiles, the ascending humidity is intensified in the internal environment, accentuating occurrences of mould and peeling (Bertolini, 2014).

In this scenario, an alternative to mitigate the ascending moisture in coatings is the use of air-entraining admixtures (AEA). The AEA are based on surfactant molecules, which stabilise the air voids formed during mixing, generating a system of macropores (> 5 µm) well-dispersed throughout the matrix (Kumar & Bhattacharjee, 2003; Du & Folliard, 2005). These macropores may exhibit variations in their dimensions, volume, degree of interconnection and opening to the external surface (Atahan, Carlos Jr., Chae, Monteiro, & Bastacky, 2008). They, thus, directly interfere with the physical characteristics of cement-based composites, such as mechanical strength, specific gravity (density), resistance to aggressive agents and thermal and acoustic conductivity (Ouyang, Guo, & Qiu, 2008; Zhao, Xiao, Huang, & Zhang, 2014; Mendes et al., 2017).

On this matter, the envelope materials are responsible not only for the health of the occupants and the aesthetics of the project, but also for aspects of thermal comfort and energy efficiency (Lamberts, Dutra, & Pereira, 1997). Therefore, the use of mortars with better thermal insulation will reduce the need of artificial conditioning during the building's entire lifecycle (Carabaño, Hernando, Ruiz, & Bedoya, 2017) (Oliveira, 2009).

Description of the problem

In this scenario, seeking to develop coating and laying mortars with increased durability, this paper evaluates the effect of AEA content in them. The macropores promote the disconnection of the capillary channels, preventing the ascension of water and allowing its evaporation (Young, Mindess, Gray, & Bentur, 1998); but they are not interconnected in a way that would increase the water permeability of the matrix (Mendes et al., 2017). Furthermore, the air entrainment improves the workability and cohesion of the mortars in the fresh state and reduces its specific gravity (density) on the hardened state, resulting in better application quality, higher productivity and lower structural load (Mendes et al., 2017; Ouyang et al., 2008). The macropores are also widely known to improve freeze-thaw durability (Felice, Freeman, & Ley, 2014; Ramachandran, 1995). Finally, it is expected that the void system will promote greater thermal and acoustic insulation to the mortar and, therefore, to the building as a whole.

Therefore, the present work aims to develop macroporous mortars for coating and laying as a sustainable alternative for the improvement of the built environment. It seeks to reduce the risk of moist-related pathologies, to improve the thermal comfort of buildings; and the technological development of envelope systems.

State of the art

Regarding thermal insulation of masonry-mortar building envelopes, Bustamante, Bobadilla, Navarrete, Vidal, & Saelzer (2009) studied the insulation potential of ceramic bricks; Demirboga (2003), the influence of mineral admixtures in the thermal conductivity of mortars; and Corinaldesi, Mazzoli, & Moriconi (2011), the effect of waste rubber particles on them. Other researchers evaluated thermal properties of concretes and cement pastes (Demirboga & Gül, 2003; Laukaitis, Zurauskas, & Keriene, 2005; Kim, Jeon, Kim, & Yang, 2003). Overall, there is little literature regarding thermal properties of mortars, and these few papers concentrate on evaluating the addition of fibres and mineral admixtures (Corinaldesi, Mazzoli, & Moriconi, 2011; Demirboga R. , 2003; Xu & Chung, 2000; Khedari, Suttisonk, Pratinthong, & Hirunlabh, 2001) . On the other hand, the present work focuses on the behaviour of mortars with the stabilisation of air voids through a chemical admixture.

In this sense, Felice et al. (2014), Ouyang et al. (2008), Kumar & Bhattacharjee (2003), Ramachandran (1995), among others, proved that AEAs significantly improve various properties of cement-based composites, e.g., lower specific gravity, more cohesion, improved workability, and increased resistance to freeze-thaw cycles. However, none showed a specific focus on mortars for laying and coating, neither on their thermal properties. The present work seeks to address both issues, also including the connection of macropores to moisture-related pathologies – the capillary absorption.

Materials and methods

Mixtures and Specimen Preparation

The present work presents an experimental research and application in engineering. Two typical mortar mixtures were evaluated: 1:2:9 and 1:1:6 (cement : lime : sand, by volume), respectively used for laying bricks and coating walls. A biodegradable AEA was added in contents of 0%, 0.05% and 0.5% over the mass of cement (c.m.).

The mortars were produced in a conventional mortar mixer (ABNT, 2016). Mix procedure included 1 min in low speed, followed by 30 s in high speed. Water/cement (w/c) ratio was defined as the necessary for the mixture to reach a flow of 260 ± 5 mm. The specimens were demoulded after 24h. Curing was performed in a moist chamber for the remaining 27 days; temperature 25 ± 2°C and relative humidity of 90% ± 5%.

Materials

The following materials were used: high early strength Portland cement (equivalent to ASTM type III); hydrated Lime; regional river sand with 92.7% silicates; potable water; and an AEA based on Linear Alkyl Benzene Sodium Sulfonate (LAS).

The high early strength Portland cement was chosen since it has the lowest content of mineral admixtures among Brazilian cement types. According to standard NBR 16697 (ABNT, 2018), this product contains 90%-100% of clinker and gypsum and only 0%-10% of inert limestone filler. Table 1 shows the properties of the cement used in the present work.

Table 1. Physical-mechanical performance of the Portland cement (Source: manufacturer Brennand Cimentos).

Parameter	Result	Standard Requirements (ABNT, 2018)
Insoluble Residue	0.86%	≤1%
Loss on ignition	3.18%	≤4.5%
MgO content	1.36%	≤6.5%
SO_3 content	3.32%	≤4.5%
CO_2 content	2.56%	≤3.0%
Na_2O content	0.07%	-
K_2O content	0.91%	-
Specific area (Blaine method)	4.743 cm^2/g	≥3.0 cm^2/g
Apparent specific gravity	3.04 g/cm^3	-
Fineness Index – % retained in sieve #200	0.27%	≤6.0%
Compressive strength at 7 days	49.1 MPa	≥34.0 MPa

Hydrated lime type CH-I was adopted due to its high level of purity (ABNT, 2003). Table 2 presents its chemical composition.

Table 2. Chemical Composition of Hydraulic Lime (Source: manufacturer Ical).

Components	Proportion (%)
CaO	53.81
SiO_2	26.06
Fe_2O_3	8.46
MgO	3.2
SO_3	2.46
Al_2O_3	1.94
CO_2	1.25
K_2O	0.5
Loss on ignition (1000°C)	2.38
Insoluble residue	0.4

This AEA originates from dishwashing detergent, which was proven, in previous works, to be effective in promoting the stabilisation of pores (Mendes et al., 2017). It consists of an association of anionic surfactants between 6 and 10%: LAS; Linear Alkyl Benzene Sulfonate Triethanolamine (CAS: 27323-41-7) and Sodium Lauryl Ether Sulphate (CAS: 9004-82-4) (Química Amparo LTDA, 2011). In addition to being widely available, non-toxic and low cost (approximately 25% the cost of commercial admixtures), the dishwashing detergent comprises biodegradable surfactants by regulation (ANVISA, 2008), thus presenting a lower environmental impact.

Physical characterisation

On the fresh state, the following investigations were performed: flow, per NBR 13276 (ABNT, 2016) and air entrained content, by the pressure method. At 28 days, the following experiments were carried out: water absorption and specific gravity (density), according to NBR 9778 (ABNT, 2009); compressive and flexural strengths, according to NBR 13279 (ABNT, 2005); and water absorption coefficient due to capillary action, NBR 15259 (ABNT, 2005).

The water absorption coefficient due to capillary action, also known as capillary index, measures the mass of water absorbed by capillary action in relation to the cross-section area of the specimen, after specific periods (1, 3, 7, 24 and 48h). For each test on the hardened state, the result comprehends a mean of 5 cylindrical specimens of dimensions φ50 ×100 mm.

Mechanical properties, compressive and flexural strength, were obtained from 6 and 3 prismatic specimens of dimensions 40×40×160 mm, respectively. A universal hydraulic press EMIC DL 20000 was employed. The tests of compressive strength were performed at a load rate of 500 N/s; the flexural strength test, 50 N/s, as prescribed by the standard.

Thermal characterisation

The thermal characterisation comprised the determination of the thermal conductivity and the specific heat of each mortar mixture. The thermal conductivity was obtained with a heat flow meter type Lambda HFM 436, manufactured by NETZSCH. For each mixture, 4 boards of dimensions 300×300×50 mm were built and cured similarly to the cylindrical specimens. Before the test, the specimens were oven dried at 80°C and weighed each 24h until the mass loss did not exceed 0.5% in two subsequent intervals. This procedure sought to level the free water content of all boards to the lowest possible level, without affecting their microstructure. The final value of the thermal conductivity was given by the average of the measurements in the mean temperature of 20°C and delta of 10°C.

Finally, specific heat was determined by a polystyrene calorimeter coupled to a HOBO Onset U12-006 temperature acquisition system. Results comprehend the average of the measurements of 4 samples of approximately 10cm^3, previously kept in an oven at 100°C for 24h. The specific heat was determined when immersing the specimens at 100°C in 200g of water at 20°C.

Morphological analysis

The scanning electron microscopy (SEM) images were obtained 90 days after moulding, in a Tecsan Vega 3 SEM coupled with Energy Dispersive Spectroscopy (EDS). The tests were performed at the Nanolab Electronic Microscopy Laboratory, at the Redemat, Escola de Minas, UFOP, MG, Brazil. Samples were simply dismantled, in order to prevent the filling of the voids in case of sanding and covered with gold. After those procedures, samples ended up with dimensions in the range of 0.5 - 1 cm.

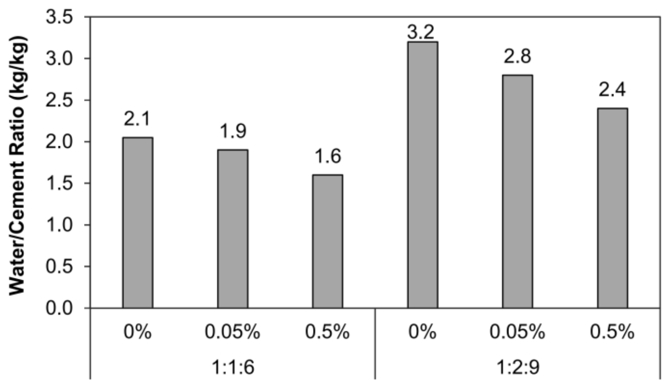
To evaluate the isolated effect of AEA, besides mortars 1:1:6 and 1:2:9, mortars without lime were produced exclusively for this test. The mixture proportion followed the same rule observed in the others: the volume of fine aggregate is 3 times that of the binders. Final mixture resulted in 1:3 (cement : sand). The same preparation and curing conditions were applied.

Results and discussion

Physical characterisation

In order to determine the amount of water for each mixture, the flow was kept fixed at 260±10 mm. We chose to present the water/cement mass ratio (w/c factor) rather than the water/binders volume ratio, conventionally used for mortars, aiming at greater precision and repeatability of the mixtures. Figure 1 shows the w/c ratio results.

Figure 1. Results of w/c ratio for mortars 1:1:6 e 1:2:9 with varying contents of AEA. (Source: Authors).



A reduction of the w/c ratio is observed as the AEA content increases. This is due to the higher workability of the mortars, a consequence of the better spread of the cement particles attributable to the action of the surfactants (Ouyang et al., 2008) (Mendes et al., 2017). A significantly higher w/c ratio is observed for mixtures 1:2:9. This is probably a result of the increase in lime content since both mixtures present the volume ratio binders/aggregates constant (1/3). Lime is a light, fine air binder that knowingly promotes water retention due to its specific surface area, pore morphology, and chemical nature (Sébaïbi, Dheilly, & Queneudec, 2003).

Another positive side effect of the use of AEA is the reduction of the amount of water in the mixtures by up to 25%. On the sustainability viewpoint, this fact reduces the massive water consumption generally observed in construction sites. On the durability side, a lower amount of water also reduces the potential of drying shrinkage and all the aesthetic issues and pathologies related to it (Dyer, 2014; Souza & Ripper, 1998).

Figure 2 shows the results for entrained air content. The air entrainment is a function of the three-dimensional cascade of aggregates falling on each other during mixing (Du & Folliard, 2005). The function of the AEA is to stabilise this entrained air voids, so they do not coalesce, do not collapse, do not emerge to the surface, and the air does not diffuse into larger surrounding bubbles (Myers, 1999; Ramachandran, 1995). In this sense, it is expected that the air-entrainment increases with the increase in AEA content, as observed.

Mortars 1:2:9 presented higher air entrainment for 0% and 0.05% matrices. This trend is probably a function of the higher amount of lime in this mixture since this binder also contributes to air entrainment effect (Silva & Campitel, 2006; Sébaïbi et al., 2003). In the mixtures of 0.5% AEA, the air entrainment effect is similar, possibly due to the wide availability of surfactant molecules in the matrices (Ouyang et al., 2008; Du & Folliard, 2005).

Figure 2. Results of Air-Entrained Content for mortars 1:1:6 e 1:2:9 with varying contents of AEA. (Source: Authors).

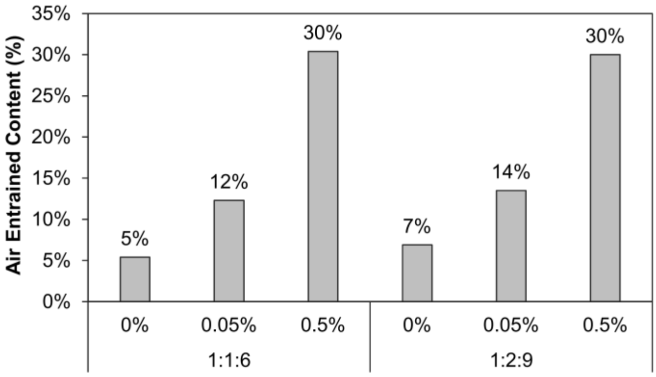
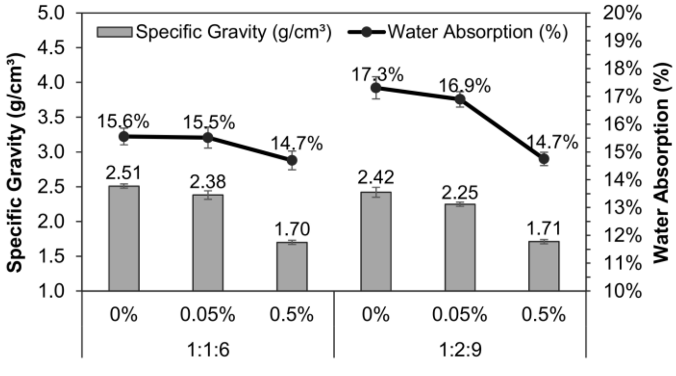


Figure 3 shows the results of specific gravity (density) and water absorption for the mortar mixtures. The behaviour in the specific gravity results follows closely those of air-entrainment (Figure 2). As expected, there is a decrease in the specific gravity as the AEA content in the mixtures increases. As the surfactant is added, the surface tension is reduced, with the formation and maintenance of a stable foam system (Ouyang et al., 2008; Du & Folliard, 2005). Thus, the porosity increases, making the mortars lighter (Mendes et al., 2017; Yang, Zhu, Wu, & Huang, 2000). Mortars 1:2:9 and 1:1:6 with 0.5% AEA were 29% and 32% less dense than the respective references. This reduction of the specific gravity entails a reduction of the permanent loads in the structure and foundation of the buildings.

Figure 3. Results of Specific Gravity (Density) and Water Absorption for mortars 1:1:6 e 1:2:9 with varying contents of AEA. (Source: Authors).



The specific gravity results prove that the specimens with 0.05% and 0.5% AEA have a more porous matrix than the reference; however, these additional pores do not translate into an increase in their water absorption. On the contrary, the opposite effect is observed. Mortars 1:1:6 and 1:2:9 with 0.5% AEA showed water absorption 6% and 15% lower than their respective references. The macropores of these mixtures do not contribute to the entry of water into the matrix because a) they are well distributed so that there is no connection between them, and b) they are interrupting the capillary channels close to the surface and preventing water penetration by surface tension (Bertolini, 2014; Dyer, 2014; Young et al., 1998).

In turn, Figure 4 and Figure 5 show the results of the water absorption coefficient due to capillary action. For both 1:1:6 and 1:2:9 mortars, the water absorbed by capillary action increased with time, less significantly at 48h, showing a tendency for stabilisation. In both mixtures, the capillary action was highest in specimens without AEA (0%). As the AEA content increased, it was observed that the capillarity coefficient decreased, reaching its lowest value in the mixtures with 0.5% AEA. At 48h, a 60% decrease was observed between 0.5% AEA and 0% AEA for mixture 1:1:6; 43% for mixture 1:2:9. Therefore, it was demonstrated that the capillary action in the mortars decreases as AEA content increases, resulting in a higher generation of macropores. These macropores, larger than the capillary canaliculi and the gel pores of the matrix (Mehta & Monteiro, 2014; Kumar & Bhattacharjee, 2003), interrupt some of the capillary canaliculi existing in the conventional mortar, preventing the rise of water due to the surface tension.

In general, the capillary absorption values for mortars 1:2:9 were higher than for mortars 1:1:6. This is probably a function of the higher lime content of the 1:2:9 mortars since this air binder promotes water retention (Sébaïbi et al., 2003; Mehta & Monteiro, 2014). In this sense, a significant amount of the water demanded will not react within the mortars, and, by evaporating, will thus contribute to the formation of pores and to the refinement of the pore system (Fontes, Mendes, Silva, & Peixoto, 2016; Sébaïbi et al., 2003). Therefore, although mortars 1:2:9 have a slightly higher overall porosity (indicated by their slightly higher water absorption values), the capillary absorption result leads us to conclude that their pore system is possibly more refined.

Figure 4. Results of Water Absorption Coefficient due to Capillary Action (capillary coefficient) for mortars 1:1:6 with varying contents of AEA. (Source: Authors).

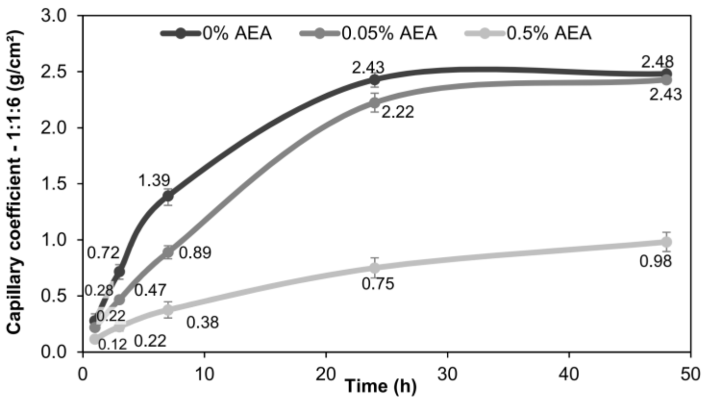
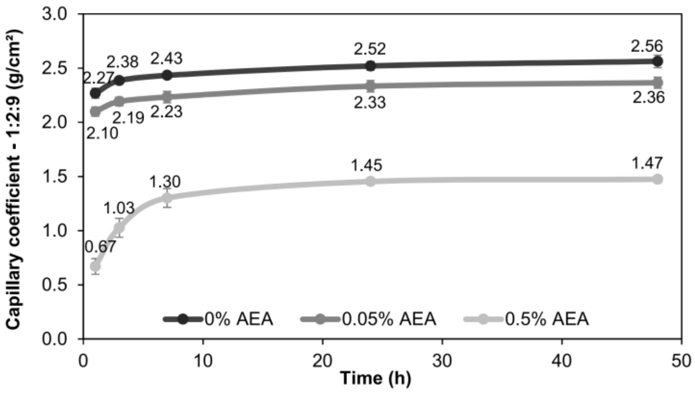


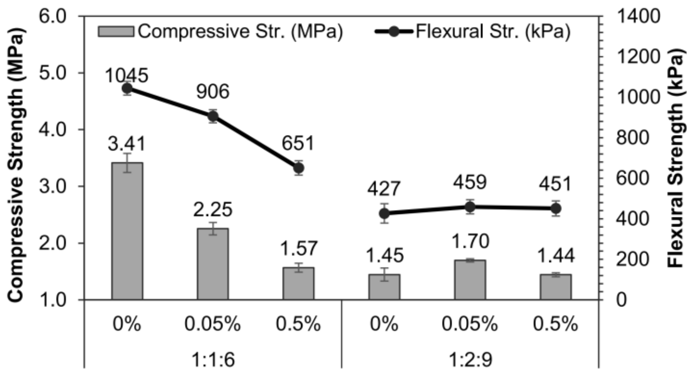
Figure 5. Results of Water Absorption Coefficient due to Capillary Action (capillary coefficient) for mortars 1:2:9 with varying contents of AEA. (Source: Authors).



Another related factor would be the improvement of the cohesion of the mortars. The use of LAS-based AEA significantly reduces the potentials for exudation and segregation of the matrices (Mendes et al., 2017; Ramachandran, 1995). Thus, there is a reduction of the phenomenon of sand deposit at the bottom of the test specimens, visually evaluated. A lower concentration of sand without binders at the bottom of the sample implies a lower porosity in this spot. Consequently, there is a lower water absorption by capillarity, as noticed for the mixtures with higher AEA content.

Finally, the mechanical properties are presented in Figure 6. Initially, it is noticeable that the compressive and flexural strengths for mortars 1:2:9 were significantly lower than for mortars 1:1:6. This reduction is a result of the reduced relative volume of cement in the mortars 1:2:9 (from 12.5% to 8.3%), their higher water/cement ratio (Figure 1) and their slightly higher air entrainment promoted by the increased content of lime (Figure 2).

Figure 6. Results of Compressive Strength and Flexural Strength for mortars 1:1:6 e 1:2:9 with varying contents of AEA. (Source: Authors)



The mechanical properties of mortars 1:1:6 presented a decreasing trend with the increase in AEA content. This behaviour was also observed by Mendes et al. (2017) and Ouyang et al. (2008). Although the AEA allowed a reduction of the w/c ratio (Figure 1), this reduction was not enough to compensate the increased porosity in mortars 1:1:6 with 0.05% and 0.5% AEA (Figure 2 and Figure 3).

On the other hand, the decline on the w/c ratio improved the results for mortars 1:2:9. From 0% to 0.05% AEA content, mortars 1:2:9 presented a 12.5% reduction on the w/c ratio, compared to 9.5% on mortars 1:1:6 (Figure 1). Since mortars 1:2:9 already presented a lower cement content, this reduction on the w/c ratio was felt more significantly, leading to an improvement on the mechanical properties of specimens with 0.05% AEA. Although the w/c ratio fell another 15.8% for mortars with 0.5%, the influence of the increased porosity resulted in a decrease in the mechanical properties to the level of mortars 0%.

Besides the w/c ratio, another factor that possibly affected the mechanical performance of mortars 1:2:9 is the increased lime content. It is known that lime promotes water retention and thus a refinement of the pore system (Fontes, Mendes, Silva, & Peixoto, 2016; Sébaïbi et al., 2003). A composite with smaller and well-distributed pores will not necessarily present a reduction in the mechanical properties, even if its overall porosity is higher (Kumar & Bhattacharjee, 2003; Ramachandran, 1995).

The mechanical strength is the ability of mortars to withstand mechanical actions of different natures, such as surface abrasion, impact and hygroscopic contractions. The majority of the mortars in the present study belong to the lower classes of mechanical strength according to Brazilian standard NBR 13281 (ABNT, 2005) (compressive strength < 3 MPa and flexural strength < 1500 kPa). However, the standard does not have a minimum requirement, even for laying mortars.

The overall low mechanical properties obtained are probably a result of the relatively high w/c ratios. The balance between the workability promoted by the AEA (and the consequent reduction on w/c ratio) and its air-entrainment potential is thus fundamental to the design of competent and durable mortars. The results therefore highlight the importance of the correct dosing and handling of AEA.

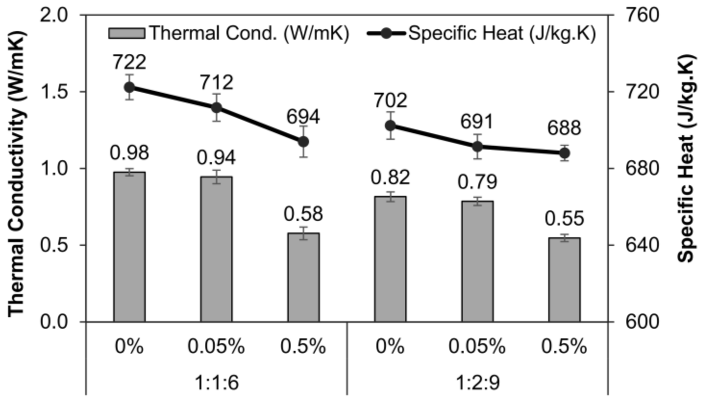
On the other hand, a relatively low compressive strength is usually linked to a low modulus of elasticity. A higher deformability improves durability, since the potential of cracking due to shrinkage and structure movement is reduced.

Thermal characterisation

Figure 7 shows the results of thermal conductivity and specific heat of the mortars. For thermal conductivity, decreasing values are observed as the AEA content increases. This behaviour is expected due to the increased porosity; which not only incorporates air into the matrix but also increases the number of interfaces (air/cement hydration products). The air is a material with known low thermal conductivity – 0.025 W/(m·K) at room temperature and free of convection (ABNT, 2003). According to Smith et al. (2013) and Burger et al. (2016), the thermal conductivity of a porous ceramic depends on (i) the intrinsic thermal conductivity of the solid phase and (ii) the thermal resistance due to phonon scattering at the interfaces. In this sense, the macropores work both reducing the conductivity of the solid phase as well as increasing the phenomenon of phonon scattering through their boundaries.

The difference observed between the 1:1:6 and 1:2:9 mixtures with 0% and 0.05% AEA is consistent with and related to their mixture proportion and air entrainment content. A lower thermal conductivity for mortars 1:2:9 might also be related to their refined pore system – more boundaries lead to increased phonon scattering and consequent lower thermal conductivity. Mortars 1:1:6 and 1:2:9 with 0.5% AEA presented thermal conductivity 41% and 33% lower than their respective references.

Figure 7. Results of Thermal Conductivity at 20°C and Specific Heat at 100°C for mortars 1:1:6 e 1:2:9 with varying contents of AEA. (Source: Authors).



The reduction of this property is essential to enhance the thermal performance of buildings, as it reduces the heat transfer rate between the internal and external environments. In addition to improving habitability, this factor promotes the reduction of the energy employed in conditioning over the operation stage of the construction (Bustamante et al., 2009; Carabaño et al., 2017; Lamberts et al., 1997).

Another important analysis is that even for reference mortars (0%), a significant difference is observed between the experimental results and the reference thermal conductivity provided by Brazilian standards: 1.15 W/(m·K) (ABNT, 2003). These variations can be related to the w/b content or measurement technique but should not be neglected. In terms of building simulations, this difference may underestimate or overestimate the thermal performance results. Hence the importance of updated, experimental results, as those provided in the present work.

On the other hand, the addition of AEA reduced the average specific heat values of the mortars (Figure 7), as a function of the macroporous system formed. This result was unexpected at first glance, since the air presents higher specific heat than the cement paste, approximately 1000 J/kg·K and 700-800J/kg·K, respectively (Yunsheng & Chung, 2000a; Yunsheng & Chung, 2000b). However, the increased porosity allows the water in the matrix (approximately 4200 J/kg·K) to evaporate more rapidly, reducing its overall specific heat. This result is corroborated by Mendes et al. (2017), who verified a greater shrinkage of mortars as the air entrainment increased.

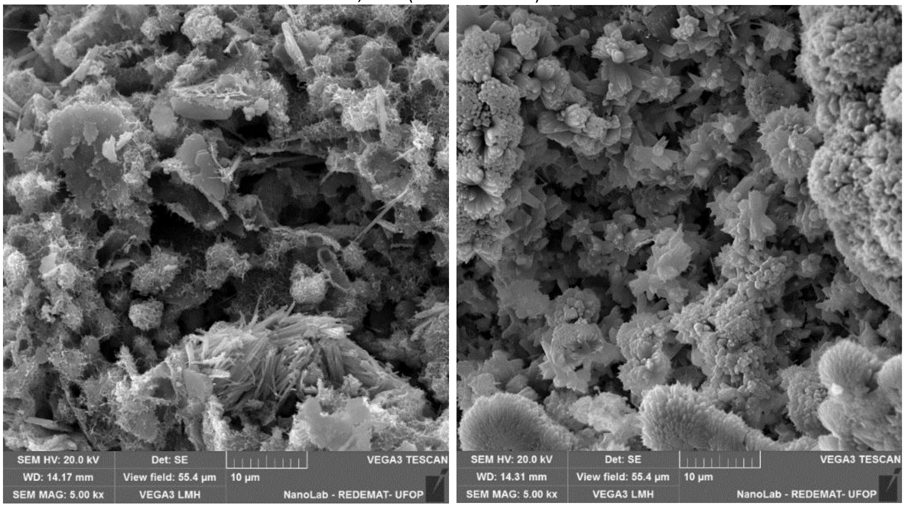
The reduction of this property is not particularly positive when analysing the efficiency of these materials as thermal insulation for temperate climates. A lower specific heat in the construction materials leaves the building more exposed to the variation of the external temperature (Yunsheng & Chung, 2000a; Lamberts et al., 1997). On the other hand, in tropical regions, the reduced specific heat prevents overheating during the night (Lamberts et al., 1997) and is, thus, rather beneficial to the overall thermal performance of the building.

In this sense, the demand of higher or lower thermal insulation and heat capacity vary with the local climate and building conditions (e.g., size, shading, orientation, wind effect) (Lamberts et al., 1997). Therefore, it is advised that a thermal simulation should be performed for each case to investigate the simultaneous behaviour of the thermal conductivity and specific heat of the materials selected.

Morphological analysis

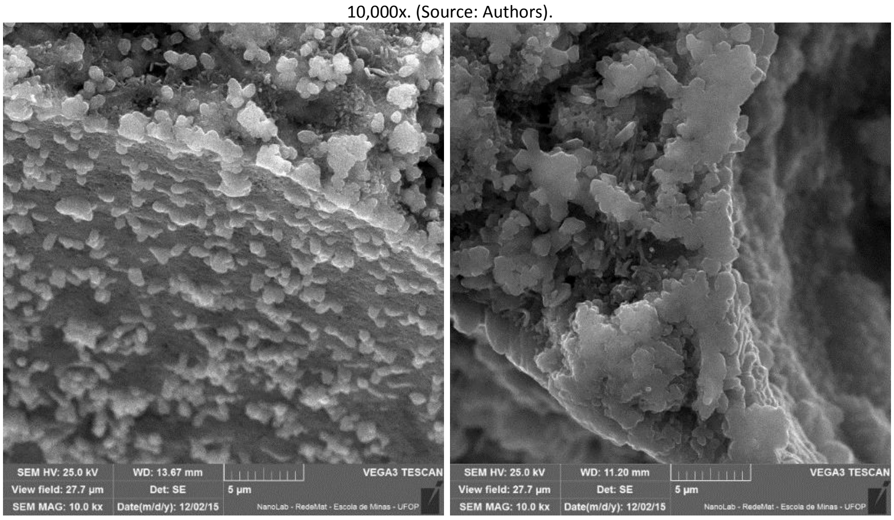
Figure 8 presents SEM images (magnification of 5,000x) of mortars 1:1:6 and 1:2:9 without AEA (0%). It is possible to observe a significant number of pores in the range from 1 µm – 20 µm, distributed throughout the matrix. The images qualitatively confirm the configuration proposed in the previous analyses: a more refined pore system for mortar 1:2:9.

Figure 8. SEM Images of the pore system in mortars without AEA (0%). On the left, 1:1:6; on the right, 1:2:9. Magnification of 5,000x. (Source: Authors).



Finally, a closer look in two macropores is taken in Figure 9 (magnification of 10,000x), in mortars 1:3 (without lime). According to the EDS analysis, associated to the study of element ratios proposed by Taylor & Newbury (1984), the hydration shell around the macropores mostly consists of hydrated calcium silicate (C-S-H), as also observed by Atahan et al. (2008) and Ley et al. (2009).

Figure 9. SEM Images of the microstructures of the pores in mortars. On the left, 0.05% AEA; on the right, 0.5%. Magnification of 10,000x. (Source: Authors).



The presence of capillary channels and micropores (or gel pores) in the vicinity of the air-entrained macropores is also noticeable in the images. The difference in the magnitude of their sizes is probably the reason why the capillary effect is prevented. Both the macropores and the micropores contribute to the reduction in the thermal coefficient and specific gravity (density) of the mortars, as previously discussed. The porosity of the hydration shell, evidenced by the number of hydration products inside the macropores, is probably responsible by greater ease of flow of the water vapour in the matrix, and thus the reduction of the specific heat (Figure 7). Regarding the AEA contents, 0.05% and 0.5%, no significant difference in the structure of the pores is observed.

Conclusions

The present work evaluated the effect of three concentrations of a biodegradable Air-Entraining Admixture (AEA) – 0%, 0.05%, and 0.5% - on the physical and thermal properties of two mortar mixtures: 1:1:6 and 1:2:9. The results showed that the macropores stabilized with AEA strongly influence the properties of the mortar. Similar characteristics were observed between the mortars with 0% and 0.05% AEA content, with a little improvement of the properties even for a content of 0.05% over the mass of cement. On the other hand, significantly different results were obtained for the 0.5% AEA content. Overall, tests showed that increasing the AEA content by up to 0.5% promotes:

- Improvement in workability and cohesion – a reduction of the water demand up to 25%;
- Increase in the air-entrained content up to 4.3 times;
- Reduction in the specific gravity up to 32%;
- Reduction on water absorption up to 15%;
- Reduction on water absorption coefficient due to capillary action up to 60%;
- Reduction on the mechanical strength of mortars 1:1:6 by up to 54% and increase of up to 17% for mortars 1:2:9.
- Reduction on thermal conductivity up to 41%; and
- Decrease in the specific heat up to 4%.
- A more refined pore system for mortars 1:2:9 due to the higher lime content.

In summary, the macropores promote lighter mortars with lower thermal conductivity, less water absorption in general and by capillarity. The reduction of the inlet of water, in turn, leads to a lower potential of occurrence of moist-related pathologies. These are significantly positive results since they impact not only on the wellbeing of the users but also on maintenance costs and renovation energy. Therefore, the introduction of a suitable amount of AEA-promoted macropores in mortars contributes to an improved built environment.

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