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Performance and Accelerated Ageing of an Industrial Hydraulic Lime Mortar Applied on Different Substrates

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Abstract: Mortar that is typically employed for interior or exterior coatings can be characterised using laboratory-prepared specimens according to specific test standards; however, its performance undergoes changes following application on substrates. When selecting mortar, it is vital to anticipate its in-service behaviour after its application on substrates to make the most informed choice. Most of the research work carried out to date analyses the characteristics of mortar in laboratory specimens. Some studies analyse these characteristics after its application to support, but very few exist that compare both behaviours. With this objective in mind, this research determined the properties of mortar when cured within laboratory moulds and assessed the behaviour of the same mortar after application on diverse substrate types. This study specifically evaluated the behaviour of a pre-dosed hydraulic lime mortar when applied on concrete blocks, lightweight concrete blocks, concrete slabs, hollow ceramic bricks, and solid ceramic bricks. Later, this behaviour was compared to the same type of mortar hardened in laboratory moulds and the same type of mortar applied on substrates and subjected to accelerated ageing. Moreover, data from previous experimental work were used to compare the behaviour of the pre-dosed hydraulic lime mortar with that of pre-dosed cement mortar when applied on similar substrates. The research drew upon a comprehensive characterisation of the physical and mechanical parameters of mortar, revealing that the performance of these types of mortar undergoes significant changes after application on substrates under in-service conditions, mainly when applied on more porous substrates. It was concluded that the application of mortar to substrates increased bulk density, decreased open porosity, enhanced compressive strength, and resulted in faster capillary absorption. For mortars subjected to accelerated ageing, a notable reduction in water vapour permeability was observed, which was attributed to changes in the pore profile.

Keywords: in-service performance; hydraulic lime mortar; substrate; accelerated ageing

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Citation: Travincas, R.; Silveira, D.; Bellei, P.; Gouveia, J.; Matias, G.; Torres, I.; Flores-Colen, I. Performance and Accelerated Ageing of an Industrial Hydraulic Lime Mortar Applied on Different Substrates. *Coatings* **2024**, *14*, 819. https://doi.org/10.3390/coatings14070819

Academic Editor: Ping Xiang

Received: 11 May 2024
Revised: 11 June 2024
Accepted: 26 June 2024
Published: 1 July 2024

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1. Introduction

Coating mortars in buildings play an essential role, as they provide the necessary protection to the substrates where they are applied, making them more aesthetically pleasing. In Portugal, in the Census carried out in 2021 [1], it was noted that around 36% of buildings needed medium to very high repairs on their outer walls. In addition, when the existing coating defects are severe, and there is no significant cultural value, it may be necessary

to proceed with partial or total replacement of the mortars. However, these interventions, which often use materials and construction processes that are very different from the original ones—such as cement mortars to replace lime mortars—do not always contribute to the conservation of this type of building and may even introduce a new pathology.

Thus, it is essential to have a sound knowledge of mortar behaviour to ensure compatibility between mortars' characteristics and their substrates. Incompatibility between a mortar and its substrate can result, for example, in mortar detachment, leaving the substrate unprotected and jeopardising the safety of the surrounding area of buildings. In addition, it should be noted that the higher the adhesion to the substrate, the better the durability and water and mechanical resistance of coatings tend to be.

Studies of mortar behaviour generally consider the characteristics of the mortars determined with controlled tests in the laboratory, using mortar specimens hardened in standardised moulds. However, the behaviour of these mortar specimens is not representative after application on the substrates since there is a set of factors that influence the characteristics of the applied mortars.

Applying a mortar on the substrate leads to the formation of an interface. As a result, several interactions occur after the mortar comes into contact with the substrate and is still in the plastic state. These interactions change over time due to hydration kinetics and substrate absorption [2,3]. The characteristics of the applied mortar are influenced by the characteristics of the substrate and by the interface that is formed between them [4].

It is essential to consider the phenomena that occur after mortars are applied on substrates to relate the characteristics of the mortars evaluated in standardised specimens to the characteristics of the applied mortars. With this knowledge, it is possible to contribute to formulating and choosing the most suitable mortar for each substrate, improving the quality and consequent durability of facade coatings in new or retrofitted buildings.

Some research has been conducted on the influence of different factors on the behaviour of coating mortars after application on substrates. For example, Zanelatto et al. [5] and Starinieri et al. [6] analysed the influence of the number and thickness of the applied mortar layers. Zanelatto et al. [5] studied the impact of mortar application techniques. Regarding the study of the influence of environmental conditions on mortar curing, the works by Faria and Martins [7] and Tongyuan et al. [8] can be highlighted. In these studies, the tests were carried out on laboratory specimens and not on the mortar hardened on the substrates. Only a few works have been developed until recently (e.g., [6,9–12]) related to the influence of substrate characteristics and preparation on the behaviour of applied mortars. These works cover few different types of mortars and substrates and generally focus only on one or two properties of mortars. This lack of knowledge is even more evident for lime mortars since studies have focused more on cement-based mortars.

The IF MORTAR research project was recently developed to address the lack of knowledge about the influence of substrates on the behaviour of applied mortars. In this project, which was preceded by a preliminary work by Torres et al. [13], the behaviour of conventional and pre-dosed mortars (cement, air-lime, and hydraulic lime mortars) characterised in standard laboratory moulds was compared with the behaviour of the same mortars after application on real substrates (concrete block, lightweight concrete block, concrete slab, stone slab, hollow ceramic brick, and solid ceramic brick) (e.g., [14–17]). With the work conducted under this project, it has been possible to contribute knowledge about the influence of substrates on the behaviour of applied mortars and, consequently, to optimise selection processes for the most suitable mortars for each type of substrate. In general terms, it was possible to conclude that ceramic and concrete substrates influence the properties of the mortar at different magnitudes.

The present study was developed within the framework of the IF MORTAR project and presents the findings related to pre-dosed mortars. Pre-dosed hydraulic lime mortar applications have increased significantly over the last few years due to the intense market competition and the advantages they present concerning conventional mortars (e.g., easy and controlled application). In addition, current construction requirements have led to

the development of new technologies in the production of novel products, with an even more significant growth trend in the production of industrial mortars expected in the coming years. These industrial mortars play an essential role, especially in rehabilitating old buildings, since they have properties compatible with existing traditional substrates.

The mortar selected for the present study was applied on a set of substrates representative of existing solutions in old buildings and new constructions. The characteristics of the mortar were evaluated in specimens hardened in laboratory moulds and specimens hardened and detached from the various substrates. Thus, assessing the substrates' influence on the mortar's characteristics was possible. A comparison was also made for the results obtained in the present study with the results of a previous study on a pre-dosed cementitious mortar applied on the same substrates, which was also conducted within the scope of the same research project and which has been previously published [16].

2. Materials and Methods

2.1. Mortar

A pre-dosed hydraulic lime mortar was chosen to develop the experimental campaign because it is compatible with various substrates, widely available on the market, and suitable for both new and old constructions. The selected mortar is "Reabilita Cal RB", manufactured by SECIL (Lisbon, Portugal), consisting of natural hydraulic lime, siliceous and calcareous aggregates, additions, and natural fibres, with pre-defined amounts of aggregate (<3.75 mm) and binder, requiring only water to be added. The manufacturer did not disclose the proportion of mortar constituents, additions, and natural fibres.

Considering the water quantity range indicated by the manufacturer (between 4 and 4.5 L per 25 kg) and the value obtained in the mortar spreading test, 4.5 L per 25 kg was added.

2.2. Substrates

The mortar was characterised in the laboratory on specimens executed following the applicable standards and was also applied on various types of substrates with different dimensions, as follows:

- Hollow ceramic brick (300 mm × 200 mm × 70 mm).
- Solid ceramic brick (215 mm × 110 mm × 55 mm).
- Concrete block (500 mm × 200 mm × 100 mm).
- Lightweight concrete block (500 mm × 200 mm × 100 mm).
- Concrete slab (300 mm × 200 mm × 40 mm).

2.3. Moulding and Curing of Samples

2.3.1. Samples of Mortar Hardened in Moulds

Tests were conducted on prismatic and circular specimens to determine different properties of the mortars in line with EN 1015-11 [18] and ISO 12572 [19] standards (Figure 1). These specimens were hardened in moulds made of non-absorbent material, which prevents the absorption of water constituents of the mortar, as indicated in the standards. Therefore, they are considered a "reference" throughout the experimental campaign.

After moulding, specimens were placed inside polyethylene bags (Figure 1), which were duly closed for five days to maintain the mortar's % relative humidity (RH). Then, the specimens were removed from the moulds and placed again under the same conditions for two days. After the first seven days, they remained in cure in a controlled environment (temperature of 20 ± 2 °C and 65 + 5% relative humidity) for up to 28 days. When the curing was finished, some prismatic specimens were cut into 15 mm thick pieces for geometric compatibility with those detached from the substrates.



(**a**) (**b**)

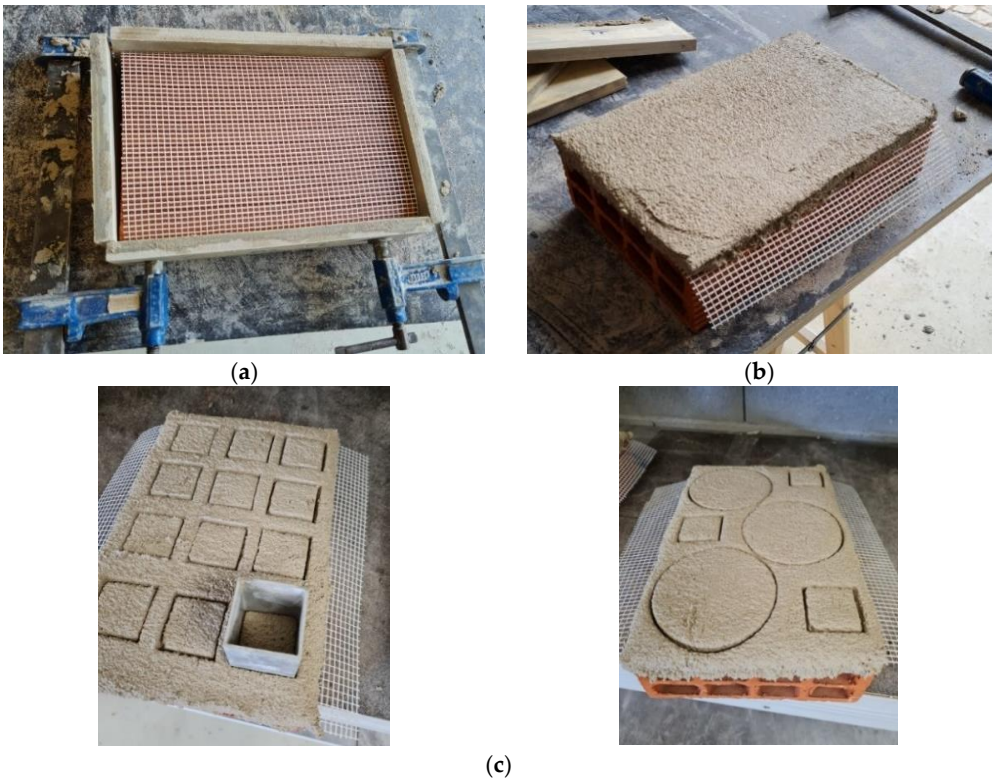
Figure 1. (**a**) Placing the prismatic samples (in metallic moulds) inside polyethylene bags; (**b**) executing circular samples.

2.3.2. Samples of Mortar Hardened on Substrates

The mortar was applied on the substrates with a thickness of 1.5 cm (manufacturer's recommendation) with the help of wooden moulds to guarantee thickness uniformity.

A fibreglass mesh was placed between the substrates and the layer of mortar to facilitate the subsequent mortar detachment process. This application technique has already been validated within the IF MORTAR project scope by comparing the results obtained in specimens with and without fibreglass mesh. The results obtained for mortars applied with and without mesh are similar [15]. The fibreglass mesh has a 5 mm × 5 mm opening and 158 g/m^3 density.

In Figure 2a, the preparation of the hollow ceramic brick substrate is shown. First, the mortar was applied manually on the substrate with a trowel (Figure 2b). Then, the specimens were marked for later detachment using square moulds measuring 40 mm × 40 mm and circular ones with 100 mm diameter (Figure 2c).



(**a**) (**b**)

(**c**)

Figure 2. (**a**) Wooden moulds and fibreglass mesh; (**b**) mortar applied on the substrate; and (**c**) square and circular specimens marked in fresh mortar.

Regarding the curing process, substrates with mortar applied remained sheltered for 28 days at an average ambient temperature of 16 °C and average relative humidity of 66%. After 28 days of curing, the samples were submitted to accelerated ageing (AA) according to standard EN 1015-21 [20].

After curing, the samples attached to the bases were removed and tested. The results from the prismatic samples, which were shaped in metal moulds and cut into 15 mm pieces, and the circular samples hardened in moulds, were compared to those from the samples removed from the bases.

Mortars applied to the substrates were submitted to tests in the fresh and hardened states. To characterise the substrates used in the experimental campaign, bulk density and open porosity, water absorption by capillarity, permeability to water vapour, and porosimetry via mercury intrusion tests were carried out. All tests were carried out considering the standards indicated in Table 1 with the necessary size adaptations of the samples. Table 2 presents the designation of all samples of mortars tested in this campaign.

Table 1. Tests conducted on mortars.

State	Test	Standard
Fresh state	Consistency test	EN 1015-3 [21]
Fresh state	Bulk density	EN 1015-6 [22]
Hardened state	Bulk density	EN 1936 [23]
Hardened state	Open porosity	EN 1936 [23]
Hardened state	Water absorption by capillarity	ISO 15148 [24]
Hardened state	Drying index	EN 16322 [25] and RILEM test No. II.5 [26]
Hardened state	Water vapour permeability	ISO 12572 [19]
Hardened state	Compressive strength	EN 1015-11 [18]
Hardened state	Mercury intrusion porosimetry test (MIP)	ISO 15901-1 [27]

Table 2. Substrate characterisation.

	Substrates	Bulk Density (kg/m^3)	Open Porosity (%)	Water Capillarity Absorption Coefficient ($kg/(m^2 \cdot s^{0.5})$)	Water Permeability Coefficient ($kg/(m \cdot s \cdot Pa)$)
Mean value	SCB	2059	18.3	0.10	0.454×10^{-11}
	HCB	2071	16.5	0.04	0.397×10^{-11}
	CB	2113	14.5	0.33	1.470×10^{-11}
	LCB	1319	16.8	0.31	1.560×10^{-11}
	CS	2224	11.5	0.02	0.329×10^{-11}
Coefficient of variation (%)	SCB	0.1	1.7	9.0	6.8
	HCB	0.6	8.9	12.0	3.2
	CB	1.0	7.2	1.0	7.2
	LCB	5.4	8.2	7.0	24.3
	CS	0.4	3.1	11.0	46.1

CS—substrate concrete slab; CB—concrete block; LCB—lightweight concrete block; SCB—solid ceramic brick; and HCB—hollow ceramic brick.

3. Results and Discussion

This section presents the results of the tests on substrates, mortars hardened in non-absorbent moulds, mortars hardened on substrates after 28 days in standard curing conditions, and mortars hardened on substrates submitted to accelerated ageing.

The abbreviations used to designate the different types of substrate and mortar are shown in the list of abbreviations at the end of the paper.

3.1. Characterisation of Substrates

Table 2 presents the results of substrate testing.

Figures 3 and 4 depict the variation in mercury intrusion volume as a function of the pore diameter obtained in the MIP test for each substrate. Table 3 indicates the total volume of intruded mercury and the average pore diameter.

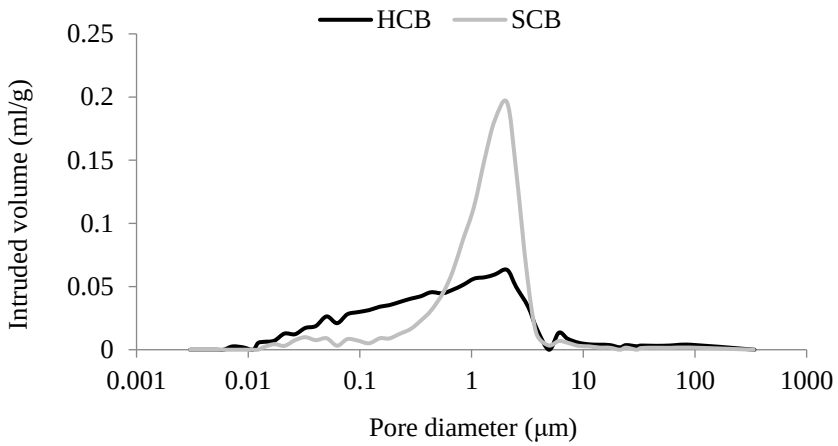


Figure 3. Variation in pore diameter of HCB and SCB substrates.

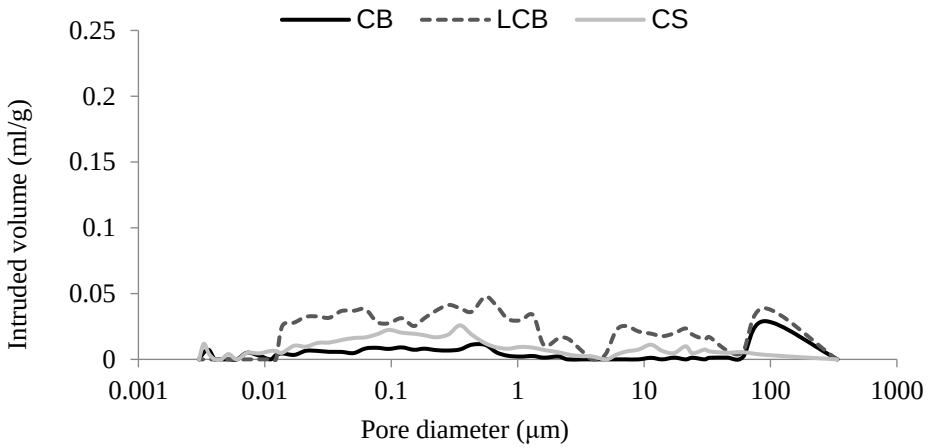


Figure 4. Variation in pore diameter of CB, LCB, and CS substrates.

Table 3. Total intruded volume and average pore diameter of the substrates.

Substrate	Total Intruded Volume (cm^3/g)	Average Pore Diameter (μm)	Open Porosity (%)
SCB	1.252	0.480	23.57
HCB	0.998	0.166	19.67
CB	0.207	0.076	7.86
LCB	1.046	0.120	19.85
CS	0.471	0.058	10.14

CS—substrate concrete slab; CB—concrete block; LCB—lightweight concrete block; SCB—solid ceramic brick; and HCB—hollow ceramic brick.

Ceramics (HCB and SCB) and concrete (CP and CB) substrates manifest characterisation values that generally exhibit congruence within the same order of magnitude. However, the lightweight concrete block (LCB) evinces notable deviations from established trends.

In particular, LCB distinguishes itself conspicuously by showing a bulk density approximately 60% lower than its conventional concrete counterparts. This pronounced reduction in density is a direct corollary of the deliberate integration of lightweight aggre-

gates into the LCB matrix. LCB exhibits an open porosity approximately 29% higher than that observed in the regular concrete substrates.

Nevertheless, it is imperative to acknowledge that these distinctive properties of LCB do not invariably correlate with capillary water absorption coefficients and water vapour permeability. These observed divergences can be attributed to the complex composition of LCB, which introduces distinctive characteristics that transcend conventional density-based considerations.

The pore distribution data, represented through mercury intrusion porosimetry (MIP), is graphically illustrated in Figures 3 and 4. Moreover, Table 3 presents a meticulous compilation of numerical MIP results for detailed analysis. Notably, CS emerges as the substrate with the lowest open porosity despite displaying a pore distribution closely resembling CB. Conversely, CB and LCB substrates display a greater abundance of pores exceeding 10 μm compared to their counterparts.

Significantly, LCB exhibits a distinct pore distribution in contrast to other substrates. HCB presents a higher frequency of smaller pores within ceramic substrates, whereas SCB exhibits a peak in pore sizes ranging from 1 μm to 10 μm. This divergence in pore distribution mirrors earlier findings, as reported by Kazmierczak et al. [9].

Upon meticulous scrutiny of the graphs, it becomes evident that LCB and SCB, characterised by a heightened count of pores within the 0.05–10 μm range and elevated open porosity values, concurrently yield higher capillary water absorption coefficients. LCB, despite its smaller average pore diameter, manifests the most significant pore volume exceeding 10 μm and displays the lowest resistance to water vapour permeability.

In ceramic substrates (HCB and SCB), their larger average pore diameter and open porosity collectively contribute to their diminished resistance to water vapour, particularly when juxtaposed with CS, which shows a higher pore count within this influential range. These findings collectively elucidate the intricate interplay between substrate composition, porosity, and various performance attributes in the context of our scientific investigation.

3.2. Characterisation of Mortars

3.2.1. Fresh State

The mortar consistency test obtained an average value of 160.4 mm. The average value obtained for the bulk density was 1661 kg/m^3.

3.2.2. Hardened State

Mercury Intrusion Porosimetry (MIP) Test

Figures 5 and 6 (pore distribution) present the mortars' MIP test results, and Table 4 indicates the total volume of intruded mercury, average pore diameter, and open porosity.

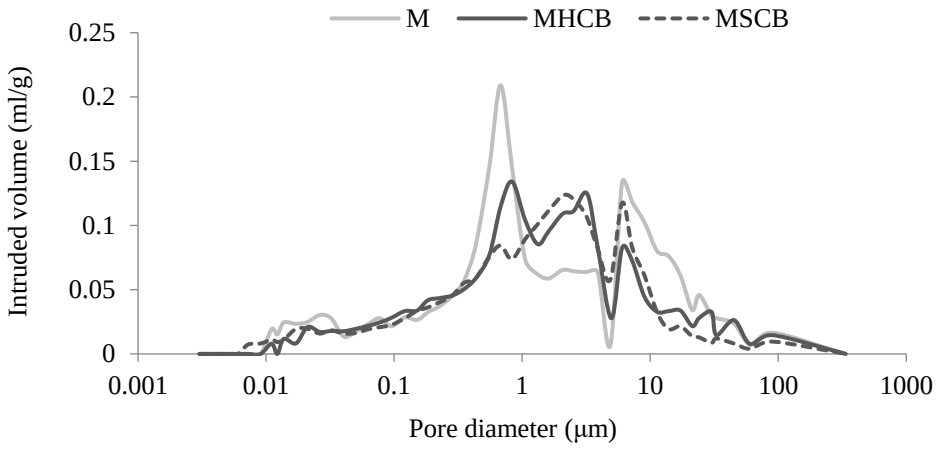


Figure 5. Variation in pore diameter after 28 days for M, MHCB, and MSCB.

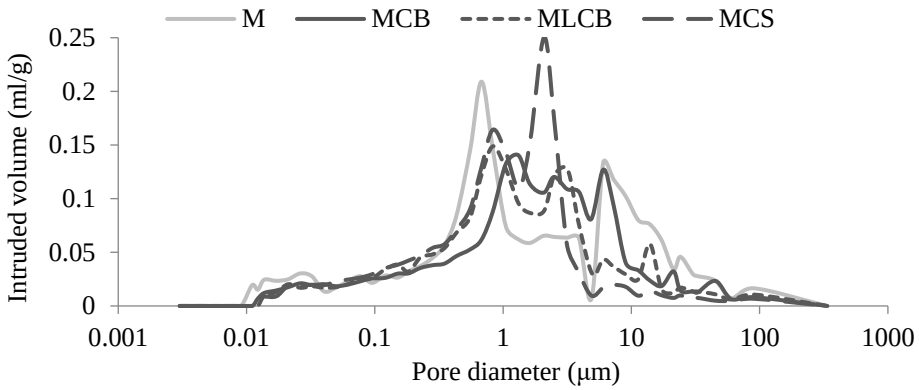


Figure 6. Variation in pore diameter after 28 days for M, MCB, MLCB, and MCS.

Table 4. Mortars total intruded volume and average pore diameter.

Mortar	Total Intruded Volume (cm^3/g)	Average Pore Diameter (μm)	Open Porosity (%)
MSCB	0.19	0.212	31.70
MHCB	0.20	0.291	32.50
MCB	0.19	0.286	31.90
MLCB	0.19	0.285	31.10
MCS	0.19	0.274	31.90
M	0.22	0.223	34.20

There is a reduction in pores in all ranges when comparing the mortar applied to the substrates with the mortar hardened in the normalised mould. This fact was also observed by Travincas et al. [16] in industrial cement mortar. There is also an increase in the average pore diameter in most cases (except for the mortar applied to SCB).

According to Rato [28] and Pipilikaki and Beazi-katsioti [29], the distribution of pores can be classified according to the influence on water transport, where the following is true:

- Pores Ø > 10 μm are, in general, air voids with no influence on water capillarity but may be interparticle voids, which may influence water vapour transport.
- Pores 0.05 < Ø < 10 μm are pores significantly affecting capillarity.
- Pores 0.01 < Ø < 0.05 μm are pores affecting water vapour permeability.
- Pores 0.025 < Ø < 0.01 μm are tiny pores that affect the shrinkage and character of hydrated cement matrices.

In the studied cases, most of the pores correspond to sizes between 0.05 and 10 μm, which means that there is a considerable impact of the pores that affect the capillarity of the mortar. It is also clear in Figures 5 and 6 that the mortar cured in a non-absorbent mould presents a higher number of pores with a diameter superior to 10 mm, which means that the increase in pores observed for the other mortars probably corresponds to pores that affect capillarity (<10 μm).

Bulk Density and Open Porosity

When considering the bulk density of mortar hardened on substrates, cured for 28 days, the bulk density of mortars detached from substrates is higher than that of mortar hardened in the mould, regardless of the substrate type. Figure 7 shows the results for bulk density and open porosity.

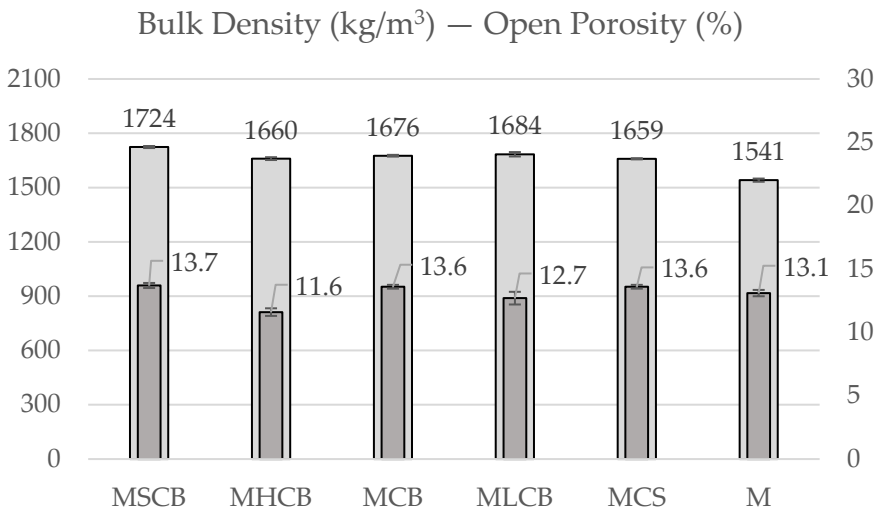


Figure 7. Bulk density and open porosity after 28 days for M, MCB, MLCB, MCS, MSCB, and MHCB.

This observation suggests that the detached mortars have lower open porosity than the mortar hardened in the mould. The higher bulk density indicates greater compactness of the mortar, implying lower porosity. The MIP test further confirmed the lower open porosity. The results showed an average reduction of 7% in the open porosity of the applied mortar compared to the mortar hardened in the metal mould.

When comparing the results obtained for the pre-dosed hydraulic lime mortar with the results obtained in the previous study with pre-dosed cement mortar [16], it was also verified that the density values of the cement mortar applied on the substrates are higher than those of hardened mortar in non-absorbent moulds.

There are, however, differences in the trend of alterations between substrates; for example, in the case of hydraulic lime mortar, the most expressive value of the bulk density concerns the mortar applied to the solid ceramic brick, while for the cement mortar, the highest corresponds to the mortar applied in hollow ceramic brick. It was also verified that the open porosity values of the cement mortar detached from the substrates were, in almost all cases, lower than those of the hardened mortar in the moulds, as expected. This reduction in the mortars' porosity might be due to the substrate capillarity water absorption in the interface, and the effects of this absorption were directly proportional to the average diameter of the pores and the number of existing pores in the range of influence of capillary absorption.

Despite the registered differences, the order of magnitude of the results obtained for each mortar type was similar for the bulk density and the open porosity. In the case of the density of the hydraulic lime mortar, the values obtained were within the range of 1541 kg/m^3 to 1724 kg/m^3, and for the cement mortar, the values ranged from 1365 kg/m^3 to 1574 kg/m^3. On the other hand, in the case of open porosity, the average reduction in values was 7% in the case of industrial hydraulic lime mortar and 27% in the case of industrial cement mortar.

The results obtained for open porosity determined according to EN 1936 [23] did not show a regular trend. There was also no correlation with the open porosity values obtained for the corresponding substrates.

Water Absorption by Capillary Action

According to Roos et al. [30], fibres and additives in the mortar's composition offer greater water absorption resistance, making the test specimens' saturation take longer. An example of this is the water absorption test by capillarity, which took place for 72 h, resulting in a non-stabilised curve, indicating that this time was not enough for the saturation of the specimens. Figure 8 shows the results for water absorption by capillary action.

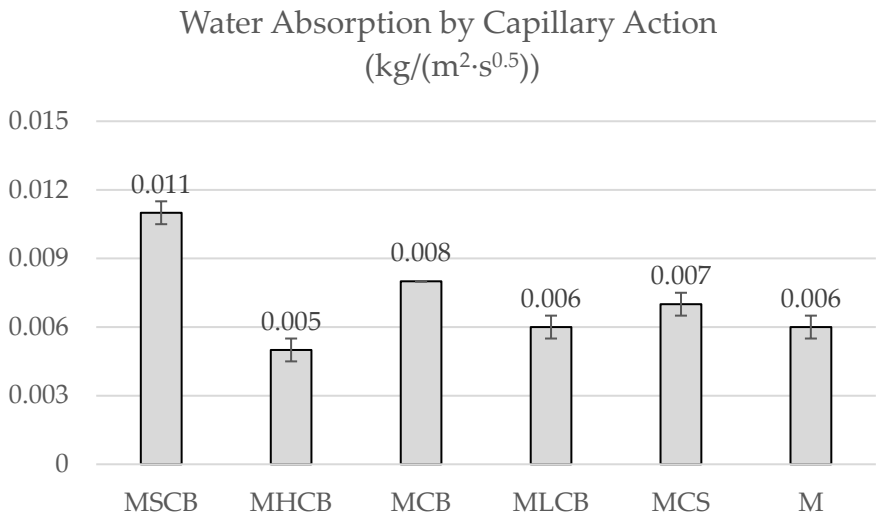


Figure 8. Water absorption by capillary action after 28 days for M, MCB, MLCB, MCS, MSCB, and MHCB.

The mortar applied to the substrates did not differ much from the mortar in the mould, except for that applied to the solid brick substrates. The justification may lie in the substrates that have different mean pore diameters. The solid brick had a much larger diameter than the others.

When the substrate has a considerable number of large pores, such as solid brick (0.480 μm), it does not have enough capillary strength to overcome the mortar pores (of smaller dimensions) and is therefore considered inoperative, and water absorption is carried out almost exclusively by the mortar. Such a conclusion was already obtained by Carasek [31]. In this sense, the capillarity effect is more substantial with the smaller pore dimensions of the mortar.

Arandigoyen et al. [32] already established a relation, opportunely mentioned, for the capillary pore radius as a function of the pressure difference, demonstrating that these two parameters are inversely proportional; that is, when the mortar pores are smaller, the capillary suction phenomenon is more significant, translating into a higher coefficient of water absorption by capillarity.

In this case, the mortar influenced by solid brick has an absorption capacity that is 92% higher than that of the mould, unlike the mortar influenced by hollow brick, which has a 14% reduction. It should also be mentioned that the application of pre-dosed hydraulic lime, due to the presence of adjuvants (in particular, water retainers) in its constitution, is more resistant, creating a kind of barrier to protect the substrate against the direct incidence of water on the plaster, which may have influenced the results achieved.

In our final analysis, it was still possible to notice a proportional trend between the open porosity and the capillary absorption coefficient, which was expected and is in line with studies already carried out by several authors, such as Torres et al. [13].

In a similar study carried out previously with a pre-dosed cement mortar [16], the values obtained for the coefficient of water absorption by capillarity were considerably higher and close to those obtained for substrates CB and LCB. The differences recorded between the two types of mortar may be associated, above all, with their composition (use of water repellents and/or fibres in the hydraulic lime mortar) since the average pore diameter of the two types of mortar applied to the different substrates has the same order of magnitude, varying between 0.16 and 0.29 μm.

Drying Index

The drying index reflects the process by which water evaporates from the porous material and this value varies depending on the resistance of the mortar itself to allow for this release. Thus, it is expected that when the open porosity of the mortar is lower, there

will be greater resistance to the release of water. This means that these two parameters are expected to vary inversely proportionally. Figure 9 shows the drying index results.

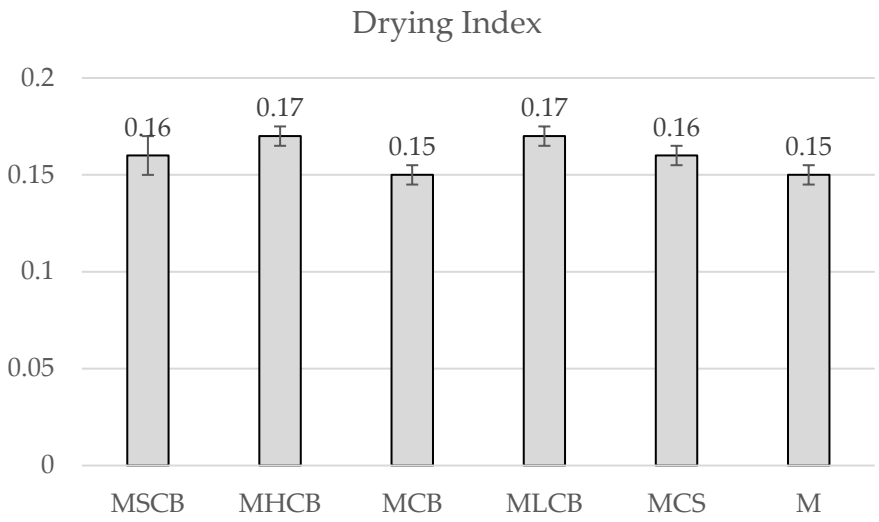


Figure 9. Drying index after 28 days for M, MCB, MLCB, MCS, MSCB, and MHCB.

The variation obtained for these two parameters is, to a certain extent, the expected for specimens influenced by the substrates. In the case of the mortar applied to the hollow brick, for example, a lower open porosity was obtained and, consequently, a higher resistance to drying. The opposite is true for the remaining substrates: higher porosity is reflected in lower resistance to drying. This happens because if the mortar applied on this substrate is resistant to water absorption, it also resists its release. The mortar applied to the remaining substrates has a drying rate similar to that obtained from the mould.

There are a few differences between mortars applied on real substrates and mortar hardened in the mould. This "atypical" behaviour may be related to the properties of the pre-dosed mortar mentioned above, with a high probability of containing water-repellent additives and air introducers, and due to the slight difference between the open porosities.

In this sense, and according to Pinto [33], it gives rise to a change in water evaporation, taking even longer to effect almost complete drying compared to conventional mortars. In this case, it took 22 days to find the minimum difference in the initial mass.

When compared with the results obtained in the previous study carried out with pre-dosed cementitious mortar, it was verified that the range of values obtained for the drying index was very similar: for the hydraulic lime mortar, values between 0.15 and 0.17 were obtained, and for cement mortar, drying indices between 0.12 and 0.16 were recorded. The slightly higher values for the hydraulic lime mortar could be related to the open porosity of the mortars, as previously mentioned. In the case of cement mortar, the open porosity was higher than that of hydraulic lime mortar, thus translating into a lower resistance to drying.

Water Vapour Permeability

Before any assessment, it should be noted that the circular specimens used in the water vapour permeability test were all challenging to detach during the experimental campaign due to their great adhesion to the substrate. This implied the use of specimens that, if not perfect, could influence the results presented. Figure 10 shows the results for water vapour permeability.

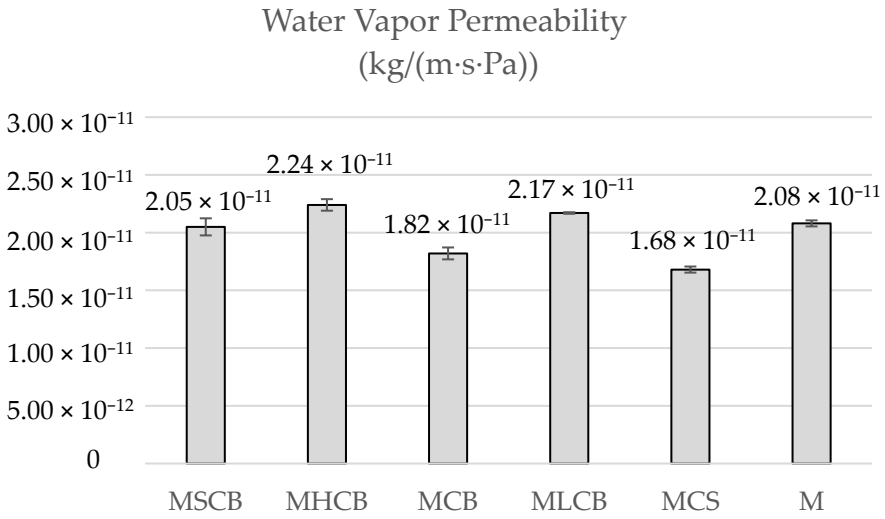


Figure 10. Water vapor permeability after 28 days for M, MCB, MLCB, MCS, MSCB, and MHCB.

According to Pereira (2008) [34], the mortar's water vapour permeability is directly related to water absorption by capillary action and, consequently, to open porosity. When the average size of the pores that make up the mortar is high, as is the case with the mortar applied to hollow bricks (0.29 µm), it is also natural that the vapour permeability increases according to this parameter.

According to Pinto [33], industrialised mortars significantly reduce vapour permeability compared to conventional mortars, making it difficult for substrates to breathe appropriately.

It is verified that all hydraulic lime mortars applied on substrates present values of permeability to water vapour higher than the values obtained for the substrates, which fulfils the principle proposed by Rodrigues [35], which states that the plaster must be more permeable to water vapour than the substrate on which it is applied. The same was observed in the previous study carried out with cement mortars, for which the permeability to water vapour was higher than that of the substrates. In the case of hydraulic lime mortar, the values ranged between 1.7×10^{-11} kg/(m·s·Pa) and 2.2×10^{-11} kg/(m·s·Pa), and in the case of cement mortar, they varied between 2.07×10^{-11} kg/(m·s·Pa) and 2.4×10^{-11} kg/(m·s·Pa).

In any case, the mortars applied to substrates of hollow brick and light concrete block continued to be those with greater prominence, presenting a higher vapour permeability of about 8% and 4%, respectively, in relation to the mortar prepared in a non-absorbent mould.

On the other hand, mortars applied to concrete block and concrete slab substrates presented vapour permeability values around 12% and 20% lower, respectively, than those of the mortars hardened in moulds.

Compressive Strength

Torres et al. [13] observed that compressive strength was inversely proportional to the open porosity presented by the mortar. This fact is easily explained since, by hypothesis, if the mortar is more porous and the number of pores is more significant for samples of equal volume, it will translate into a lower resistance when a given sample is compressed. Figure 11 shows the compressive strength results.

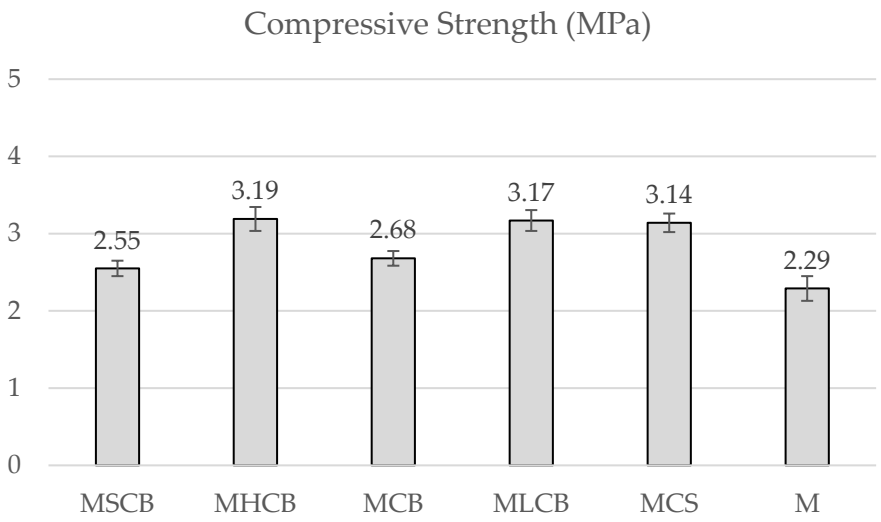


Figure 11. Compressive strength after 28 days for M, MCB, MLCB, MCS, MSCB, and MHCB.

Despite the increase in compressive strength, confirming the relationship between the two parameters (open porosity and compressive strength) is difficult. However, in all cases, the compressive strength of the mortars applied to the substrates is higher than that of the mortar hardened in the mould.

Thus, the compressive strength increases after application on real substrates, with particular emphasis placed on hollow brick, with an increase of approximately 40%.

A tendency like that in this study was verified by comparing compressive strength tests carried out with specimens of cement mortar applied on the same substrates. On the one hand, the resistance to compression of the mortar prepared in a metallic mould is considerably lower than the others, with a variation of 54% for the mortar applied on a substrate with lower resistance (in this case, the cement mortar applied on the solid concrete substrate). On the other hand, in this previous study, there was a trend toward an increase in compressive strength with a decrease in open porosity.

3.2.3. Accelerated Ageing

As mentioned, the mortars subjected to accelerated ageing were tested according to standard EN 1015-21 [20]. Figures 12 and 13 show the MIP test results, and Table 5 shows the total intruded volume and average pore diameter.

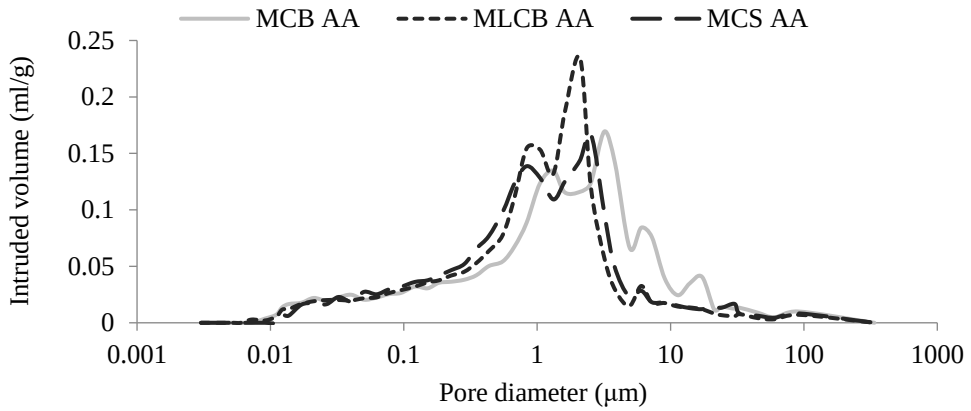


Figure 12. Variation in pore diameter after accelerated ageing for MCB AA, MLCB AA, and MCS AA.

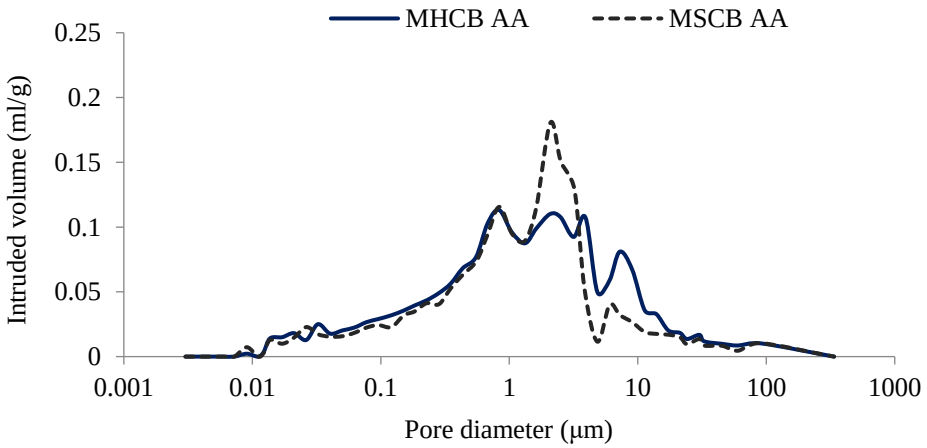


Figure 13. Variation in pore diameter after accelerated ageing for MHCB AA and MSCB AA.

Table 5. Mortars submitted to accelerated ageing—total intruded volume and average pore diameter.

Mortar	Total Intruded Volume (cm^3/g)	Average Pore Diameter (μm)	Open Porosity (%)
MSCB AA	0.17	0.255	30.28
MHCB AA	0.19	0.262	31.72
MCB AA	0.20	0.236	32.88
MLCB AA	0.19	0.226	31.65
MCS AA	0.19	0.262	31.53

For the variation in pore diameter, when compared with the mortar hardened at 28 days of curing, a reduction in the average pore diameter and a greater similarity between the mortar pore diameter x intruded volume curve can be seen.

Table 6 presents the results for bulk density, open porosity, water absorption by capillary action, drying index, water vapour permeability, and compressive strength of the mortars submitted to accelerated ageing.

Table 6. Mortar results at 28 days of curing and after accelerated ageing.

	Mortar	BD (kg/m^3)	OP (%)	WCA ($kg/(m^2 \cdot s^{0.5})$)	DI	WP ($kg/(m \cdot s \cdot Pa)$)	CS (MPa)
Mean	MSCB AA	1716	15.2	0.013	0.12	1.70×10^{-11}	2.54
	MHCB AA	1649	12.5	0.008	0.13	1.74×10^{-11}	3.08
	MCB AA	1649	15.0	0.015	0.13	1.76×10^{-11}	2.64
	MLCB AA	1663	13.7	0.011	0.14	1.78×10^{-11}	3.04
	MCS AA	1657	15.0	0.011	0.13	1.46×10^{-11}	3.08
CV (%)	MSCB AA	1.2%	2.7%	12.3%	9.7%	3.5%	8.4%
	MHCB AA	1.1%	3.5%	9.6%	9.2%	2.7%	8.0%
	MCB AA	1.1%	5.7%	5.8%	6.5%	8.4%	12.2%
	MLCB AA	1.2%	4.9%	6.7%	5.5%	4.3%	6.3%
	MCS AA	1.7%	2.0%	7.8%	6.8%	4.3%	5.7%

BD (bulk density); OP (open porosity); WCA (water capillary absorption coefficient); WP (water permeability); CS (compressive strength); AA (accelerated ageing); M (mean values); and SD (standard deviation); and CV (coefficient of variation).

A reduction of around 1% was observed in the bulk density of the mortar subjected to accelerated ageing. This may be related to the accelerated ageing test simulation of mortar degradation mechanisms.

The results of open porosity align with the expected outcomes. Consequently, the hardened mortar's open porosity in the accelerated ageing samples exhibited higher values than the others. Also, there was a reduction in compressive strength, confirming the results.

The water absorption coefficient of the mortars submitted to accelerated ageing denote faster drying. This fact is in line with the increase in open porosity.

When comparing the detached mortars, a reduction in water vapour permeability can be seen, compared to mortars subjected to accelerated ageing, despite the latter having greater open porosity. This fact is related to the distribution of pores (Table 7), where a reduction in the number of pores with influence on transport of vapour and an increase in pores in the range of absorption by capillarity can be observed.

Table 7. Mortar's intruded volume by pore size distribution.

Mortar	0.025–0.01 μm		0.01–0.05 μm		0.05–10 μm		>10 μm	
	28 Days	AA	28 Days	AA	28 Days	AA	28 Days	AA
MSCB	0.015	0.007	0.496	0.464	1.290	1.204	0.142	0.123
MHCB	0.000	0.002	0.502	0.529	1.269	1.250	0.245	0.178
MCB	0.000	0.004	0.445	0.503	1.373	1.401	0.186	0.112
MLCB	0.000	0.005	0.505	0.534	1.217	1.339	0.182	0.083
MCS	0.000	0.000	0.552	0.576	1.367	1.266	0.081	0.112

For 28 days—samples were submitted to 28 days of regular curing; AA—samples were submitted to accelerated ageing.

4. Conclusions

Coating mortars are usually characterised in the laboratory, using specimens made in standard, non-porous moulds and according to the applicable standards. However, mortars are applied on substrates, which potentially have properties different from those considered in the laboratory and which lead to different interactions between these elements.

The reason for this study was the uncertainty associated with the behaviour of mortars when applied to different types of substrates. It was intended to make the application of mortars compatible on different substrates, deepening the knowledge of the constraints of each application.

It was concluded that the mortar applied to substrates increased bulk density, decreased open porosity, increased compressive strength, and had faster capillary absorption. In the case of mortars subjected to accelerated ageing, the permeability to water vapour reduction due to the change in the pore profile stood out.

Concerning accelerated ageing, the following was observed:

- As the average pore diameter decreases, there is a slight reduction in the bulk density and an increase in the open porosity. These results are coherent with the compressive strength results, as the mortar suffers a decrease in compressive strength with the accelerated ageing process, and the results are also coherent with the water absorption by capillary action results, which increase accompanied by the increase in the drying index.
- A decrease in water vapour permeability can be seen in the detached mortars compared with mortars not subjected to accelerated ageing, despite the first ones with greater open porosity. This fact is related to the distribution of pores since there is a reduction in the number of pores with influence on the transport of water vapour and an increase in the pores in the range of absorption by capillarity.

When comparing the behaviour of the hydraulic lime mortar from this research with the cement mortar from a previous study, the following was observed:

- The bulk density of the mortar applied to the solid ceramic brick was the most expressive, while for the cement mortar, the highest value was obtained for the mortar applied in the hollow ceramic brick.
- For open porosity, the average reduction in values when the mortar was applied to the substrate was 7% in the case of the industrial hydraulic lime mortar and 27% in the case of the industrial cement mortar. This reduction might be related to the substrate capillarity water absorption in the interface, and the effects of this absorption are

directly proportional to the average diameter of the pores and the number of existing pores in the range of influence of capillary absorption.

- For the cement mortar, the values obtained for the coefficient of water absorption by capillarity were considerably higher and closer to those obtained for concrete block and lightweight concrete block substrates. In this case, the differences recorded between the two types of mortar may be associated, above all, with their composition (use of water repellents and/or fibres in the hydraulic lime mortar) since the average pore diameter of the two types of mortar applied to the different substrates are similar.
- For both mortars, it was observed that the values of water vapour permeability were higher than those obtained for the substrates and that the range of values obtained for the drying index was very similar.
- The tendency to increase compressive strength with the application on the substrates was identical for both mortars.

Despite the difficulty in analysing the influence of the constituents of the mortar used on its general performance, since it is a pre-dosed product for which the dosage and type of admixtures and fibres are not known, it is possible to conclude that there is some influence of the substrate on the final characteristics of the mortar. When comparing the results of the mortar moulded in metallic moulds with the mortars applied on the substrates, all properties generally underwent positive improvement. However, no significant differences indicated a better global compatibility with a specific substrate. All results obtained were very satisfactory. Through the conclusions obtained, it can be reported that the knowledge of the characteristics of the mortars and their behaviour after entry into service makes it possible to optimise the maintenance of the facade coating systems, reducing costs and using optimised resources.

Author Contributions: Conceptualisation, J.G., I.T. and I.F.-C.; Methodology, J.G., I.T. and I.F.-C.; Validation, I.T. and I.F.-C.; Formal Analysis, R.T., D.S., P.B., J.G. and G.M.; Investigation, R.T., D.S., P.B., J.G. and G.M.; Data Curation, R.T., D.S., P.B., J.G. and G.M.; Writing—Original Draft Preparation, R.T., D.S., P.B. and G.M.; Writing—Review and Editing, R.T., D.S., P.B., G.M., I.T. and I.F.-C.; Supervision, I.T. and I.F.-C.; Project Administration, I.T. and I.F.-C.; Funding Acquisition, I.T. and I.F.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FEDER through the POCI program (Programa Operacional Competitividade e Internacionalização) and FCT (Foundation for Science and Technology), grant number POCI-01-0145-FEDER-032223, PTDC/ECI-EGC/32223/2017. The authors are also grateful for the Foundation for Science and Technology's support through funding UIDB/04625/2020 from the research unit CERIS (DOI: 10.54499/UIDB/04625/2020). The funding from Foundation for Science and Technology, through grant number UI/BD/151151/2021, is also acknowledged.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, and further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank Itecons and the CERIS research unit from IST for all the support provided.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

SCB	solid ceramic brick.
HCB	hollow ceramic brick.
CB	concrete block.
LCB	lightweight concrete block.
CS	concrete slab.
M	"slices" of the prismatic specimen.
MSCB	mortar applied and detached from the solid ceramic brick substrate.

MHCB	mortar applied and detached from the hollow ceramic brick substrate.
MCB	mortar applied and detached from the concrete block substrate.
MLCB	mortar applied and detached from the lightweight concrete block substrate.
MCS	mortar applied and detached from the concrete slab substrate.
AA	mortar subjected to accelerated ageing.

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