

Assessment of the Compressive Strength of Lime Mortars with Admixtures Subjected to Two Curing Environments

Evaluación de la resistencia a compresión de morteros de cal adicionados sujetos a dos ambientes de curado

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ABSTRACT

This article presents the assessment of the compressive strength of three types of lime mortar, one without admixtures and the remaining two added with metakaolin and brick dust. The chemical composition of the lime and the pozzolans was evaluated using the X-ray fluorescence technique. The mortars were subjected to two curing conditions: a humidity and temperature-controlled chamber and an accelerated carbonation chamber. Then, they were tested at the ages of 7, 28, 60, and 90 days. The results showed that the samples cured in the carbonation chamber had higher compressive strength values than the ones cured in the humidity and temperature-controlled chamber because lime mortars increase their strength with the carbonation of the calcium hydroxide present in the lime. Likewise, when adding metakaolin to the lime mortars cured in the humidity and temperature-controlled chamber, the compressive strength values were close to those of the mortars with lime only, which were cured in the carbonation chamber. From the results of this research, it is worth noting that the use of pozzolans in lime mortars improves the short-term compressive strength, which is attractive for the rehabilitation of heritage buildings, given that, in short periods of time, it manages to match the strengths that lime mortars acquire over time.

Keywords: mortar, lime, metakaolin, brick dust, carbonation, compressive strength

RESUMEN

En este artículo se presenta la evaluación de la resistencia a compresión de tres tipos de morteros con cal, uno sin adición y los dos restantes adicionados con metacaolín y polvo de ladrillo. La composición química de la cal y las puzolanas se evaluó mediante la técnica de fluorescencia de rayos X. Los morteros fueron sometidos a dos condiciones de curado: una cámara de humedad y temperatura controladas y una cámara de carbonatación acelerada. Posteriormente fueron ensayados a las edades de 7, 28, 60 y 90 días. Los resultados mostraron que las muestras curadas en cámara de carbonatación presentaron resistencias a la compresión superiores a las de los especímenes curados en cámara de humedad y temperatura controladas, ya que los morteros de cal aumentan su resistencia con la carbonatación del hidróxido de calcio presente en la cal. De igual manera, al incorporar metacaolín a los morteros de cal curados en la cámara de humedad y temperatura controladas, los valores de resistencia a la compresión fueron cercanos a aquellos de los morteros con solo cal y curados en cámara de carbonatación. A partir de los resultados de esta investigación, se destaca que el uso de puzolanas en morteros de cal mejora la resistencia a la compresión a corto plazo, lo cual resulta atractivo para la rehabilitación de edificaciones patrimoniales, pues, en cortos periodos de tiempo, este logra igualar las resistencias que adquieren los morteros de cal a lo largo del tiempo.

Palabras clave: mortero, cal, metacaolín, polvo de ladrillo, carbonatación, resistencia a compresión

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Introduction

Lime mortars are materials that have been frequently used throughout history, and their use has expanded since ancient times (Luo *et al.*, 2020; Luque *et al.*, 2010; Zhang, *et al.*, 2020; Zhang *et al.*, 2018). Thus, most masonry buildings built before the 20th century contain mostly lime mortars (Delgado Rodrigues, 2020; Pozo-Antonio, 2015). However, with the introduction of Portland cement in 1824 and its benefits, such as rapid hardening and high mechanical strength, the usage of lime binders decreased Radonjic *et al.*, 2001, as cited in Luque *et al.*, 2010; Zhang *et al.*, 2018).

A great number of masonry buildings that have lime mortar as a bond of their masonry units have begun to show

deterioration after a good part of their service life. This is due to the incidence of different factors, such as the changes in the use of the structure (Mercado, 2007; Peñaranda,

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2011), partial demolition of the property (Peñaranda, 2011), foundation settlement (Maldonado *et al.*, 2011), the use of materials that are incompatible with the original ones (Lourenço *et al.*, 2014), or simply because of the effects of the passage of time (Maravelaki-Kalaitzaki *et al.*, 2005; Torney *et al.*, 2015).

This is how, during most of the 20th century, cement mortars were employed in the restoration of heritage buildings (Vejmelková *et al.*, 2012). Over time, different authors indicated that using cement mortars in heritage restorations resulted in some inconveniences for the structures, such as the crystallization of salts and the low flexibility of cement-based mortars (Pozo-Antonio, 2015; Vavričuk *et al.*, 2018; Zhang *et al.*, 2020). Therefore, in some historical buildings, it has been observed that the deterioration process accelerates after restoration interventions (Gleize *et al.*, 2009; Vejmeková *et al.*, 2012), due to the incompatibility between cement mortars and the original materials (Aalil *et al.*, 2019; Lanas and Álvarez, 2003).

Certainly, at the moment of rehabilitating a heritage building, the starting point for an adequate selection of the repair materials is analyzing the ones that already exist in the structure (Forster, 2010; Gleize *et al.*, 2009; Maravelaki-Kalaitzaki *et al.*, 2005; Morillas *et al.*, 2019; Torney *et al.*, 2015). Hence, it is important to consider that historic structures have constructive characteristics and materials that differ from modern ones (Lucolano *et al.*, 2013).

Moreover, the materials vary in their composition, which is why there are uncertainties related to the environmental conditions to which they are exposed (Ball *et al.*, 2011; Koutník *et al.*, 2020). Thus, restoration mortars must be selected from the study of the ancient materials and their decay, as well as from the environmental factors affecting the structure (Apostolopoulou *et al.*, 2018).

Lime mortars, in turn, have certain advantages, such as physical-chemical compatibility with older binders; higher plasticity, which allows them to accommodate to the deformations implied by masonry; and good water vapor permeability (de Nardi *et al.*, 2017; Lanas and Álvarez, 2003; Pozo-Antonio, 2015; Vavričuk *et al.*, 2018; Zhang *et al.*, 2018). On the other hand, there are some inconveniences when using lime binders, such as low strength, slow hardening, poor water resistance, high retraction, and low cohesion between the mortars and the masonry units (Vavričuk *et al.*, 2018; Zhang *et al.*, 2018). To mitigate these problems, admixtures rich in aluminum-silicates (Zhang *et al.*, 2020) such as metakaolin or brick dust are employed (Nežerka *et al.*, 2016).

Furthermore, the hardening process of lime mortars stems from the reaction between the CO₂ present in the atmosphere and the Ca(OH)₂ of the lime (Pavlík *et al.*, 2012; Zhang *et al.*, 2020), which transforms into CaCO₃ (Arizzi *et al.*, 2011; Ergenç *et al.*, 2018; Luque *et al.*, 2010). Thus, the carbonation ratio of these mortars is a decisive

factor that influences the strength and durability of these mixtures (Arizzi *et al.*, 2011; El-Turki *et al.*, 2009; Pavlík *et al.*, 2012). This is due to the fact that the reaction with the environment generates changes in the structure of the mortars (Arandigoyen and Álvarez, 2006; Cazalla, 2002; Ergenç *et al.*, 2018). Moreover, it seems that, during the process, there is an increase in the mass and volume of the hardened particles (Pavlík *et al.*, 2012). Likewise, it has been observed that said phenomenon starts from the outer zone to the inner zone of the binders (Arizzi *et al.*, 2011; Delgado Rodrigues, 2020).

Therefore, different works of research have been conducted at an international level to evaluate lime mortars. These studies have found that the development of strength is related to the quality of the lime (Lanas and Álvarez, 2003) since it influences the mechanical and hydraulic properties of the mixtures (Vejmelková *et al.*, 2012). It has been noted that the hardening ratios of these mortars are low, which is reflected on the evolution of their mechanical properties (Moropoulou *et al.*, 2005). This is due to the fact that the maximum strength that these binders achieve is linked to the presence of non-carbonated portlandite (Garijo *et al.*, 2020; Lanas and Álvarez, 2003). Additionally, the stiffness of the mortars increases during the hydration of the materials' hydraulic components. Due to the chemical reactions that take place, the curing conditions influence the mechanical strength (Pozo-Antonio, 2015). Likewise, as the lime/aggregate ratio decreases, so does the strength (Lanas and Álvarez, 2003), which is why mortars with higher lime contents show higher strength values. This is explained by the fact that, as they are more porous, the carbonation process occurs at a higher rate, and, therefore, the development of the mechanical properties improves (Lanas *et al.*, 2006).

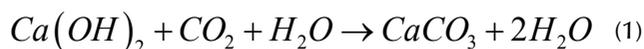
As mentioned before, using admixtures rich in aluminum-silicates can mitigate some problems encountered in lime mortars. Among these admixtures is metakaolin, a material that has several advantages when used in mortar mixtures, such as an increased mechanical strength, improved resistance to chemical attacks, increased durability, decreased retraction, and more (Cazalla, 2002; Siddique, 2008; Vavričuk *et al.*, 2018). Accordingly, in lime mortars added with metakaolin, mechanical and micro-structural properties compatible with those found on traditional materials have been observed (Vejmelková *et al.*, 2012). Thus, they are useful for masonry rehabilitations (Aggelakopoulou *et al.*, 2011). On the other hand, some studies have evidenced a decrease in the long-term strength of this type of mortar, which is attributed to the emergence of micro-cracks due to the mixtures' retraction (Aggelakopoulou *et al.*, 2011; Velosa *et al.*, 2009). It seems that this decrease deepens as the metakaolin content increases (Vavričuk *et al.*, 2018). Another relevant factor is the type of metakaolin, which can affect the properties of the mortar, as is the case of Velosa *et al.* (2009), who found that metakaolin rich in kaolinite and alumina can lead to mixtures with higher strength values.

Another material that has been used in lime mortar mixtures is brick dust, which can provide both economic and environmental benefits, considering that it has a high degradation resistance that hinders the conditioning of industrial waste (Matias *et al.*, 2008). Additionally, crushed brick particles have been identified in some historic mortars. Even the roman architect Vitruvius, in his work *The Ten Books on Architecture*, recommended adding a portion of crushed bricks to the mortar mixtures, with the objective of increasing their durability and strength (Nežerka *et al.*, 2016). Authors like Navrátilová Rovnaníková (2016), Matias *et al.* (2008), Nežerka *et al.* (2016), and Aalil *et al.* (2019) observed that adding brick dust to mortar mixtures improved their mechanical properties, which can be attributed to the reduction of retraction-related cracks, due to the presence of the brick grains (Nežerka *et al.*, 2016). Therefore, this type of binder may be acceptable for repair mortars (Matias *et al.*, 2008).

Considering the information provided above, the aim of this research was to evaluate the strength of mortars subjected to an accelerated carbonation process, in order to simulate the conditions of heritage building mortars. Furthermore, it was sought to evaluate the effect of admixtures such as metakaolin and brick dust, with the objective of obtaining the same properties of carbonated mixtures, therefore highlighting them as a rehabilitation alternative for lime mortar masonry in heritage buildings. This is important, as it opens the possibility of reinforcing existing structures by using materials with properties similar to those that are currently part of the structure.

Carbonation in lime mortars

The carbonation process of the mortars influences their hardening ratio, durability, and mechanical strength (Pavlík *et al.*, 2012) because the captured CO₂ fixes into a matrix to form calcites, thus improving its properties (Luo *et al.*, 2020). In general, five stages occur during this phenomenon (Arandigoyen and Álvarez, 2006; Papadakis *et al.*, 1991, as cited in Cazalla, 2002; Kang *et al.*, 2020; Pavlík *et al.*, 2012): diffusion of the CO₂ in the mixture, condensation of the water in the pores, dissolution of the Ca(OH)₂, dissolution of the CO₂ in the pore solution, and the precipitation of CaCO₃. To summarize, carbonation is represented as the transformation of Ca(OH)₂ into CaCO₃ due to the presence of CO₂. Equation (1) describes the entire process:



Reactions that occur between metakaolin and lime

Since metakaolin is a product based on silica and alumina, a reaction between the components of the pozzolan and the Ca(OH)₂ of the lime is produced when mixing it with lime and water. In this way, calcium silicate hydrate (CSH) and crystalline products that include calcium aluminate hydrate (CAH), and aluminum silicate hydrates are produced

(Gameiroa *et al.*, 2014 as cited in Khatib *et al.*, 2018; Siddique, 2008; Tebbal and Abidine Rahmouni, 2019).

Reactions that occur between brick dust and lime

The reactivity of the pozzolan can be affected by different factors: the quantity of silica and alumina, the firing temperature of the ceramic materials, the quantity and type of the clay that constitutes the ceramic pieces, the granulometry of the admixture, and the fineness of the crushed material. Therefore, when mixing the Ca(OH)₂ of the lime with water and the silico-aluminous components of the ceramic pieces, a reaction occurs which produces calcium silicates and calcium aluminates. However, some studies indicate that the pozzolanic reaction depends on the reaction of silica and alumina with the CaO of the lime (Matias *et al.*, 2014). This is analogous to the chemical phenomenon that occurs between metakaolin and lime when being hydrated with water. Moreover, the amorphous phase of the material has a large impact on its pozzolanicity.

Given the importance of preserving heritage buildings and using materials for their rehabilitation which are compatible with the existing ones, a project was developed to evaluate the evolution of the compressive strength of lime mortars subjected to two curing environments: a humidity and temperature chamber and an accelerated carbonation chamber. The mechanical behavior of lime mortar mixtures added with metakaolin (MK) and brick dust (BD) was assessed as well, with the objective of finding a short-term strength similar to that of the lime mortars in heritage buildings, which also increases due to the presence of CO₂ in the atmosphere.

Materials and experimental methodology

For this study, lime (hydraulic) and pit sand (yellow or washed) with a bulk density of 2,68 g/cm³ and an absorption of 2,1% were acquired, which are representative of the typical Colombian heritage buildings. The metakaolin used as admixture was supplied by the Colombian company Insumos Industriales Corona, while the brick dust (maximum particle size of 300 μm) was obtained from non-structural hollow clay bricks (33 cm x 11,5 cm x 23 cm, 'No. 5' in the Colombian market) that were residues from other tests. These were initially fragmented with a crusher (Figures 1 and 2), and then pulverized in a Los Angeles abrasion machine. The obtained dust was sieved through a 300 μm sieve. The chemical composition of the materials was determined with a MagixPro PW-2440 (WDXRF) X-ray fluorescence spectrometer. Additionally, granulometric analyses of the sand and the brick dust were performed.

Physical and chemical properties of the materials

Table 1 shows the chemical composition of the lime, metakaolin (MK), and brick dust (BD) employed in this research.



Figure 1. Crushing process
Source: Authors



Figure 2. Crushed brick dust
Source: Authors

It can be observed that the lime has a high content of CaO, which is expected to transform into Ca(OH)₂ when hydrated. This, in turn, will precipitate as CaCO₃ during the carbonation process. Likewise, it can be appreciated that the material contains SiO₂ and Al₂O₃, compounds that intervene in the formation of CSH and CAH when the lime is hydrated.

Regarding the metakaolin, it is mainly composed of SiO₂ and Al₂O₃, making up 96,18% of its composition. Thus, when incorporating the admixture to lime and water, the components of the pozzolan intervene in the formation of CSH, CAH, and hydrated aluminum-silicates. The chemical composition of the metakaolin is similar to the one registered by authors such as Aggelakopoulou *et al.* (2011), Velosa *et al.* (2009), Vavričuk *et al.* (2018), and Vejmelková *et al.* (2012).

Table 1. Chemical composition of the materials. XRF-148-16, XRF-024-17, and XRF-228-17 reports from the X-ray fluorescence laboratory of Universidad Nacional de Colombia, Bogotá.

Lime		MK		BD	
Component	%	Component	%	Component	%
CaO	86,83	SiO ₂	58,04	SiO ₂	67,27
SiO ₂	6,67	Al ₂ O ₃	38,14	Al ₂ O ₃	23,13
Al ₂ O ₃	2,36	Fe ₂ O ₃	1,36	Fe ₂ O ₃	5,56
Fe ₂ O ₃	1,88	TiO ₂	1,23	K ₂ O	1,59
MgO	0,88	K ₂ O	0,59	TiO ₂	1,08
SO ₃	0,60	MgO	0,20	MgO	0,43
K ₂ O	0,24	CaO	0,14	Na ₂ O	0,35
TiO ₂	0,22	Na ₂ O	0,07	CaO	0,17
P ₂ O ₅	0,16	SO ₃	0,05	Ba	0,14
SrO	0,09	Ba	0,05	P ₂ O ₅	0,08
MnO	0,06	P ₂ O ₅	0,04	SO ₃	0,06
ZnO	0,03	Zr	0,04	V	0,03
				Zr	0,03
				Cr	0,02
				Zn	0,02
				Sr	0,02
				Cl	0,01
				MnO	0,01

Source: Authors

Regarding brick dust, it can be observed that it is largely composed of SiO₂ and Al₂O₃, which make up 90,40% of its composition. This agrees with the results reported by Böke *et al.* (2006) and Aail *et al.* (2019), who determined a high content of SiO₂ in brick composition. Moreover, Matias *et al.* (2014) indicated that the pozzolanic reaction depends mainly on the presence of SiO₂ and Al₂O₃, and that, when these compounds are mixed with water and lime, they may intervene in the formation of calcium silicates and calcium aluminates.

Figure 3 shows the granulometric curve of the sand. It can be observed that it has a high content of material passing through the No. 100 sieve (34%) and 20% of material passing through the No. 200 sieve.

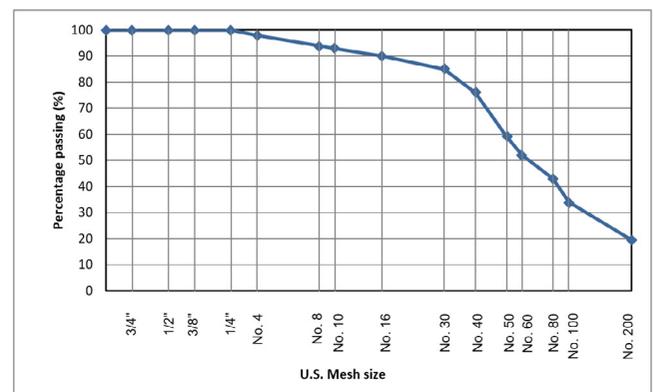


Figure 3. Granulometric curve of the sand

Source: Authors

Figure 4 presents the granulometric curve of the brick dust, which has approximately 42% of material passing through the No. 100 sieve and 12% passing through the No. 200 sieve.

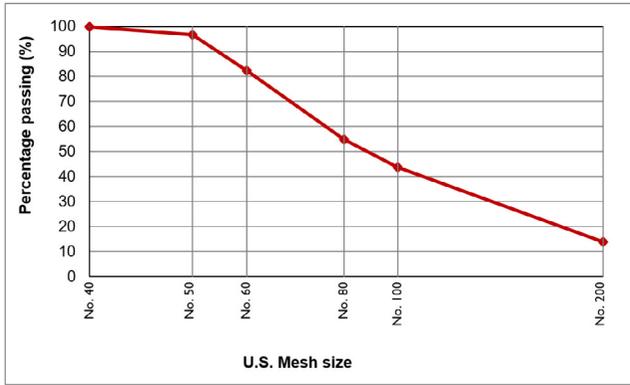


Figure 4. Granulometric curve of the brick dust
Source: Authors

Table 2 shows the weight proportions used in the elaboration of the mortars. These are typical dosages used in heritage buildings.

Table 2. Mortar weight proportions

Mortar	Denomination	Proportion
Lime : Sand	MLS	1:3
Lime : Sand : Metakaolin	MMK	1:3:0,2
Lime : Sand : Brick Dust	MBD	1:3:1

Source: Authors

Table 3 presents the amount of materials per cubic meter of each mortar mixture. Additionally, to determine the amount of water required, a fluidity close to 100% was sought. To that effect, fluidity tests were performed following the guidelines of the NTC 5784 (ICONTEC, 2017) standard, since no other regulation exists at a national level which applies to the type of mortars employed in this study.

Table 3. Dosages of the mortars per cubic meter

Mortar	Lime (kg)	Sand (kg)	MK (kg)	BD (kg)	Water (kg)	Fluidity (%)
MLS	450	1 350	-	-	405	101
MMK	430	1 290	86	-	452	97
MBD	360	1 080	-	360	454	100

Source: Authors

Figure 5 shows the fluidity test that guaranteed a proper workability of the mortars under study.

The compressive strength test specimens were mortar cubes with a 50 mm length, as shown in Figure 6. For their elaboration, the procedure described in the NTC 220 (ICONTEC, 2021) was used as reference. To that end, the materials were mixed, and the mixtures were placed on cubical molds. These were left for three days in a humidity and temperature chamber under the following controlled conditions: a temperature of 25 ± 2 °C and a relative humidity of $55 \pm 5\%$. Afterwards, the samples were taken out of the molds and then cured. In total, 72 cubes were elaborated.



Figure 5. Mortar fluidity test
Source: Authors



Figure 6. Elaboration of the mortar cubes
Source: Authors

As mentioned before, two curing environments were evaluated: the first one consisted of a chamber with the humidity set at $55 \pm 5\%$ and a temperature of 25 ± 2 °C (Figure 7); the second one was an accelerated carbonation chamber (Figure 8) with the following controlled parameters: a temperature of 23 °C, a relative humidity of 65%, and a CO₂ concentration of 5%. This process was conducted to accelerate the aging process of the mixtures, with the objective of simulating the mortar of heritage buildings when exposed to the CO₂ of the environment.



Figure 7. Curing environments
Source: Authors

The compressive strength tests were performed in a Shimadzu Universal Testing Machine with a load capacity of 1 000 kN. Three cubes were tested at each of the following ages: 7, 28, 60, and 90 days.



Figure 8. Curing environments
Source: Authors

Results and discussion

Compressive strength

Figure 9 shows the compressive strength results of the samples, which are identified as follows: MLS (sample with lime/sand), MMK (sample with metakaolin), and MBD (sample with brick dust). Moreover, the samples cured in the humidity chamber were identified as (NC), while (C) was for the samples cured in the accelerated carbonation chamber. There are records at ages 7, 28, 60, and 90 days, with three specimens from each age.

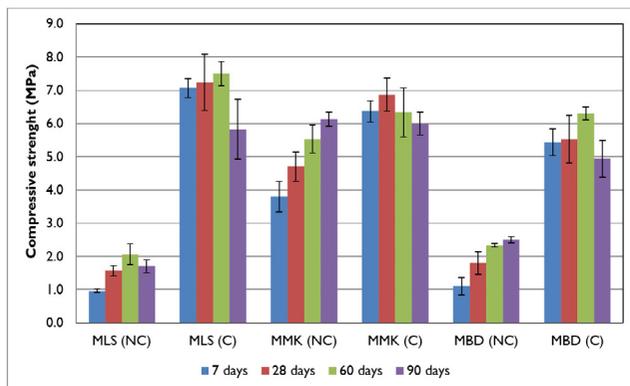


Figure 9. Evolution of the compressive strength of mortars cured in humidity chamber and accelerated carbonation chamber
Source: Authors

When assessing the results, a considerable increase in strength can be observed for the MLS (C) mixture with respect to the MLS (NC) mortar. At 7, 28, 60, and 90 days, said increase was of 631, 362, 263, and 243%, respectively. This phenomenon confirms the low hardening ratio of this type of mortar, which is favored by the CO₂ surrounding it over time, just as stated by Moropoulou *et al.* (2005). Likewise, in the carbonated cubes, a 22% decrease in strength was observed between days 60 and 90. In this regard, authors such as Velosa *et al.* (2009) and Aggelakopoulou (2011) attribute this decrease to the formation of micro-cracks caused by the retraction of the mortar. In the non-carbonated specimens, the decrease in strength was of 18%, which may be due to the presence of non-carbonated portlandite, as evidenced by Lanás and Álvarez (2003).

By comparing the strength values of the MMK (C) mortar samples with those of the MMK (NC) mixtures, the former reported values 68, 46, and 14% higher than the latter at the ages of 7, 28, and 60 days. However, at 90 days, their strength was 2% lower. Similarly, the strength of the carbonated samples showed a 13% decrease with respect to the maximum reached value, which is a phenomenon that was also observed by Velosa *et al.* (2009) and Aggelakopoulou (2011) in their research, due to the formation of micro-cracks as a result of retraction. On the other hand, the strength values of the MMK (NC) mortars were between 168 and 293% higher than those obtained in the samples made of MLS (NC) mortar. Also, the strength values of the MMK (C) mixture were between 5 and 16% lower than the ones of the MLS (C) mortar during the initial 60 days. At 90 days, that value was 3% higher.

As for the MBD (C) mortars, their strengths were 394, 207, 170, and 97% higher at the ages of 7, 28, 60, and 90 days, respectively, in comparison with those of the MBD (NC) mixtures. Regarding the carbonated samples, a 22% decrease in strength was observed, similar to the one observed for the MLS (C) mortar. Furthermore, the strength values of the MMK (NC) specimens were between 14 and 47% higher than those of the MLS (NC) mixture. The strength values of the MBD (C) mixtures were between 16 and 24% lower than those of the MLS (C) mortar.

With respect to the evolution of the compressive strength of the mortars, it was evidenced that the MMK (C) and MBD (C) mixtures presented strength values similar to those obtained for the MLS (C) mortar. This can be attributed to the accelerated aging process achieved in the carbonation chamber, since the components of the admixtures could react faster with the Ca(OH)₂ of the lime, thus forming other compounds like calcium silicates and calcium aluminates, which indicates that a lower amount of CaCO₃ may have precipitated in the added mixtures. In the case of the mixtures cured in the humidity chamber, the admixtures improved the compressive strength.

Carbonation depth

To study the carbonation process of the different samples, cylinders with a 10 cm diameter and 20 cm height were made using the same dosages as the mortars. These were taken to the carbonation chamber with the temperature set at 23 °C, a relative humidity of 65%, and a carbon dioxide concentration of 5%. Initially, the probes were left inside the chamber for a 5-day period. After that, a slice with a thickness of approximately 5 cm was taken from the samples. After that, phenolphthalein was applied to the sliced surface, and the depth of the carbonation front was measured. Afterwards, epoxy was applied to the affected surface of the cylinders, and then they were taken back to the chamber. The lime and sand samples, as well as those added with brick dust, were in the chamber for a 2-day period, and the specimens added with metakaolin were carbonated for 1 day more, since the initial carbonation was

higher on these samples. Once the samples reached those ages, the procedure was repeated to record the carbonation depth. Figure 10 shows the advancement of the carbonation front of the mortars under study.

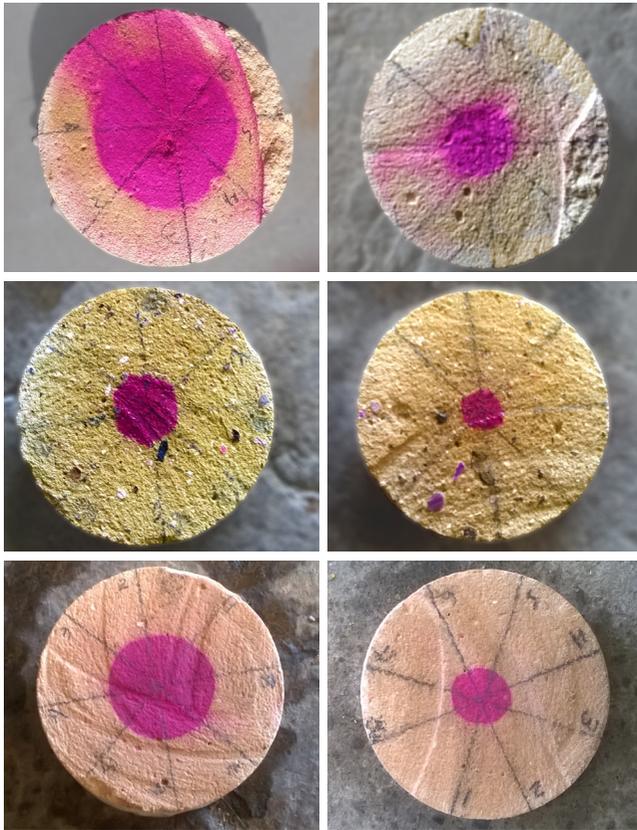


Figure 10. Advancement of the carbonation front
Source: Authors

The rapid penetration of CO_2 into the specimens is evident, and it accelerates the compressive strength gain. It can be observed that, at 7 days, values close to the compressive strengths at 90 days were already being obtained in the samples subjected to the carbonation process. Nevertheless, Garijo *et al.* (2020) indicate that the results of this method must be treated carefully because the reaction tends to advance along the cracks and voids beyond the front.

Conclusions

In general, the compressive strength values determined for the mortars added with metakaolin and cured in the humidity and temperature chamber tripled those registered for the lime and sand mixtures cured under the same conditions. They also matched the strength of the lime and sand mortars that were subjected to the accelerated carbonation chamber. This demonstrates the benefit of using metakaolin as an admixture in lime mortar mixtures for repairing or reinforcing heritage buildings since, in a very short period of time, it would match the properties of the mortars present in these structures, which have been subjected a carbonation process, thus improving their properties over time.

It was observed that the carbonated samples had similar strength values, which is explained by the fact that the carbonation process seeks to emulate the material properties through the passage of time, and it is known that strength increases with time. However, regarding the non-carbonated samples, the high variation between the metakaolin mixtures and the others was attributed to the early high pozzolanic activity of this material, which increases the strength of the mixture in short periods. This also implies that the carbonation process had less impact on the metakaolin samples, as most of its strength was gained due to its pozzolanic properties, and not by the simulation of the passage of time.

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