heritage

MDPI

Article

Physical and Mechanical Characterization of Lime Pastes and Mortars for Use in Restoration

Elena G. Navarro-Mendoza [1,2,*], Elia M. Alonso-Guzman [1,2,*], Adria Sanchez-Calvillo [1], Juan A. Bedolla-Arroyo [1], Habid Becerra-Santacruz [1], Antonia Navarro-Ezquerra [3], Belén Gonzalez-Sanchez [3] and Wilfrido Martinez-Molina [2]

[1] Faculty of Architecture, Universidad Michoacana de San Nicolas de Hidalgo, Morelia 58040, Mexico
[2] Faculty of Civil Engineering, Universidad Michoacana de San Nicolas de Hidalgo, Morelia 58040, Mexico
[3] Barcelona School of Building Construction, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain
* Correspondence: elena.navarro@umich.mx (E.G.N.-M.); elia.alonso@umich.mx (E.M.A.-G.)

Abstract: Slaked lime is traditionally a suitable material for use in construction activities in historic and traditional buildings whose constitutive characteristics demand compatible and appropriate material solutions. Therefore, knowing the physical and mechanical characterization of lime pastes and mortars for use in restoration is considered an important step in the process of scientific development of a material that, in the Mexican case, has lacked scientific rigor in its production, use and commercialization. With this in mind, the present article aims to investigate the characteristics of lime pastes and mortars that have been used in the traditional way and the new limes that exist in the market, offering suitable options for restoration, for which an integrated methodology was used consisting of physical tests such as surface area, electrical resistivity, pulse velocity, colorimetry, and mechanical tests such as compressive strength, giving as a result that "traditional slaked" lime is more likely to deteriorate than powdered lime, which leads us to conclude that powdered hydrated lime has optimal characteristics for restoration activities.

Keywords: lime mortars; high-purity lime; restoration of monuments; cultural heritage conservation; materials characterization; traditional techniques

Citation: Navarro-Mendoza, E.G.; Alonso-Guzman, E.M.; Sanchez-Calvillo, A.; Bedolla-Arroyo, J.A.; Becerra-Santacruz, H.; Navarro-Ezquerra, A.; Gonzalez-Sanchez, B.; Martinez-Molina, W. Physical and Mechanical Characterization of Lime Pastes and Mortars for Use in Restoration. *Heritage* **2023**, *6*, 2582–2600. https://doi.org/10.3390/heritage6030136

Academic Editors: Andrea Macchia, Fernanda Prestileo and Alexandra Jeberien

Received: 31 January 2023
Revised: 24 February 2023
Accepted: 26 February 2023
Published: 28 February 2023

1. Introduction

Building materials such as lime, gypsum and clayey soils were traditionally used as binders and adhesives, but about two centuries ago, Portland cement began to displace them [1,2]. These binders, thanks to their physical and mechanical properties, contributed to the development of vernacular architecture and traditional techniques [3], taking part in different structural construction systems, mainly in the form of mortars, with lime acting as the essential binder [4]. Mortars used before the end of the 19th century are considered old, traditional, or historical mortars [5]; therefore, lime is currently considered a material basically used for restoration or rehabilitation [6].

Regarding the knowledge of the performance and possibilities of lime as a construction material, it is necessary to know its manufacturing process and traditional application techniques [7]. Furthermore, it is important to understand the durability properties and behavior of the material against inclemency, as well as its own characteristics [8]. The restoration of historic buildings is a complex process that requires much effort and a large workforce to repair and preserve the architectural elements [9]. In Mexico, restoration is one of the fields of study within the construction sector that has less scientific development oriented to the use and study of materials compatible with the existing ones, with lime being the main material to carry out this type of intervention [10].

The objective of this research is to characterize and analyze the properties of the different types of current lime products, comparing them with slaked lime and thus exploring some alternatives for restoration projects. This material is the one and only recommended by Mexican heritage institutions to carry out interventions due to its characteristics of adherence, workability, plasticity, and compatibility with the original materials found in the existing heritage. However, although these intervention criteria are strictly applied, there is still no scientific endorsement to demonstrate the suitability of this recommendation since historic mortars are very versatile and variable according to their application [1].

Slaked Lime and Its Traditional Use in the Architectural Heritage and Restoration Works in Mexico

Lime is a material that has been known since ancient times and has contributed to the architectural development of many civilizations. It has great qualities of durability and inalterability against climatic conditions [8], being the reason why different and distant cultures explored its use. Vitruvius was one of the first authors to write about the use of lime; in his treatise, he describes the selection process of the best limestone and the considerations to be taken during calcination and hydration until the paste is obtained and it can be used as a mortar [11]. Its use was widespread due to its easy production process since it was obtained from the calcination of carbonate rocks [12]. The lime production process has evolved a lot over time, thanks to the studies carried out by L. Vicat in the 19th century and the subsequent development of technology, which has allowed us to find different types of quality lime available today.

Lime production begins with the extraction of calcium carbonate in the quarries, crushing it to obtain a stone of homogeneous size, and transporting it to the kilns for calcination at 900 °C. In this process, the CO_2 contained in the stone is released into the atmosphere, transforming the resulting product into calcium oxide, also known as quicklime. Subsequently, the product obtained is hydrated to obtain calcium hydroxide or paid lime. In Mexico, restorers still prefer to work with quicklime by "slaking the lime by hand", that is, placing it in sinks with water until it becomes a paste (see Figure 1); while in the lime industry, the most common process is hydration by aspersion, turning it into powder, to later place it in paper sacks and start commercial distribution.

Figure 1. Traditional slaking process of lime in Michoacan, Mexico.

The development of modern technology has generated a variety of different types and products of lime available at present, which can be classified from their degree of purity to their chemical components. In Mexico, the Asociación de Fabricantes de Cal A.C. has catalogued a total of six different types of limes: chemical lime, construction lime, food-grade chemical lime, steel lime, agricultural lime, and dolomitic lime. Each one of them has unique characteristics that make them suitable for the different industries and processes where they are used.

Despite all this modern development, in the restoration field, these products are little or no utilized. Slaked lime has been used in rehabilitation and conservation mainly to elaborate mortars, which are used to restore, rebuild, and join existing pieces with new elements in such a way that they work together as a single element, ensuring the necessary characteristics to perform such an action [13]. In addition, these mortars and refurbishments are used as sacrificial protections to safeguard the structure from inclemency and erosion [14].

For the restoration of historical buildings, the materials selected play an important role in guaranteeing the feasibility and success of the intervention. In this sense, the choice of calcium carbonate is very important regarding its origin, chemical characteristics, and color. For example, when blue limestone is used, the resultant color of the lime tends to be white; nevertheless, in the case of Michoacan (Mexico), lime usually has a beige tone due to the natural color of the stones selected. We can see how in the Mexican context; the color parameter is a conditioning factor for the final choice of the materials employed in restoration works.

The aggressive environments and the modifications or alterations of the constructions are some of the factors that negatively affect this heritage. One of the biggest problems we face as professionals is the progressive degradation of the mortar joints of the structures [15]; therefore, it is necessary to know in depth the type of binder used so that it resists the weather and assures compatibility with the structures. This can be achieved with the study of the material from the mineralogical, chemical, mechanical and physical points of view. This is why given that lime is one of the materials most traditionally used in built heritage, it is of vital importance to understand it better for the correct conservation of the artistic and built heritage [16].

The process of restoring traditional buildings requires great work and effort for the in-depth repair of their architectural elements [9], so knowing the materials that can contribute to the realization of quality work executed in the shortest time is indispensable for any restorer. In this case, the calcium hydroxide powder currently on the market, which can be easily acquired and applied without a previous traditional "lime slaking" process, is likely to be compatible with the original materials with which traditional buildings are constructed [17]. Regarding the compatibility of materials, it is necessary that these new materials incorporated do not have a harmful effect on the original elements and that they guarantee their affinity [18]. The lack of maintenance and conservation techniques applied to heritage are factors that can produce severe deterioration [2], so the proper choice of mortars to be used can ensure the success of the intervention [19].

Lime pastes are used for minor finishes since, with the incorporation of water, they become a slurry that is used to repair discontinuities in the mortar layers [20]. This is why it is necessary to know its behavior since lime mortars have not only been used for the bonding of stone and masonry partitions but have also been traditionally used as finishes in both interior and exterior walls [1], protecting the structure from the aggressions of the environment.

2. Materials and Methods

2.1. Materials and Preparation of the Specimens

In Mexico, the lime industry is present in several companies. For this research, we looked for reliable products with quality certifications; according to the technical data sheets, the limes have properties (see Table 1). For this research, powdered limes were taken directly from the kraft paper sack, while the pastes were hydrated for 900 days until they were converted into a paste.

Table 1. Properties of the limes according to the manufacturers' data sheets.

Lime	pH	Calcium Hydroxide (%)	Silica (%)	Molecular Weight (g/mol)	Relative Density (kg/L)	Water Solubility (mg/L)
HP95	12.45	95–96	0.1–0.5	74.10	0.4–0.6	1650
HP90	12.45	90–94	0.1–2.0	74.10	0.6–0.7	1650
SL	12.45	75–85	0.1–2.0	74.10	0.5–0.7	1650
CL	12.45	80–95	0.1–2.0	56.10	0.7–1.3	1650
HCL	12.45	80–95	0.1–2.0	56.10	0.7–1.3	1650

The limes used for this research are: powdered, high-purity lime with a calcium hydroxide content of 95% (HP95), high-purity lime with a calcium hydroxide content of 90% (HP90) and construction lime (CL) with a calcium hydroxide content between 75% and 85%, the latter being the most widely used and known by builders. For the limes in paste, powdered construction lime was hydrated in a container until a paste (HCL) was obtained, while for slaked lime, calcium oxide was taken and placed in a container until a paste (SL) was obtained; both were left to macerate with a water mirror of more than one centimeter. Most of the limes studied came from a lime mill in the state of Michoacán, while HP95 came from the state of Puebla (Table 2).

Table 2. Lime samples used in this research.

ID	Description	Format	Origin Quarry
HP95	High-purity lime with 95% calcium hydroxide	Powder	Acajete, Puebla, Mexico
HP90	High-purity lime with 90% calcium hydroxide	Powder	Piedras de Lumbre, Michoacán, Mexico
SL	Traditional slaked lime matured for more than 900 days	Paste	Piedras de Lumbre, Michoacán, Mexico
HCL	Construction industry lime hydrated for more than 900 days	Paste	Piedras de Lumbre, Michoacán, Mexico
CL	Construction industry lime	Powder	Piedras de Lumbre, Michoacán, Mexico

Regarding the characterization of traditional, historical and archaeological mortars, we can find some methodologies and proposals in the literature [21–23], being interesting topics of study with several examples of heritage monuments [24]. In this research work, the methodology included different testing methods to obtain the physical and mechanical properties of the limes studied.

In this process, since there are no specific regulations for mortars in restoration, the water/lime ratio of the mortar mixtures was determined by studying the ideal consistency according to its use. For the three types of powdered lime studied, the volume ratio was 4:5:1.5, meaning 4 volumes of lime, 5 of sand and 1.5 of water were used. The sand used for the mortars was obtained from the Joyitas quarry near Morelia in Michoacan, Mexico. In Table 3, we can see the X-ray fluorescence (XRF) spectroscopy of the sands analyzed, while in Table 4, the parts per million (ppm) of the different elements are displayed.

Table 3. X-ray fluorescence of the Joyitas sand.

FRX (%)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LC	Total
	59.74	0.782	17.024	5.909	0.089	3.426	5.264	3.636	1.648	0.217	0.55	98.285

Table 4. Parts-per-million of the Joyitas sand.

ppm	Rb	Sr	Ba	Y	Zr	Nb	V	Cr	Co	Ni	Cu	Zn	Th	Pb
	50	591	567	31	177	56	96	76	75	64	148	107	<3	9

The total alkali silica (TAS diagram) for volcanic stones was: SiO_2 = 59.74% and $\Sigma = Na_2O + K_2O = 5.284$, which means that the volcanic sands surrounding Morelia are andesites. These aggregate materials have been characterized in the materials laboratory of the Universidad Michoacana de San Nicolas de Hidalgo (UMSNH) in previous research works under international standards [25–27], as can be seen in Table 5.

While the lime pastes contained a higher amount of water, there was no need to add more. The percentage of water contained in the lime pastes was obtained indirectly once the ideal consistency had been determined (see Table 6). To obtain the water content of the lime pastes, the specimens were weighed for days until the water completely evaporated, obtaining a constant weight of the sample (see Figure 2).

Table 5. Characterization and standards followed for the aggregate material.

Standard	2002 [25]	2008 [26]	2015 [27]
ASTM D75/D75M-19. Standard Practice for Sampling Aggregates, (kg) [28]	500	500	500
ASTM C128-22. Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate, (%) [29]	2.41	2.33	2.3
ASTM C29/C29M 17a. Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate, (Ton/m^3) [30]	1.305	1.14	1.23
ASTM C136/C136M19. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, (FM) [31]	3.58	3.03	2.19
ASTM C40/C40M-20. Standard Test Method for Organic Impurities in Fine Aggregates for Concrete, (Level) [32]	1	1	3
ASTM D2419-22. Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate, (%) [33]	96.98	98.19	97.5
ASTM C117-17. Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing, (%) [34]	3.01	5.3	1.98

Table 6. Water content of pastes.

Type	Lime Paste kg	Water Content
SL	10.89 *	31%
HCL	11.35	26%

* The lime paste had already been strained to remove the non-hydrated parts (lumps).

Figure 2. Fresh and dried state of the lime paste specimen.

To carry out the experimental campaign, specimens of 5 × 5 × 5 cm^3 were made, both of pastes and lime mortars. Since there are no specific regulations on the preparation of lime mortars in restoration, the standard for lime mortars NMX-C-061-ONNCCE-2015 [35] was used. In the regulation, it is indicated that the samples should be demolded 24 h after elaborating, but since the samples are made with lime, and especially for the pastes, they were allowed to set 7 days before demolding to avoid damage due to handling (see Figure 3).

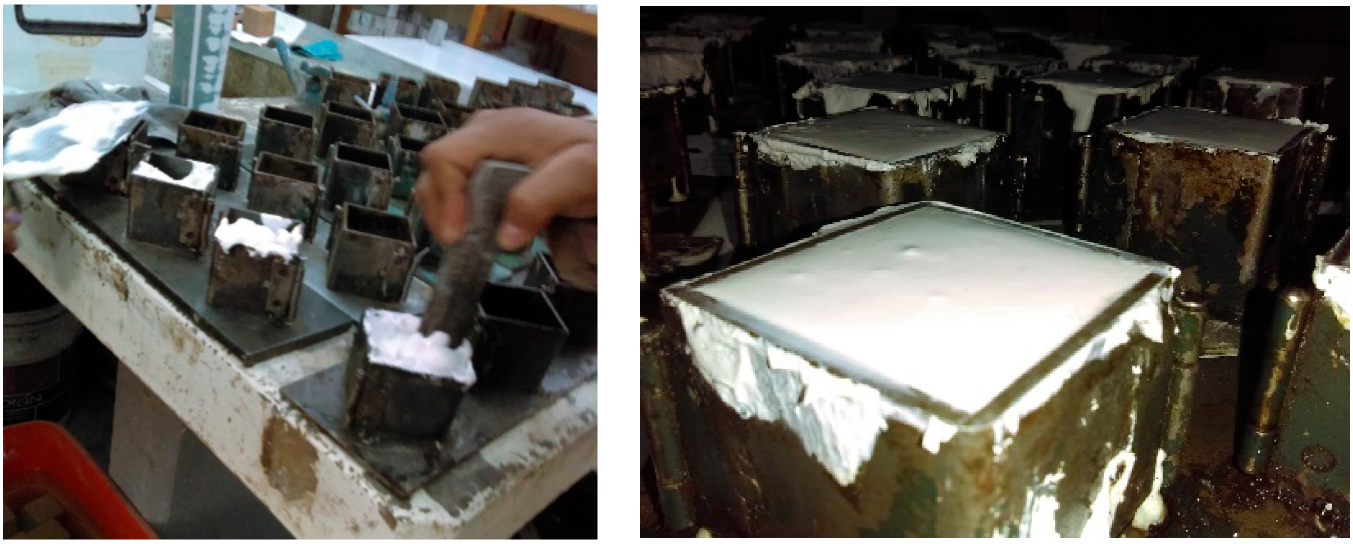

Figure 3. Processing of the paste specimens in molds.

2.2. Surface Area

The purpose of this test is to determine the surface of the material in m^2/g; with larger areas, we obtain higher reactivity [36]. The samples were analyzed in the Institute for Research in Metallurgy and Materials, at UMSNH, in Horiba equipment Model SA9601 STNE, MO (see Figure 4). The lime pastes were transformed into powder by drying the pastes in an oven at a temperature of 60° before performing the test.

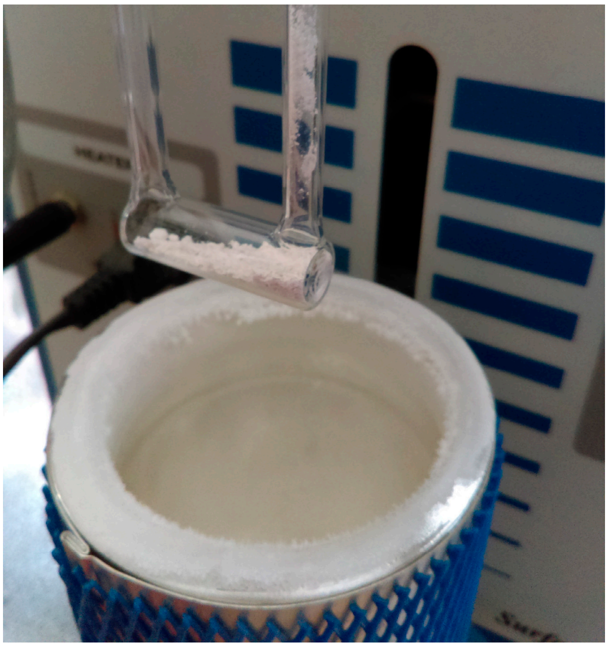

Figure 4. Horiba SA9601 STNE equipment for surface area test.

2.3. Flowability Test

The mortars were tested with the flowability test in a fresh state to determine their workability (see Figure 5). This test was performed based on the cement standard NMX-C-144-ONNCCE-2015 [37]. The standard values for cement mortars should be around 110% ± 5% to be acceptable, being similar to the common masonry mortars.

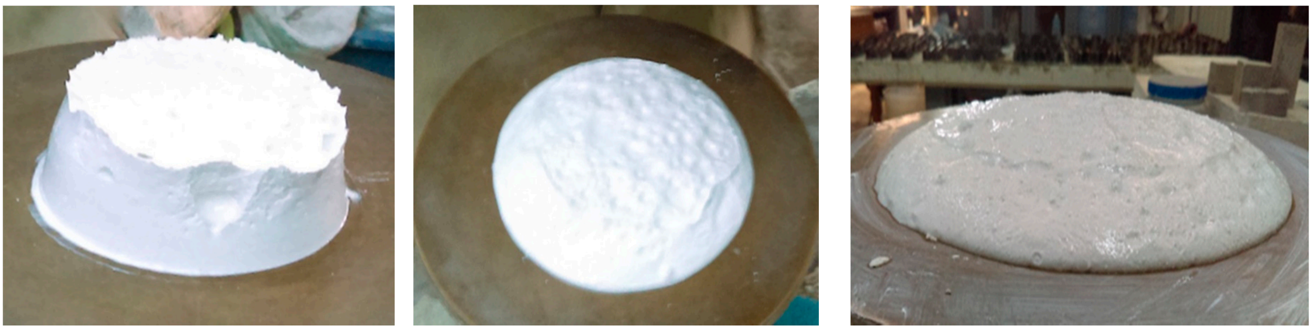

Figure 5. Flowability test.

2.4. Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity (UPV) is a non-destructive test by means of ultrasonic wave propagation, which allows us to know the homogeneity and density of the mortar based on the NMX-C-275-ONNCCE-2020 [38] standard. The V-Meter MKIV equipment of the JAMES INSTRUMENTS brand was used to perform this test (see Figure 6). With this test, we can estimate the durability of mortars and pastes since limes have a higher water absorption compared to cement mortars, and therefore the deterioration factors related to environmental conditions can be studied comparatively [39]. For this test, specimens were tested at 100, 200, and 1400 days.

Figure 6. Ultrasonic velocity pulse equipment and testing on a sample.

2.5. Electrical Resistivity Test

The electrical resistivity test can be used to determine the characteristics of some material, its porosity, and also its saturation state [40]. The Mexican standard NMX-C-514-ONNCCE-2019 [41] was used to perform this test. Porosity is a very important factor to study since the greater the porosity of the mortar, the greater its water absorption capacity will be, and consequently, its degradation speed will increase [42]. To perform this test, it is necessary that the specimens are saturated in water, but since lime is a material with a certain water solubility, the specimens were placed in molds submerged in one centimeter of water and were sprayed daily with water for seven weeks until a constant weight was reached. The saturated weight of the specimens was considered at 200 days and 1400 days, and after that, the test was performed according to the previously mentioned standard (see Figure 7).

Figure 7. Electrical resistivity performance of the test.

2.6. Colorimetry

Colorimetry is a non-destructive test [43], which allows us to determine the real colour of an object with the following three parameters: the luminosity "L" (black-white range); and the chromatic coordinates "a" (red-green axis) and "b" (yellow-blue axis) [44]. This test was carried out to know the colour of the lime pastes and mortars studied since restorers consider the white color of lime as an important aesthetic value in restoration works. The CRLM-200 equipment was used (see Figure 8), which calculates the measurement through a spectrophotometer that measures the response of the luminosity by means of light emission on the surface of each specimen.

Figure 8. Utilization of the colorimetry equipment.

2.7. Compressive Strength

The compressive strength trial is a destructive test, and its performance was based on the Mexican standard NMX-C-061-ONNCCE-2010 [35]. The TINIUS OLSEN Universal Testing Machine, with a capacity of 50 tons and approximations to 1 kgf, was used to carry out the tests (see Figure 9); the specimens were tested at 100 days. In the case of lime pastes and mortars, their strengths were expected to be low at early ages, compared to the cement mortars, which are the objects of the regulations.

Figure 9. Universal Testing Machine and specimen failure.

3. Results

3.1. Surface Area

The surface area helps to understand the behavior of materials. In this case, having a greater surface area means that there are more particles and they are smaller. Therefore, the mixtures can be better agglomerated, making them more workable and adherent to the surfaces. Previous research works in the laboratory allowed us to characterize the surface area of lime specimens [36], as is shown in Table 7.

Table 7. Surface area results of limes.

Type	HP95	HP90	SL	HCL	CL
Surface area m^2/gr	13.45	11.67	23.80	18.81	3.07

The surface area of SL is the highest of all, so its workability and adherence characteristics are the best, and this is the reason why restorers have used it for centuries. Nevertheless, it was proved that powdered limes, if macerated for a period (900 days in this research), increase their surface area, and deflocculates. It was also observed that high-purity limes (HP90 and HP95) have a higher surface area, being in powder form, than the common construction lime (CL), so that the characteristics desired for restoration can be obtained without having the extra process of slaking.

For restorers, the use of SL always was the best option since it had better empirical workability, but they did not know that this parameter depended on the surface area. It has been demonstrated that this characteristic increases when it is dissolved in water. In the case of CL, it has a considerably low surface area value; however, with the hydration process, its surface area increases.

3.2. Flowability

The standard specifies flowability is 110% ± 5% for cement mortars. The results obtained for lime mortars deviate from the standard, but it should be considered that the standard is based only on cement-based mortars, as can be seen in Table 8.

Table 8. Flowability results for lime pastes and mortars.

Type	HP95	HP90	SL	HCL	CL
Paste	115%	118%	132%	185%	139%
Mortar	125%	145%	132%	115%	112%

For the limes that were macerated, there is no exact control over the water content, so the value obtained is higher. In restoration, there are no standards that determine the necessary fluidity of the lime pastes; the data that exist are simply based on the workability required by the applicator for the different uses.

As for the fluidity of the mortars, it was observed that these are different from cement mortar data; therefore, it is not possible to have a base parameter, and it should be considered that each mixture is prepared according to the work to be done, the material to be worked with, and the type of use of the mixture in the same way that happens with the pastes.

The samples of mortars and pastes were kept in the molds for seven days since the setting is a slow process, and it was observed, as expected, that the macerated limes presented a higher volumetric shrinkage (see Figures 10–12). The lime pastes (CAA and CCA) had the greatest shrinkage, about one centimeter, followed by HP95 and HP90 lime. On the other hand, the volumetric shrinkage of CL lime was at least 1 mm. As for the mortars, the volumetric shrinkage was lower than the pastes. This is due to the aggregate, but even so, it can be observed that in the SL, there is minimal shrinkage.

Figure 10. SL and HCL pastes.

3.3. Ultrasonic Velocity Pulse

The tests were carried out at 100, 200, and more than 1400 days on pastes and mortars. This test provides information on the homogeneity and porosity of the samples and on possible discontinuities by detecting cracks, crevices or voids that may affect the strength. In this case, the parameters described in the standards are only for cement mortars, so the values obtained are low compared to the reference ones. Therefore, the analyzed samples have higher porosity [45].

Figure 11. Lime paste specimens.

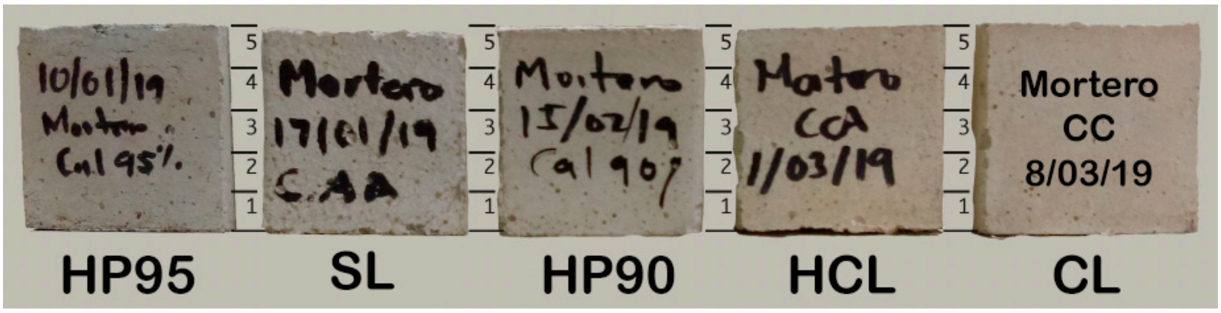

Figure 12. Lime mortar specimens.

The values of the pastes do not exceed 2000 m/s in any case except for HP95, while the values of the mortars do exceed 2000 m/s at 1400 days. On the other hand, a change in the values is observed with the aging, achieving higher values and, therefore, obtaining a better homogeneity and lower porosity of the samples (see Table 9 and Figures 13 and 14). This increase is highly appreciated in the mortars since the values of pastes remain more constant over time.

Table 9. Ultrasonic pulse velocity of lime pastes and mortars.

	Pastes (m/s)		Mortars (m/s)	
Type	**200 Days**	**1400 Days**	**200 Days**	**1400 Days**
HP95	2043.0	1757.67	1663.3	2096.09
HP90	1781.7	1804.12	1772.7	2638.34
SL	1897.3	1712.29	1286.7	1304.51
HCL	1631.0	1836.97	1229.3	1867.00
CL	1584.0	1945.65	1925.0	2605.91

The ultrasonic pulse velocity gives us information on the homogeneity and porosity of the materials based on how long it takes for an electric pulse to pass through the material, as measured in m/s. The paste samples tested at 100, 200 and 1400 days remained in a range greater than 1400 m/s and less than 2050 m/s, except for HP95 at 100 days. From 100 to 200 days, there was an increase in all the samples analyzed. As for the samples analyzed at 1400 days, the results that were low, such as CL and HCL, increased; the value of HP90 remained within the range, and the SL and HP95 samples decreased.

The decrease in UPV may be due to the formation of cracks in the pastes in the absence of sand, which acts as an inert addition that regulates and reduces the generation of cracks; this did not occur in the mortars that contain sand.

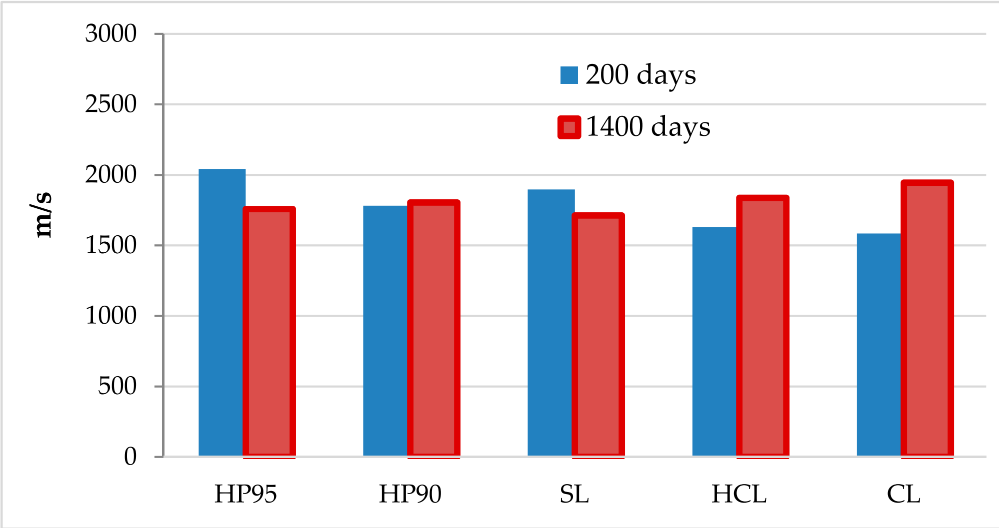

Figure 13. Ultrasonic pulse velocity in pastes.

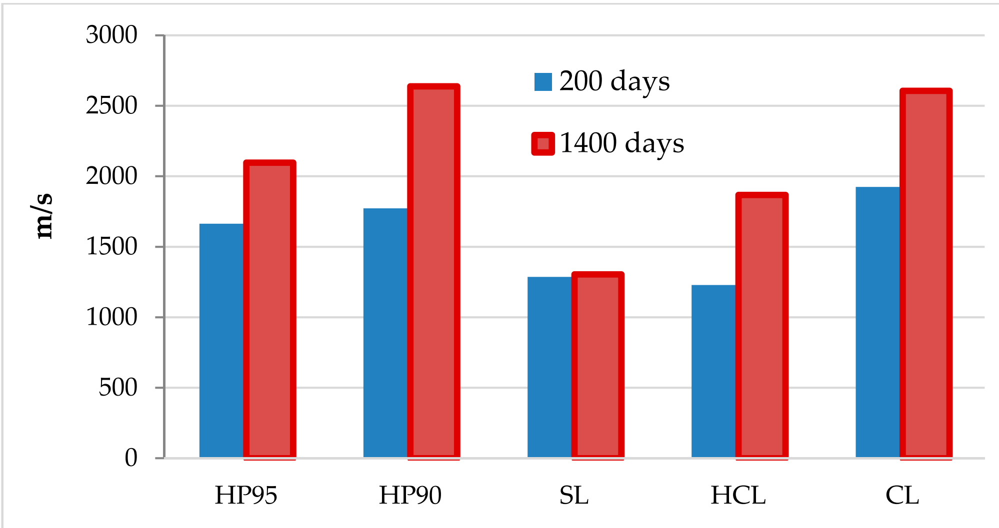

Figure 14. Ultrasonic pulse velocity in mortars.

In mortars, the UPV remained between 1200 and 2700 m/s, with UPV increasing with respect to the age of processing between 200 and 1400 days in all cases. Therefore, we can consider that the pastes and mortars with the highest homogeneity and lowest porosity, tested at more than 1400 days, are the CL samples, followed by HP90, HP95 and HCL, with lower SL values. Therefore, it is considered that CL and HP90 are the ones with the best characteristics to avoid deterioration of the material and have the least number of cracks.

3.4. Electrical Resistivity

The results of the electrical resistivity were carried out with specimens at 200 days and 1400 days, both in pastes and mortars. Table 10 shows the results of all the specimens in Ω·cm, while Figures 15 and 16 display the variation over time of pastes and mortars separately. Mortars reached higher values since the presence of the aggregates obstructs the passing of the electrical current.

Table 10. Electrical resistivity of lime pastes and mortars.

	Pastes (Ω·cm)		Mortars (Ω·cm)	
Type	**200 Days**	**1400 Days**	**200 Days**	**1400 Days**
HP95	882.07	119.97	1546.35	1420.88
HP90	765.8	285.74	2433.1	2656.91
SL	418.94	647.29	1061.06	1113.77
HCL	520.23	686.01	2579.69	3361.05
CL	513.36	464.05	1533.07	3151.43

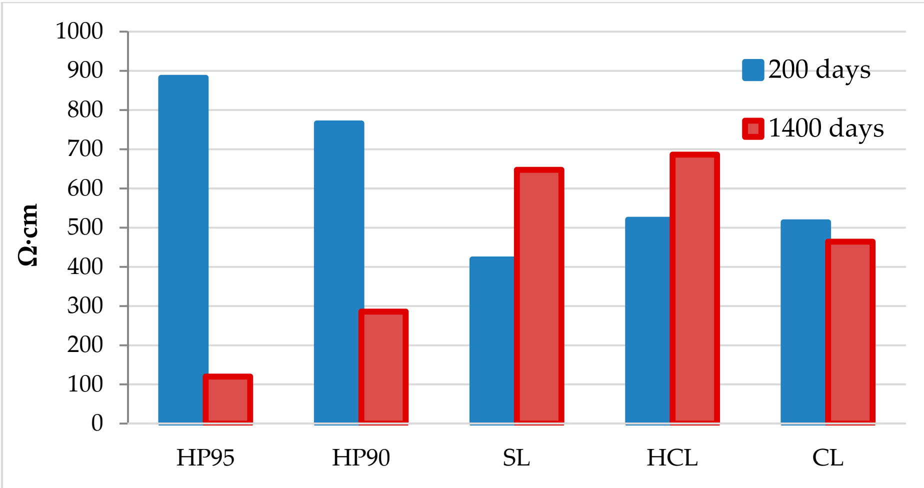

Figure 15. Electrical resistivity in pastes.

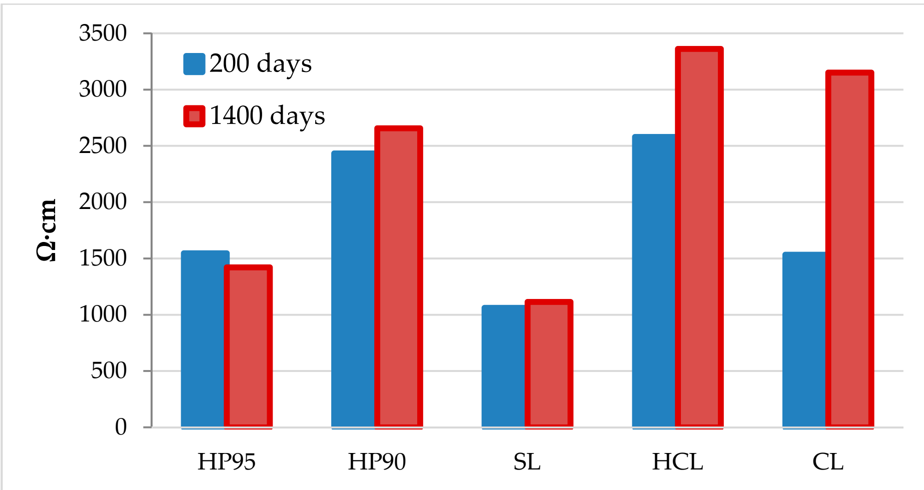

Figure 16. Electrical Resistivity in Mortars.

Electrical resistivity is the test that indicates how the material opposes the passing of electric current. This parameter is related to the porosity, and the higher the electrical resistivity of the sample, the higher its porosity. The pastes tested at 200 days ranged between 400 and 900 Ω·cm, while the ones tested at 1400 days ranged between 100 and 700 Ω·cm. The SL and HCL pastes are the only ones that showed an increase over time, while CL had a slight decrease, and HP95 and HP90 reported more variability, the latter being the ones with lower porosity and more suitable for use. Theoretically, an increase in the electrical resistivity over time would be expected; however, the values diminished for the HP95 and HP90 specimens, which could be on account of the formation of fissures in the samples, which prevent the continuity of the electric current.

For the mortars, at 200 days of age, the range values obtained varied between 1000 and 2600 Ω·cm. The lowest measurement is SL, and the highest is HCL. For the tests performed at 1400 days, the range was 1100–3400 Ω·cm, with HCL being the highest and SL the lowest. In general, in the case of the mortars, the samples presented an increase in electrical resistivity, except HP95, which demonstrated a negligible decrease, probably due to the presence of some fissures.

3.5. Colorimetry

The results are shown in Table 11, where the "a*" parameter represents the red-green axis, the "b*" parameter represents the yellow-blue axis of the chromatic scale, and the "L*" parameter represents the lightness from pure black to pure white. The table also displays the real color of the samples generated with the CIE scale. The nearer a sample is to L = 100, the whiter it is; thus, we can see how the HP95 lime paste is the one closest to the "purest" white, while the traditional slaked lime mortar (SL) is the darkest. It is notable how the volcanic sands provide grey and darker tones to the mixtures, but at the same time, they are needed for the other properties they achieve.

Table 11. Colorimetry values for pastes and mortars with respect to the CIE system.

Pastes	a*	b*	L*	Color	Mortars	a*	b*	L*	Color
HP95	0.73	4.55	93.53		HP95	0.25	2.55	87.42	
HP90	1.41	6.59	90.60		HP90	0.93	4.98	85.53	
SL	1.65	7.13	89.40		SL	0.93	5.10	83.33	
HCL	2.00	7.60	90.29		HCL	0.85	5.31	86.96	
CL	1.70	6.39	90.08		CL	1.10	4.75	87.45	

To identify the color variations between the different limes, the "a*" and "b*" coordinates are shown in Figure 17. The mortars are farther away from both axes, except for mortar HP95. Nevertheless, the tone of the pastes and mortars is totally influenced by the quarry and the place of extraction.

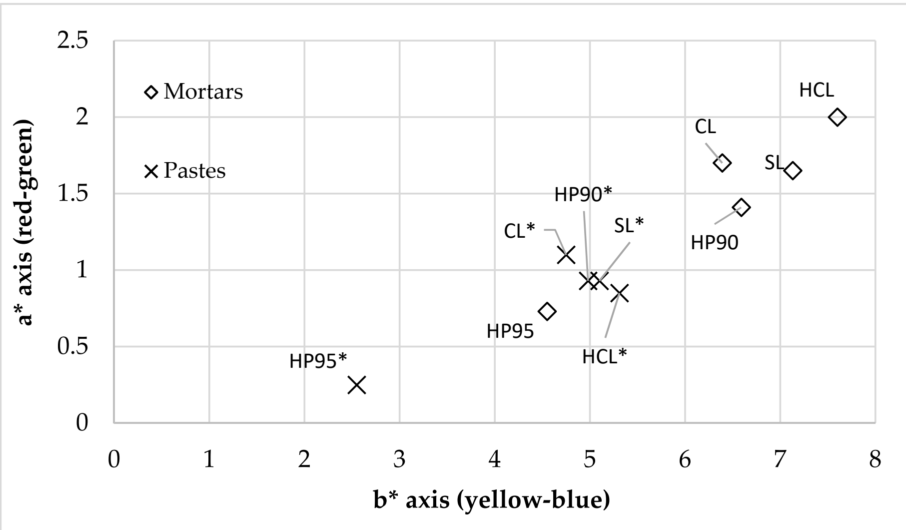

Figure 17. Colorimetric values a* and b*.

In the colorimetric study of the pastes and mortars, it was observed that the values of paste and mortar for HP95 lime, coming from Acajete (Puebla, Mexico), are in a more distant range than the other limes that come from Piedras de Lumbre (Michoacan, Mexico). However, all the specimens present an acceptable color for their use in restoration, being the cause of the lime quarry where the calcium carbonate is extracted for its production.

3.6. Compressive Strength

Table 12 shows the compressive strength of the paste and mortar specimens at 100 and 1400 days, with a logical improvement in the mechanical capacities of the materials. Figures 18 and 19 display these increases for each one of the groups. It is notable that the performance of pastes reaches high values, especially for SL, with a considerable increase in the resistance over time. On the other hand, the best specimens for mortars were HP90 and CL.

Table 12. Compressive strength of specimens.

	Pastes (MPa)		Mortars (MPa)	
Type	**200 Days**	**1400 Days**	**200 Days**	**1400 Days**
HP95	0.84	2.58	1.34	2.47
HP90	1.09	2.23	1.60	4.66
SL	1.90	4.42	1.11	1.77
HCL	1.57	2.97	0.91	1.10
CL	1.53	3.13	1.80	4.57

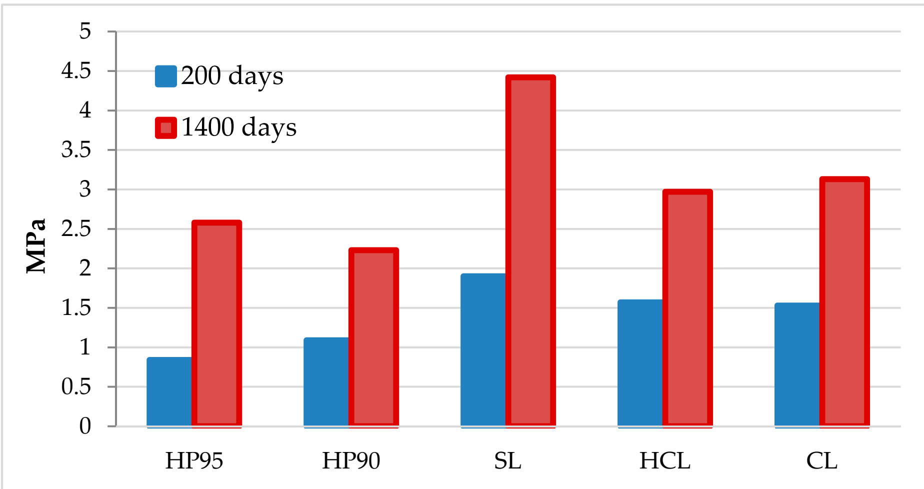

Figure 18. Compressive strength of pastes.

Regarding compressive strength, the results obtained in the pastes tested at 100 days were between 0.8 and 2 MPa, with the HP95 paste having the lowest value and the SL paste having the highest value. There was an increase in the results obtained in the tests carried out at 1400 days, obtaining results in a range of 2.2 to 4.6 MPa; SL obtained the highest value, while the lowest was for HP90. In the pastes, it was observed that the macerated limes obtained higher values than the powdered limes.

For mortars tested at 100 days, the results were between 0.9 and 1.9 MPa; CL was the highest value, and HCL was the lowest. An increase could also be observed in all the samples tested at 1400 days, with the lowest value obtained for HCL at 1.12 MPa and the highest obtained for HP90 at 4.75 MPa.

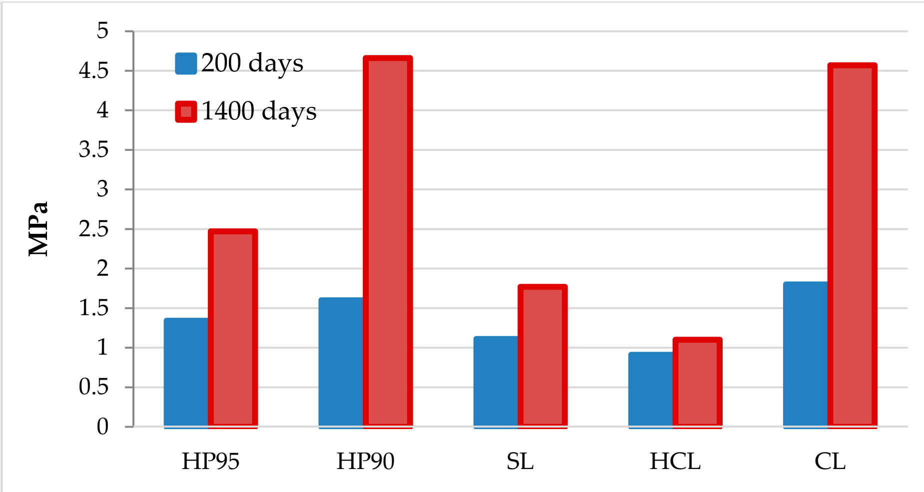

Figure 19. Compressive strength of mortars.

4. Conclusions

The objective of this research is to characterize and analyze the physical and mechanical properties of the different affordable types of lime in Mexico for restoration works. New alternatives, such as the high-purity or chemical limes, are compared with the artisanal slaked lime, which is the material recommended and applied for these purposes. With knowledge of the characteristics and behavior of these different limes, we can assess the suitability of each one for different restoration processes, finding new developments of the traditional techniques.

Properties such as the surface area show us the suitability of the different limes for specific works. With the experimentation, it has been demonstrated how the slaking process increases the value of the surface area. This is widely known for the artisans and restorers and, at the same time, is precisely one of the more appreciated features of slaked lime in the field. Nevertheless, it is interesting how HP90 and HP95 reached high values and great workability properties without having to be dissolved in water, as they can be applied immediately, significantly reducing their work time.

Non-destructive testing, such as UPV and electrical resistivity, is extremely useful when working with heritage. These tests give us information about the internal composition of the specimens, the homogeneity, and the porosity of the different mixtures. The UPV results presented good values, with considerable increases over time for the mortars, especially the ones prepared with high-quality limes. On the other hand, the electrical resistivity reported more variation of the results in both pastes and mortars; nevertheless, it is important to consider that this test is designed mainly for Portland cement, and it is expected to find different values for lime. According to the standards applied, the pastes do not comply with the required values, while the mortars do; HP90 correlates with normal quality mortars, while CL and HCL are correlated with high-quality mortars, as all of them are limes in powder with easier and quicker application.

Regarding compressive strength, the use of mortars and pastes in restoration works does not demand particularly high mechanical resistance, as they are used to repair and protect the masonries and structures. Both pastes and mortars experience a substantial increase in their resistance over time, reaching remarkable values at 1400 days. All the limes in powder format (CL, HP90 and HP90) showed good performance, denoting how they could be used instead of the traditional mixtures.

In general, HP95 and CL obtained interesting results, as both reached acceptable and good results, and consequently, they could be of value for alternative use. The high-purity limes achieved great results regarding their surface area, better than construction lime and inferior to the slaked limes; however, they avoid the entirety of the long process of slaking. In this sense, they give the restorers the option to improve the adherence and workability of these materials through their maceration process in shorter periods. These limes are easy to access and handle since they are acquired in powder form. To take advantage of the characteristics of these two limes, it is necessary to make correct dosages and to have a qualified labor force.

Author Contributions: Conceptualization, E.G.N.-M., E.M.A.-G., J.A.B.-A.; methodology, E.G.N.-M., E.M.A.-G.; validation, A.S.-C., H.B.-S., J.A.B.-A.; formal analysis, A.N.-E., W.M.-M., B.G.-S.; investigation, E.G.N.-M., E.M.A.-G.; resources, E.M.A.-G., E.G.N.-M.; writing—original draft preparation, E.G.N.-M., E.M.A.-G., A.S.-C., A.N.-E.; writing—review and editing, B.G.-S., A.S.-C., H.B.-S., W.M.-M.; supervision, J.A.B.-A., A.S.-C., B.G.-S.; project administration, E.M.A.-G., H.B.-S., W.M.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research work and project was funded by CIC UMSNH, SEP Prodep and CONACYT.

Acknowledgments: The authors acknowledge the Materials Laboratory "Ing. Luis Silva Ruelas" of the Faculty of Civil Engineering of the UMSNH for the equipment support, the Postgraduate Program PIDA of the Faculty of Architecture of the UMSNH, and the economic support given by CONACYT and CIC-UMSNH. This research has been partially supported by the International Contest for Cooperation and Development Projects' award within the 15th International Conference on Durability of Building Materials and Components (DBMC 2020), Barcelona, Spain.

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

References

1. Elsen, J. Microscopy of historic mortars—A review. *Cem. Concr. Res.* **2006**, *36*, 1416–1424. [CrossRef]
2. do Rosário Veiga, M.; Fragata, A.; Velosa, A.L.; Magalhães, A.C.; Margalha, G. Lime-Based Mortars: Viability for Use as Substitution Renders in Historical Buildings. *Int. J. Archit. Herit.* **2010**, *4*, 177–195. [CrossRef]
3. Alonso, I.V.; Pingarrón, L.B. Los orígenes tecnológicos de la cal. *Cuicuilco* **2012**, *55*, 11–41.
4. Aggelakopoulou, E.; Bakolas, A.; Moropoulou, A. Lime putty versus hydrated lime powder: Physicochemical and mechanical characteristics of lime based mortars. *Constr. Build. Mater.* **2019**, *225*, 633–641. [CrossRef]
5. Liu, X.; Ma, X.; Zhang, B. Analytical Investigations of Traditional Masonry Mortars from Ancient City Walls Built during Ming and Qing Dynasties in China. *Int. J. Archit. Herit.* **2016**, *10*, 663–673. [CrossRef]
6. Carran, D.; Hughes, J.; Leslie, A.; Kennedy, C. A Short History of the Use of Lime as a Building Material beyond Europe and North America. *Int. J. Archit. Herit.* **2012**, *6*, 117–146. [CrossRef]
7. Jaime-Ledesma, P.J. La técnica constructiva en la arquitectura. *Legado Arquit. Y Diseño* **2014**, *9*, 21–30.
8. Fernandez, F.; Germinario, S.; Basile, R.; Montagno, R.; Kapetanaki, K.; Gobakis, K.; Kolokotsa, D.; Lagou, A.M.; Dania, P.; Enna, M.T.; et al. Development of Eco-Friendly and Self-Cleaning Lime-Pozzolan Plasters for Bio-Construction and Cultural Heritage. *Buildings* **2020**, *10*, 172. [CrossRef]
9. Speziale, A.; González-Sánchez, J.F.; Taşcı, B.; Pastor, A.; Sánchez, L.; Fernández-Acevedo, C.; Oroz-Mateo, T.; Salazar, C.; Navarro-Blasco, I.; Fernández, J.M.; et al. Development of Multifunctional Coatings for Protecting Stones and Lime Mortars of the Architectural Heritage. *Int. J. Archit. Herit.* **2020**, *14*, 1008–1029. [CrossRef]
10. Loganina, V.; Sergeeva, K.; Fediuk, R.; Klyuev, S.; Vatin, N.; Vasilev, Y. Modified Lime Binders for Restoration Work. *Buildings* **2021**, *11*, 98. [CrossRef]
11. *Vitruvius, The Ten Books on Architecture*; Alianza Forma: Madrid, Spain, 2000.
12. Kotlyar, V.; Pishchulina, V.; Beskopylny, A.; Meskhi, B.; Popov, Y.; Efremenko, I. Estimation of the Age of Architectural Heritage Objects by Microstructural Changes of Calcite in Lime Mortars of Ancient Brickwork and Masonry. *Buildings* **2021**, *11*, 240. [CrossRef]
13. *NMX-C-486-ONNCCE-2014*; Industria de la Construcción-Mampostería–Mortero Para Uso Estructural–Especificaciones y Métodos de Ensayo. Organismo Nocional de Normalización y Certificación de la Construcción y la Edificación (ONNCCE): Ciudad de Mexico, Mexico, 2014.
14. Villaseñor, I.; Schneider, R. Principios generales para la elaboración de argamasas. In *La Cal: Historia, Propiedades y Uso*; Barba Pingarrón, L., Villaseñor Alonso, I., Eds.; UNAM, Instituto de Investigaciones Antropológicas, Asociación Nacional de Fabricantes de Cal: Ciudad de Mexico, Mexico, 2013; pp. 97–114.
15. Curulli, A.; Montesperelli, G.; Ronca, S.; Cavalagli, N.; Ubertini, F.; Padeletti, G.; Ciprioti, S.V. A multidisciplinary approach to the mortars characterization from the Town Walls of Gubbio (Perugia, Italy). *J. Anal. Calorim.* **2020**, *142*, 1721–1737. [CrossRef]
16. Caroselli, M.; Ruffolo, S.A.; Piqué, F. Mortars and plasters—How to manage mortars and plasters conservation. *Archaeol. Anthr. Sci.* **2021**, *13*, 188. [CrossRef]
17. Biçer-şimşir, B.; Griffin, I.; Palazzo-Bertholon, B.; Rainer, L. Lime-based injection grouts for the conservation of architectural surfaces. *Stud. Conserv.* **2009**, *54*, 3–17. [CrossRef]

18. Sepulcre Aguilar, A.; Hernández-Olivares, F. Interfacial Transition Zone (ITZ) Analysis in Hydraulic Lime Restoration Mortars for Grouting of Historical Masonries. *Int. J. Archit. Herit.* **2012**, *6*, 396–414. [CrossRef]
19. Silva, B.A.; Ferreira Pinto, A.P.; Gomes, A. Natural hydraulic lime versus cement for blended lime mortars for restoration works. *Constr. Build. Mater.* **2015**, *94*, 346–360. [CrossRef]
20. Pachta, V.; Papayianni, I.; Spyriliotis, T. Assessment of Laboratory and Field Testing Methods in Lime-based Grouts for the Consolidation of Architectural Surfaces. *Int. J. Archit. Herit.* **2020**, *14*, 1098–1105. [CrossRef]
21. López Martínez, T.; García, M.d.R.B.; García Bueno, A. Metodología para el estudio de morteros arqueológicos de revestimiento. *Ge-Conservacion* **2021**, *19*, 31–44. [CrossRef]
22. Tavares, M.; Magalhaes, A.C.; Veiga, M.D.R.; Aguiar, J. Métodos de diagnóstico para revestimientos de edificios antiguos. Importancia y aplicabilidad de los ensayos in situ. *Rev. PH* **2005**, *53*, 11–17. [CrossRef]
23. RILEM TC 203-RHM: Repair mortars for historic masonry. *Mater. Struct.* **2012**, *45*, 1277–1285. [CrossRef]
24. Lara Calderón, M.L.; Sanz-Arauz, D.; López-Andrés, S.; del Pino, I. Characterization and Analysis of the Mortars of the Church of Santo Domingo in Quito (Ecuador). *Heritage* **2022**, *5*, 4024–4036. [CrossRef]
25. Alonso, E.; Martı, L.; Martı, W.; Villaseñor, L. Mechanical properties of concrete elaborated with igneous aggregates. *Cem. Concr. Res.* **2002**, *32*, 317–321. [CrossRef]
26. Martínez, W.; Alonso, E.M.; Rubio, J.C.; Bedolla, J.A.; Velasco, F.A.; Torres, A.A. Comportamiento mecánico de morteros de cal apagada artesanalmente adicionados con mucílago de cactácea y ceniza volcánica, para su uso en restauración y conservación de monumentos coloniales. *Rev. Constr.* **2008**, *7*, 93–101.
27. Molina, W.M.; Guzman, E.A.; Garcia, H.C.; Gomez, C.L.; Valdez, F.G.; Lica, O.F.; Acosta, A.T.; Alonso, W.M.; Arroyo, J.B.; Barrios, H.H. Mechanical Response of Portland Cement Mortars with added Expanded Polystyrene Spheres (EPS) under Accelerated Attack. In Proceedings of the 2015 International Conference on Structural, Mechanical and Material Engineering, Dalian, China, 6–8 November 2015. [CrossRef]
28. *ASTM D75/D75M-19*; Standard Practice for Sampling Aggregates. ASTM International: West Conshohocken, PA, USA, 2019.
29. *ASTM C128-22*; Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate. ASTM International: West Conshohocken, PA, USA, 2022.
30. *ASTM C29/C29M 17a*; Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate. ASTM International: West Conshohocken, PA, USA, 2017.
31. *ASTM C136/C136M19*; Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International: West Conshohocken, PA, USA, 2019.
32. *ASTM C40/C40M-20*; Standard Test Method for Organic Impurities in Fine Aggregates for Concrete. ASTM International: West Conshohocken, PA, USA, 2020.
33. *ASTM D2419-22*; Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate. ASTM International: West Conshohocken, PA, USA, 2022.
34. *ASTM C117-17*; Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing. ASTM International: West Conshohocken, PA, USA, 2017.
35. *NMX-C-061-ONNCCE-2015*; Building Industry–Hydraulic Cements–Determination of Compressive Strength of Hydraulic Cements. Organismo Nacional de Normalización y Certificación de la Construcción y Edificación (ONNCCE): Ciudad de Mexico, Mexico, 2015.
36. Mendoza, E.G.N.; Bedolla-Arroyo, J.A.; Calvillo, A.S.; Guzmán, E.M.A.; Blancas-Herrera, V.H.; Molina, W.M.; García, H.L.C. High Purity Lime as an Ecologic Alternative for Construction Mortars and Pastes. *Key Eng. Mater.* **2020**, *841*, 188–192. [CrossRef]
37. *NMX-C-144-ONNCCE-2015*; Building Industry–Hydraulic Cement–Specifications for the Aparatus used in the Flow Test for Mortars made of Hydraulic Cements. Organismo Nacional de Normalización y Certificación de la Construcción y Edificación (ONNCCE): Ciudad de Mexico, Mexico, 2015.
38. *NMX-C-275-ONNCCE-2020*; Building Industry–Hydraulic Concrete–Determination of the Ultrasonic Pulse Velocity through Concrete–Test Method. Organismo Nacional de Normalización y Certificación de la Construcción y Edificación (ONNCCE): Ciudad de Mexico, Mexico, 2020.
39. Ravi, R.; Selvaraj, T.; Sekar, S.K. Characterization of Hydraulic Lime Mortar Containing *Opuntia ficus-indica* as a Bio-Admixture for Restoration Applications. *Int. J. Archit. Herit.* **2016**, *10*, 714–725. [CrossRef]
40. Barnaure, M.; Bonnet, S.; Poullain, P. Earth buildings with local materials: Assessing the variability of properties measured using non-destructive methods. *Constr. Build. Mater.* **2021**, *281*, 122613. [CrossRef]
41. *NMX-C-514-ONNCCE-2019*; Building Industry–Electrical Resistivity of Hydraulic Concrete–Specifications and Testing Methods. Organismo Nacional de Normalización y Certificación de la Construcción y Edificación (ONNCCE): Ciudad de Mexico, Mexico, 2019.
42. La Russa, M.F.; Ruffolo, S.A. Mortars and plasters—How to characterize mortar and plaster degradation. *Archaeol. Anthr. Sci.* **2021**, *13*, 165. [CrossRef]
43. Sánchez-Calvillo, A.; Alonso-Guzmán, E.M.; Ruvalcaba-Sil, J.L.; Martínez-Molina, W.; Chavez-Garcia, H.L.; Bedolla-Arroyo, J.A.; Navarro-Mendoza, E.G.; Blancas-Herrera, V.H.; Perez, J.A.V. Colorimetry of clays as a tool to identify soil materials for earthen buildings restoration. *Key Eng. Mater.* **2020**, *862*, 56–60. [CrossRef]

44. Berns, R.S. *Billmeyer and Saltzman's Principles of Color Technology*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 2019.
45. Borinaga-Treviño, R.; Orbe, A.; Canales, J.; Norambuena-Contreras, J. Experimental evaluation of cement mortars with recycled brass fibres from the electrical discharge machining process. *Constr. Build. Mater.* **2020**, *246*, 118522. [CrossRef]