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Alternatives to Lime Plaster: Evaluation of Paints with Inorganic Pigments for the Conservation of Heritage Buildings in Peru

Carlos Guillermo Vargas Febres [1,*], Juan Serra Lluch [2], Ana Torres Barchino [2] and Edwin Roberto Gudiel Rodríguez [3]

[1] Professional School of Architecture, Faculty of Engineering and Architecture, Universidad Andina del Cusco, Cusco 08006, Peru
[2] Higher Technical School, Architecture Universitat Politècnica de València, 46022 Valencia, Spain; juaserl1@ega.upv.es (J.S.L.); atorresb@ega.upv.es (A.T.B.)
[3] Faculty of Architecture and Urban Planning, Pontificia Universidad Católica del Perú, Lima 15088, Peru; egudiel@pucp.edu.pe
* Correspondence: cvargasf@uandina.edu.pe; Tel.: +51-984767144

Abstract

Lime plaster has historically been a key material in the preservation of architectural heritage in Peru; however, its availability has been restricted by state regulations that limit its production and commercialization. This study evaluates the performance of paints formulated with inorganic pigments extracted from soils in the Cusco valley, combined with natural and synthetic binders, as a sustainable alternative for the protection of heritage buildings in this Andean region characterized by high altitude, wide thermal variations, and high solar radiation. Adhesion, hardness, drying time, and weather resistance tests were conducted according to applicable ASTM standards for architectural coatings. The results show that these formulations exhibit good adhesion to historic surfaces and greater durability against extreme environmental conditions compared to traditional lime plaster. Their potential compatibility with historic substrates and lower environmental impact suggest that these paints represent a viable alternative in sustainable conservation strategies; however, further studies are needed to more accurately characterize the mineralogical composition of the pigments used.

Keywords: inorganic pigment; lime plaster; sustainable paint

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1. Introduction

The conservation of architectural heritage is a crucial challenge at the global level, particularly in regions with significant historical wealth. This process requires materials that are compatible with traditional construction systems to ensure long-term stability [1]. Among these materials, lime plaster has been widely used for its physicochemical properties, which allow the walls to breathe and prevent the accumulation of moisture [2].

In the city of Cusco, whose viceregal architecture dates from the sixteenth to the eighteenth centuries [3,4], the interior and exterior surfaces of historic buildings were covered with lime plaster, following hygiene criteria rather than merely aesthetics [5,6]. This Andean region, characterized by its high altitude, has a constant solar radiation of between 5.5 and 6.5 kWh/m^2/day [7], with higher intensities in the dry season (May–August) [8], which accelerates the degradation of the exposed coatings.

Restoration in Cusco is carried out by entities such as the Ministry of Culture and private actors [9], applying techniques recorded in historical archives, including the cleaning of substrates and the application of slaked lime ($Ca(OH)_2$) [10–12]. However, pathologies such as cracks, landslides, and discoloration are evident on private properties, which are frequently treated with non-conservationist methods [13–15].

These practices are partly a consequence of Peruvian regulations that restrict the use of lime due to its link to the production of cocaine hydrochloride [16], which imposes bureaucratic obstacles to its commercialization and use [17,18]. This has encouraged the use of synthetic latex-type paints, which not only compromise the authenticity of the material but also generate chemical reactions that affect the mortar and substrates of colonial constructions [19,20].

Faced with this problem, inorganic pigments have emerged as a viable alternative due to their chemical stability and resistance to weathering [21,22]. Previous research, such as that of Vignola in Italy, showed that local soils can be used to produce durable coatings [23], while studies in Brazil detected pathologies similar to those in the Peruvian context in heritage buildings [20]. In addition, other research has evaluated paints with mineral pigments and different binders, highlighting the effectiveness of synthetic ones compared to natural ones [24,25].

In Peru, studies in Puno, a region with characteristics similar to Cusco, evaluated paints formulated with titanium dioxide and carboxymethylcellulose, obtaining good results in terms of strength and stability [26]. Likewise, analyses carried out in the temple of Kuñotambo tested different formulations with lime, sand, linseed oil, and silicate, showing a better adhesion of silicate paints, although with certain deficiencies in compatibility with humidity [27].

Considering the current restrictions on lime and the aforementioned background, this study aims to evaluate paints formulated with inorganic pigments from the Cusco valley and natural and synthetic binders (see Figure 1), as a sustainable alternative to lime plastering. Common pathologies (cracks, blistering, detachment, discoloration) and key properties such as adhesion (ASTM D3359) [28], drying time (ASTM D1640) [29], and hardness (ASTM D3363) [30] are analyzed, with a view to validating their viability in the conservation of architectural heritage in climatic conditions typical of the Andean environment. Unlike previous studies, this research focuses on the long-term performance of these coatings in the Peruvian context.

Figure 1. Viceroyalty architecture of Cusco with lime plaster coatings. Note: Examples of facade deterioration on heritage buildings in Cusco's historic center. Graffiti, plaster detachment, and patches made with incompatible materials are visible issues linked to the limited access to lime for traditional maintenance because it is a regulated input in Peru.

2. Materials and Methods

The inorganic pigments used in this study were obtained from naturally pigmented soils located in rural areas surrounding the Cusco Valley, specifically from quarries situated in the southern outskirts of the city, in zones characterized by dry, rocky terrain with sparse vegetation. These soils, selected for their distinct coloration and traditional use in local construction, served as the base material for pigment extraction.

Two distinct soil extraction sites were selected for this study, corresponding to two different natural pigment sources, labeled as M-01 and M-02. These served as the base pigments for the preparation of experimental paints. From each of these two pigment sources, six different formulations were developed by varying both the type of binder (natural—Aloe vera mucilage, and synthetic-Polyvinyl Acetate, PVA) and its concentration (20%, 40%, and 60% by weight relative to the dry pigment mass). This factorial design resulted in a total of twelve distinct paint samples, allowing for a systematic evaluation of the influence of both pigment origin and binder characteristics on the physical–mechanical behavior of the coatings. These two locations were chosen due to their contrasting mineral compositions and traditional use in local construction practices. To enable a reliable comparison of the influence of each soil's origin on the performance of the paints, a standardized sampling and preparation protocol was implemented at both sites. This ensured consistency in the treatment of the raw material prior to pigm Two distinct soil extraction sites were selectedent processing.

The following procedure outlines the steps taken from the moment of soil identification to the acquisition of usable pigment:

(a) Sample Extraction: After identifying the designated extraction points, the collection of samples followed a systematic protocol as described below:
Step 1: The surface in the selected area was cleaned; this procedure ensured the removal of organic matter such as roots, stems, leaves, and other elements that could alter the pigment's tone. In Step 2, the first layer was removed to eliminate impurities, as well as the presence of animals and other agents that significantly influence sample contamination. Then, in Step 3, 20 kg of soil with representative pigmentary characteristics (color) was extracted, coding each sample by assigning unique identifiers to each one for accurate tracking.

(b) Preparation of Pigments: This process was carried out following the methodology established by Cardoso (2020), adapted to the conditions and characteristics of the selected quarries in Cusco, proceeding as follows.

   I. Drying, coarse grinding, and sieving: The drying was carried out by exposing the samples to room temperature to eliminate the moisture present from the quarry extraction. The coarse grinding involved crushing the samples with manual tools until reaching a granulation size not exceeding two centimeters, and the sieving process utilized an ASTM No. 200 sieve with a hole size of 0.841 mm (841 microns) and mesh with an opening of 850 µm (micrometers) or 0.85 mm. Sieving, as a method of particle size separation, involves applying vibrations to the mesh, which facilitates the passage of smaller particles while retaining those whose size exceeds the opening.

   II. Obtaining pigments through sedimentation and oven drying: The aggregate was obtained with maximum integrity and quality through liquid grinding. A proportion of 3 L of water was mixed with one kilogram of pigment. Mechanical disintegration was performed using a Cowles disc, which is attached to a galvanized threaded rod of 3/8″. This rod is secured to the rotor of a motor, initiating the grinding process that lasts for a period of 15 min. The resulting mixture is allowed to rest for 24 h, after which decantation is carried out to extract as much liquid as possible, leaving the concentrated material at the bottom, which can now be considered as pigment; the wet mixture is poured into galvanized trays, which are then placed in a dehydration oven for 48 h at a temperature of 80 °C to eliminate residual moisture and consolidate the pigment.

(c) Paint Production: As inorganic pigments have a high mineral content, each one reacts chemically in a different way; so, a fixed proportion of pigment and solvent (water) addition is not established, starting with a ratio of 1:3 pigment to water. The mixture is stirred using a Cowles disk for ten minutes, after which the viscosity is measured using a Ford cup viscometer. The mixture is considered adequate if the total volume flows through the viscometer in a time interval between 12 s and 14 s. Samples that do not meet this time period undergo viscosity adjustment by increasing the pigment if the sample is too liquid or increasing the water if it is too dry; these additions are made in batches of 20 g at a time until the necessary viscosity test is met. Subsequently, natural (Aloe vera mucilage) and synthetic (Polyvinyl Acetate) binders were added to each sample in proportions of 20%, 40%, and 60% relative to the dry mass of the pigments, with 3 repetitions applied for each dosage, meaning that each formulation was tested three times independently in order to ensure the reproducibility and accuracy of the measured properties, as shown in Table 1.

(d) Application of paints: Two types of soil and clay bases were produced in a ratio of 7:3, the first molded into reinforced wooden frames of 30 cm × 50 cm for exposure to atmospheric factors, and the second measuring 5 cm × 5 cm for ASTM testing. Each base received two coats of paint with drying periods of 6 h between each layer, after which they were placed on easels inclined at 45° and oriented to the north to maximize exposure to solar radiation, winds, and rainfall typical of the city of Cusco. Meanwhile, the second batch of samples was applied with two coats, measuring the drying time of each layer according to ASTM D1640 [29] and recording it in the corresponding sheet (see Figure 2).

For indoor exposure conditions, the test panels were placed in naturally ventilated, non-climate-controlled rooms that simulate typical interior environments of heritage buildings in the Andean region. These interiors are characterized by low relative humidity fluctuations, limited exposure to direct sunlight, and stable ambient temperatures ranging from 15 °C to 22 °C throughout the day. The absence of artificial lighting with UV components and minimal air movement reduce the intensity of environmental stressors, thereby enabling the evaluation of coating performance under conditions representative of indoor heritage conservation settings.

(e) Evaluation of the paints: The analysis of resistance to natural weather conditions involved exposing the samples to uncontrolled environmental conditions. For the hardness evaluation, the ASTM D3363 [30] standard was employed. This test method determines the resistance of the paint film to surface scratching by using graphite pencils with graded hardness levels, ranging from 6B (very soft) to 9H (very hard). The procedure involves drawing each pencil at a 45° angle under controlled pressure across the coated surface, following a standardized protocol to ensure repeatability.

The hardness rating of each paint sample corresponds to the hardest pencil that does not leave a visible permanent mark on the film. For example, if the 3H pencil creates a scratch but the 2H pencil does not, the hardness is recorded as 2H. Higher values indicate greater resistance to mechanical abrasion and improved film integrity. This property is particularly relevant in architectural conservation, where surface wear from handling, cleaning, or environmental exposure can compromise coatings over time.

The test allows for a comparative analysis of the mechanical robustness of each formulation. In this study, paints formulated with synthetic binders (PVA) generally achieved higher hardness ratings (up to 6H), indicating better performance under abrasive conditions. In contrast, paints with natural binders such as Aloe vera showed a wider variability, depending on the pigment source and concentration, reflecting less consistent film formation.

(f) Statistical Analysis: To determine the statistical significance of the differences in drying times among the various formulations, a one-way analysis of variance (ANOVA) was conducted. The independent variable was the type and concentration of binder (Aloe vera or PVA at 20%, 40%, and 60%), while the dependent variable was the average drying time measured in minutes. Each formulation was tested in triplicate (n = 3) to ensure reproducibility. The analysis was performed using IBM SPSS Statistics version 27.0, with a significance level set at $\alpha = 0.05$. Post hoc Tukey HSD tests were applied to identify statistically significant differences between groups when applicable. This allowed us to assess whether the binder type and dosage had a measurable effect on the drying performance.

The drying time was determined following ASTM D1640 [29] which measures the time for film formation in different layers of paint applied to a substrate. The elapsed time between application and the formation of a dry surface film was recorded, considering the drying progression in each layer to evaluate the speed and efficiency of the coating's hardening.

Figure 2. Process of pigment extraction, paint production, and sample evaluation.

Table 1. Factorial mixture design for inks.

Pigment Sample	Binder Type	Binder Content (%)
M-01	Aloe vera	20
M-01	Aloe vera	40
M-01	Aloe vera	60
M-01	PVA	20
M-01	PVA	40
M-01	PVA	60
M-02	Aloe vera	20
M-02	Aloe vera	40
M-02	Aloe vera	60
M-02	PVA	20
M-02	PVA	40
M-02	PVA	60

3. Results

The evaluation of paints formulated with inorganic pigments as alternatives to lime plaster was performed using standardized ASTM methods. Critical properties, including the adhesion (ASTM D3359) [28], hardness (ASTM D3363) [30], and drying time (ASTM D1640) [29], were assessed to determine the mechanical performance of the coatings on various substrates. The results facilitate comparative analysis of different binder systems and their impact on coating durability, offering technical guidance for their application in architectural heritage conservation.

3.1. Exposure to Environmental Factors

3.1.1. Testing of External Samples (See Figure 3)

In terms of cracking, paints with Aloe vera show the first appearance of fissures in week 3 for 20% binder, while at concentrations of 40% and 60%, this issue manifests in weeks 4 and 5, respectively. In contrast, formulations with PVA exhibit better performance, with the first appearance of cracking occurring in week 5 at the 20% level and extending to week 7 at the 60% concentration. The trend indicates that a higher binder content delays the onset of cracking in both formulations, with a 30% improvement in durability for PVA compared to Aloe vera.

Regarding blistering, the results show that the paints with Aloe vera exhibit this pathology earlier, appearing in week 2 for the 20% formulation and in week 3 for the 40%, while the 60% concentration shows signs in week 4. On the other hand, the formulations with PVA delay the onset of blisters by approximately two weeks, with occurrences recorded in week 4 for the 20%, in week 5 for the 40%, and in week 6 for the 60%. This demonstrates that the resistance of PVA to blistering is approximately 40% higher than that of Aloe vera, suggesting greater stability of the film under fluctuating humidity and temperature conditions.

Regarding discoloration and detachment, the results reflect a differential behavior. Discoloration in paints with Aloe vera appears in week 3 for the 20%, in week 4 for the 40%, and in week 5 for the 60%. In contrast, the formulations with PVA show a slower progression, starting in week 5 for the 20% and extending to week 7 for the higher concentrations. In the case of detachment, the paints with Aloe vera show early failures in adhesion, with the first appearance at week 2 for the 20%, in week 3 for the 40%, and in week 4 for the 60%. On the other hand, the samples with PVA exhibit detachment in week 4 for the 20%, in week 5 for the 40%, and in week 6 for the 60%, indicating a 50% difference in resistance between the two binders. These results demonstrate that, while Aloe vera is a sustainable alternative, its performance against climatic factors is inferior to that of PVA, particularly concerning mechanical and chromatic stability.

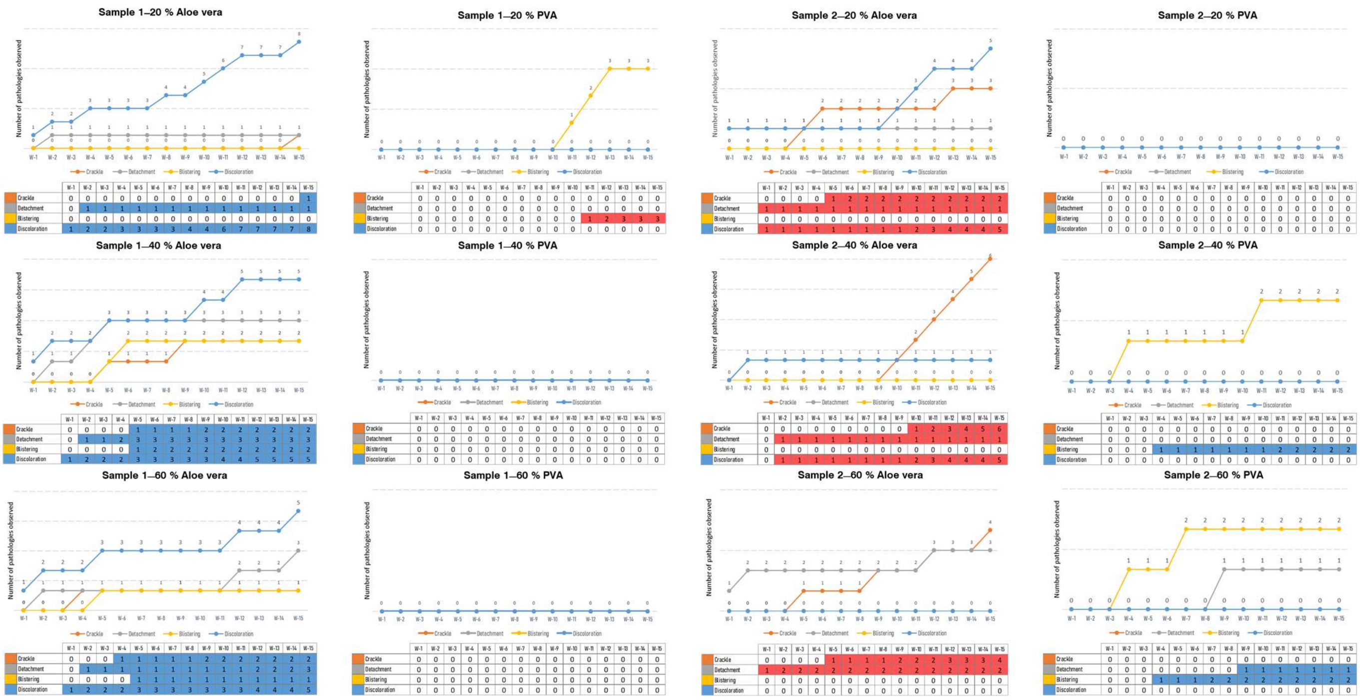

Figure 3. Pathologies due to exposure to outdoor environmental factors in Samples 01 and 02.

3.1.2. Testing of Internal Samples (See Figure 4)

Regarding cracking, the samples with Aloe vera show the first appearance in week 4 for the 20% binder, while for the 40% and 60% concentrations, this pathology ap-pears in weeks 5 and 6, respectively. In contrast, the formulations with PVA demonstrate greater stability, with the first appearance of cracks in week 6 for the 20% and in week 7 for the 40% and 60% samples, suggesting a better structural performance of PVA under indoor conditions, with a 25% improvement in crack resistance compared to Aloe vera.

In relation to blistering, paints formulated with Aloe vera showed the first signs of this pathology in week 3 at a 20% binder concentration, in week 4 at 40%, and in week 5 at 60%. On the other hand, with formulations containing PVA, blistering is delayed by about 2 weeks, with blisters appearing in the fifth week for 20%, sixth week for 40%, and seventh week for 60%. This behavior reveals that the resistance of PVA to the incipient blistering is 40% higher than that for Aloe vera, emphasizing its better stability in humidity and controlled indoor environments.

Regarding discoloration and delamination, a differentiated pattern is observed. Discoloration in paints with Aloe vera appears in week 3 for 20%, in week 4 for 40%, and in week 5 for 60%, while in formulations with PVA, it manifests later, starting in week 5 for 20% and extending until week 7 for higher concentrations. Concerning delamination, paints with Aloe vera show adhesion failures in week 3 for 20%, in week 4 for 40%, and in week 5 for 60%, whereas samples with PVA demonstrate this pathology in week 5 for 20%, in week 6 for 40%, and in week 7 for 60%, indicating a 50% increase in the resistance of PVA compared to Aloe vera. These results suggest that although Aloe vera is a sustainable alternative, its performance is inferior compared to PVA, particularly in chromatic and mechanical stability within indoor environments.

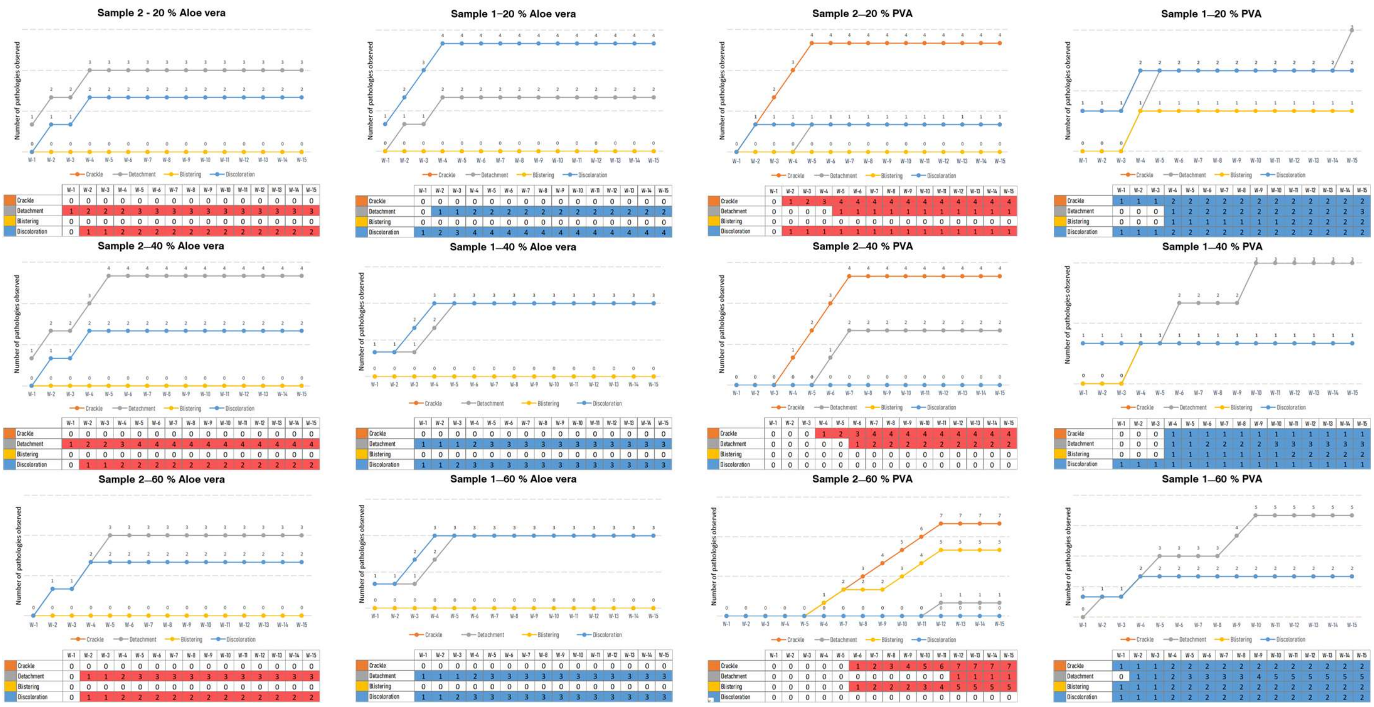

Figure 4. Pathologies due to exposure to indoor environmental factors in Samples 01 and 02.

3.1.3. Pathologies in Lime and Latex Paint Due to Exposure to Indoor and Outdoor Environmental Factors (See Figure 5)

To evaluate the comparative performance, two reference coatings were included alongside the experimental samples: a traditional lime plaster prepared according to historical formulations (hydrated lime mixed with sieved local sand in a 1:2 ratio, applied in two coats), and a commercially available synthetic latex paint widely used in local restoration projects (labeled in Results as “latex duck paint”). Both were applied to identical substrates and subjected to the same exposure conditions.

Under both indoor and outdoor exposure, the latex paint showed a steady, gradual increase in surface degradation, with accumulated pathologies not exceeding 10% after 15 weeks of observation. In contrast, lime plaster experienced a more rapid rate of deterioration, with pathologies accelerating after week 6 and surpassing 40% accumulated damage by week 15. This indicates the lower resilience of lime plaster under fluctuating environmental conditions, particularly without sufficient drying periods.

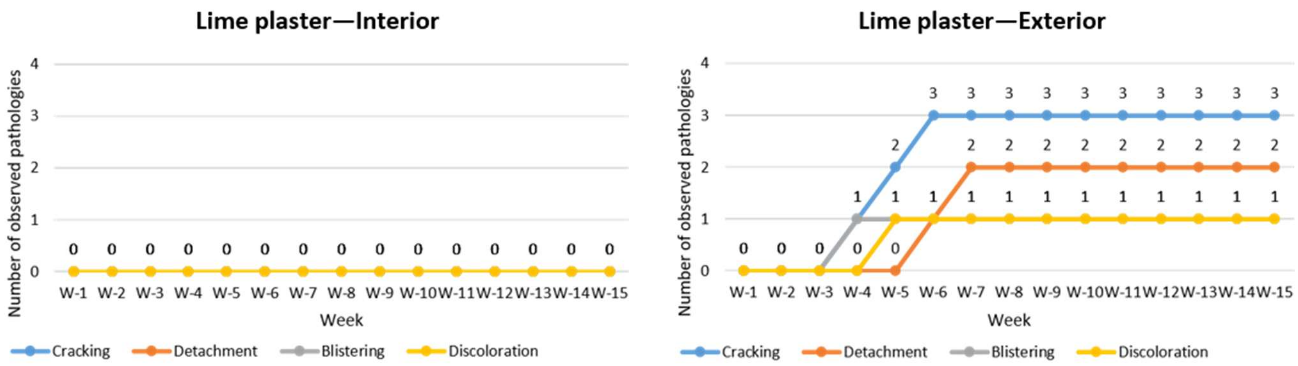

Figure 5. *Cont.*

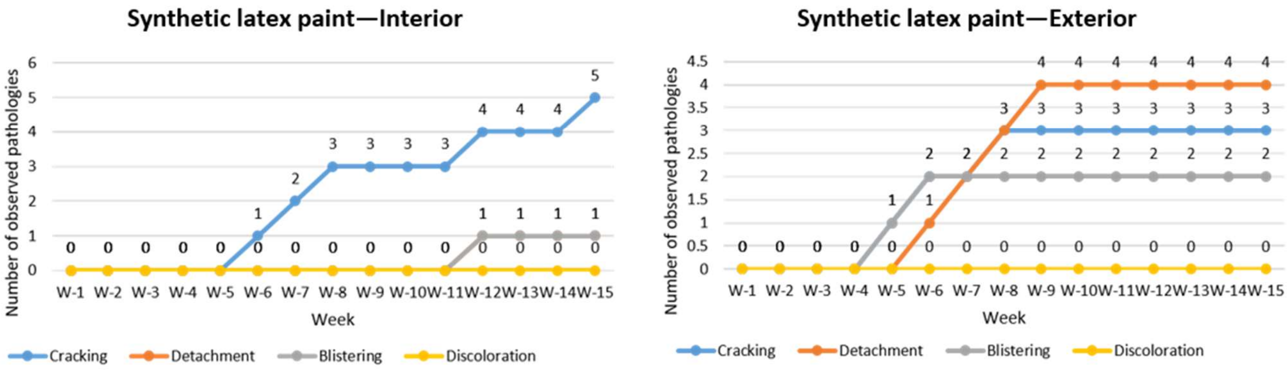

Figure 5. Pathologies in lime and latex paint due to exposure to environmental factors indoors and outdoors.

3.1.4. ASTM D3359 Adhesion Test (See Table 2)

The adhesion test according to ASTM D3359 [28] evaluates the resistance of paints to removal under controlled conditions. The results show that formulations with synthetic binder (PVA) exhibit the best adhesion, achieving 5B in all samples, which indicates that no perceptible detachment occurs. In comparison, paints with Aloe vera demonstrate inferior performance, with values ranging from 1B to 4B depending on the concentration and the source quarry. In the case of Sample 1, the formulation with 60% Aloe vera averaged 4B, while those with lower concentrations recorded values from 1B to 3B, indicating that a higher Aloe vera content improves adhesion but does not reach the levels of PVA.

In Sample 2, the results follow a similar pattern, although with a slight decrease in adhesion at lower concentrations, with values reaching up to 1B in certain repetitions. This suggests that the quality of the substrate influences the adhesion of Aloe vera, generating variability in the results. Compared to lime plaster and synthetic latex duck paint, the formulations with PVA exhibit superior adhesion, while those with Aloe vera show a performance comparable to these conventional coatings. The lime plaster obtained values from 1B to 4B, showing inconsistencies in its performance, while the synthetic latex duck paint reached values from 3B to 4B, indicating intermediate adhesion.

The statistical analysis suggests that PVA paints exhibit a consistent performance with a 60% adhesion across all concentrations and repetitions, while Aloe vera paints show a variability of 25% in adhesion depending on the quarry and the concentration of the binder. This indicates that, although Aloe vera may be a sustainable alternative, its performance in terms of adhesion is less reliable than that of PVA. Therefore, for applications where mechanical strength and durability are critical, PVA remains the best option, while Aloe vera may require optimized formulations to enhance its performance.

Table 2. ASTM D3359 adhesion test.

		M1	M2	M3
Sample 1—Aloe vera	20%	3B	2B	3B
	40%	1B	3B	3B
	60%	4B	4B	4B
Sample 1—PVA	20%	5B	5B	5B
	40%	5B	5B	5B
	60%	5B	5B	5B

Table 2. *Cont.*

		M1	M2	M3
Sample 2—Aloe Vera	20%	3B	3B	1B
	40%	3B	3B	1B
	60%	4B	4B	4B
Sample 2—PVA	20%	5B	5B	4B
	40%	5B	5B	5B
	60%	5B	5B	5B
Lime Plaster		1B	3B	3B
Synthetic duck latex		3B	2B	3B

Note: According to the ASTM D3359 standard, adhesion is evaluated by making a lattice pattern cut into the paint film and applying adhesive tape over it. The degree of paint removal upon tape removal determines the rating, on a scale from 0B (greater than 65% removal, poor adhesion) to 5B (no removal, excellent adhesion). The higher the rating, the better the paint adheres to the substrate.

3.1.5. ASTM D3363 Hardness Test (See Table 3)

The ASTM D3363 [30] tests demonstrate that paints with synthetic binder (PVA) show consistent and improved resistance across all proportions and executions, achieving a 6H rating for both types of pigments. This indicates remarkable mechanical resistance and pigment adhesion to the surface, making PVA an excellent choice for applications where durability is essential. In contrast, formulations with Aloe vera show greater variability, especially in Sample 2, where the values range between B and 6H depending on the concentration, suggesting lower stability in the formation of the paint film.

The comparative study reveals that Sample 1 with Aloe vera exhibits superior performance in hardness, reaching up to 6H at a concentration of 60%, although it varies at lower concentrations. Additionally, Sample 2 with Aloe vera shows a wider dispersion of values, suggesting less uniformity in the paint film structure, likely attributable to variations in pigment mixing or its interaction with the binder. This diversity suggests that, although aloe vera may contribute to supporting the paint film, its substantial formula requires adjustment to improve adhesion and surface resistance.

Compared to conventional materials, lime plaster exhibits lower hardness values, ranging from B to 5H, indicating reduced mechanical resistance to scratching com-pared to PVA paints. Similarly, the synthetic dust artwork expresses even more reduced values, with a hardness that ranges between 3B and 4B, confirming its lower resistance. The results highlight the suitability of PVA as a robust adhesive, although the Aloe vera plant, with its promising capacity, needs refinement to increase its cohesion and firmness.

Table 3. ASTM D3363 hardness test.

		M1	M2	M3
Sample 1—Aloe vera	20%	5H	3H	HB-F-2H-3H
	40%	6H	3H-4H	3H-4H-5H-6H
	60%	6H	6H	6H
Sample 1—PVA	20%	6H	6H	6H
	40%	6H	6H	6H
	60%	6H	6H	6H

Table 3. *Cont.*

		M1	M2	M3
Sample 2—Aloe Vera	20%	2B-3H-6H	3H	F-3H-6H
	40%	5H-6H	6H	3H-6H
	60%	B-HB-F-H-2H-3H-4H-5H-6H	HB-2H-3H-6H	4H-6H
Sample 2—PVA	20%	F-2H-5H-6H	6H	6H
	40%	6H	6H	6H
	60%	6H	6H	6H
Lime Plaster		2H	B	5H
Synthetic duck latex		3H	4B	3B

3.1.6. Analysis of Variance on Drying Time Tests (See Table 4 and Figure 6)

Table 4 summarizes the average drying times and variances for each formulation. It can be observed that paint mixtures with Aloe vera take longer to dry and exhibit greater dispersion, particularly for Sample 2. On the other hand, formulations with PVA display faster and more consistent drying times, especially for Sample 1. These trends, while visually observable in the tabulated data, were not statistically significant according to the ANOVA test ($p > 0.05$).

The results show that the drying times are significantly different depending on the type of binder used and the concentration of the binder used for the drying process. It is noted that the size of the binder is significantly larger in the drying times compared to the standard drying times. In general, paint mixtures with Aloe vera take longer to dry and show more differences, especially in Experiment 2, where the dispersion is maximum with a variance value of 6433 at 20% Aloe vera. This suggests that Aloe vera, being a natural binder, produces films that dry more slowly and are more sensitive to environmental conditions.

On the other hand, formulations with PVA show a tendency for faster and more uniform drying times, particularly for Sample 1, where the variance values are lower (ranging from 3 to 10.91). However, for Sample 2, the drying times tend to increase while dispersion becomes greater, indicating that the interaction of PVA with the pigments from this quarry may influence the homogeneity of the drying process.

Lime plaster presents intermediate drying times (8–9 min) with moderate variability, which is consistent with its traditional behavior in construction. Meanwhile, latex paint shows the fastest and most stable drying times (6–7 min, with a variance of only 0.5–4.5), confirming its high efficiency in film formation and rapid water evaporation.

Table 4. Analysis of variance on drying time tests.

Sample	Average Drying (Min)	Variance (Max–Min)	General Trend
Sample 1—20% Aloe Vera	9–10 min	16–34.33	Moderate variability, stable times
Sample 1—40% Aloe Vera	12–13 min	8.25–20.25	Longer drying time with less variability
Sample 1—60% Aloe Vera	9–13 min	24.66–55.58	Increase in variability with higher concentration
Sample 2—20% Aloe Vera	12 min	56.33–64.33	Longer drying time and high dispersion
Sample 2—40% Aloe Vera	13–14 min	32.91–48.91	Slight increase in drying, stable variance

Table 4. *Cont.*

Sample	Average Drying (Min)	Variance (Max–Min)	General Trend
Sample 2—60% Aloe Vera	13 min	32.91–49.58	Uniform drying but with greater dispersion
Sample 1—20% PVA	5–6 min	3–6.33	Fast drying with minimal variability
Sample 1—40% PVA	8 min	5.58–8.25	Stable drying with slight dispersion
Sample 1—60% PVA	8–9 min	2.25–10.91	More uniform drying with low dispersion
Sample 2—20% PVA	12–13 min	30.91–54.25	Longer drying time and significant variability
Sample 2—40% PVA	12–13 min	30.91–54.25	Behavior similar to 60%
Sample 2—60% PVA	13–14 min	32.91–55.00	Trend toward longer drying times
Lime Plaster	8–9 min	17.33–26.33	Moderate drying with medium dispersion
Duck latex synthetic paint	6–7 min	0.5–4.5	Shorter drying time and high uniformity

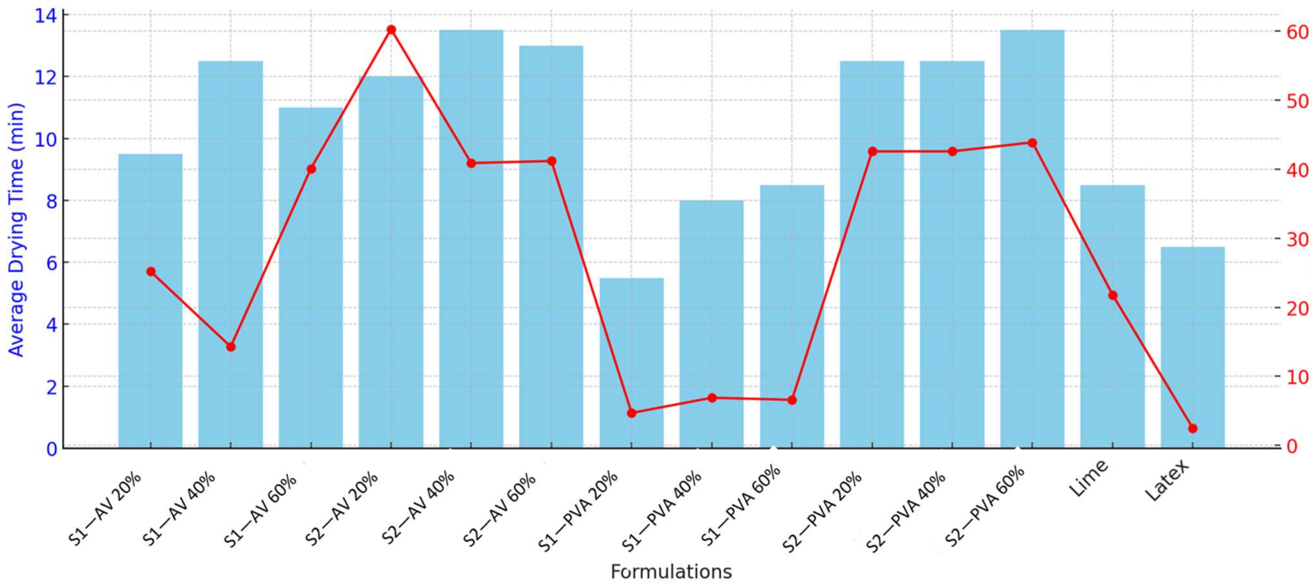

Figure 6. Average drying time and variance by formulation.

4. Discussion

The results obtained in this study show that paints formulated with inorganic pigments and synthetic binders (PVA) have a better overall performance in terms of adhesion, hardness, and drying time compared to traditional lime plaster and formulations with natural binders such as Aloe vera. These observations are in line with previous studies by Salto Llivichuzhcaand Zhagui Chunchi (2018) [24], which pointed to greater mechanical resistance and moisture stability in paints with synthetic polymers compared to those that use organic binders such as prickly pear mucilage or animal collagen.

As for adhesion, evaluated by ASTM D3359 [28], the 5B values achieved by PVA formulations confirm a strong cohesion of the paint film with the substrate, with no visible loss of material after the adhesive tape test. This behavior suggests a strong physical and chemical interaction between the polymer and the mineral particles, which facilitates the formation of a continuous, adherent film, particularly on porous surfaces such as adobe or lime mortar; on the contrary, formulations with Aloe vera show variable adhesion (1B to 4B), possibly attributable to the colloidal and more hydrophilic nature of this natural binder, which can limit the penetration of the binder into the pores of the substrate and generate a weaker interface. This behavior is consistent with what was described by Quispe (2021) [26], who identified important differences in the adhesion of natural formulations under high humidity conditions.

Regarding the hardness of the film (ASTM D3363) [30], the results show that the PVA coatings reach levels up to 6H in both samples, indicating high scratch resistance. This behavior can be explained by the formation of a rigid polymeric matrix, where the pigment particles are encapsulated and firmly cohesive, increasing the mechanical resistance. In contrast, formulations with Aloe vera have a greater dispersion in hardness values (B to 6H), which may be due to the variability in the distribution of mucilage during mixing or to the low structural cross-linking of the natural polymer, which forms a less dense film. This difference has important implications in heritage environments subject to abrasion or frequent handling.

Drying time (ASTM D1640) [29] also showed a significant advantage of PVA paints, with lower mean times and lower variability, especially for Sample 1 (red pigment). This is operationally critical, as a shorter drying time speeds up restoration processes and reduces exposure to contaminants during application; on the other hand, formulations with Aloe vera have longer and more dispersed times, particularly for sample 2 (yellow pigment), which suggests a greater sensitivity to environmental conditions. The chemistry of Aloe vera mucilage, rich in polysaccharides and with a high capacity for water retention, can slow down the evaporation of the solvent, affecting drying and generating inconsistencies in the formation of the film.

It is relevant to note that, although lime coatings show some aesthetic and textural compatibility with historical materials, their mechanical properties are inferior compared to paints formulated with inorganic pigments and synthetic binders. The hardness values between B and 2H and the variable adhesion observed in the tests reflect the vulnerability of the lime plaster to humidity cycles, intense solar radiation, and sudden thermal changes, common conditions in Andean regions such as Cusco; studies have reported similar results when evaluating lime-based formulations against more modern alternatives in exposed heritage contexts.

From the point of view of compatibility with traditional substrates, the inorganic pigments used (of mineral origin and extracted locally) have a chemical affinity with historical materials, which minimizes the risk of adverse reactions such as efflorescence, salt migration, or delamination, this compatibility is essential to prevent the loss of original material and preserve the physical integrity of historic walls; however, further studies of accelerated aging and microanalysis are needed to evaluate the long-term interaction between the pigments and binders used, particularly when using synthetic polymers such as PVA, which could limit the breathability of the substrate under certain conditions.

Likewise, although Aloe vera is a sustainable alternative with low environmental impact, its lower mechanical performance and variability in its results suggest the need to optimize its formulation, possibly by adding natural stabilizers or combinations with low-viscosity polymers that improve film formation without compromising the reversibility or compatibility with the original materials.

This research provides concrete technical evidence on the potential of these paints as viable and sustainable alternatives to lime plastering in heritage contexts, contributing to the discussion on preventive conservation with accessible materials with low environmental impact. The combination of local inorganic pigments with binders of different origin offers a range of solutions adaptable to the particular conditions of the built heritage in high mountain regions such as Cusco.

5. Conclusions

Paints made with inorganic pigments, whether using natural or synthetic binders, are a viable alternative to lime stucco, demonstrating great aesthetic and technical compatibility. In some cases, these formulations even surpass lime stucco in terms of mechanical and physicochemical properties. However, it is crucial to consider the limitations in the functional compatibility of natural binders, as well as the environmental impact and maintenance requirements associated with synthetic binders. Following the sustainability principles of the Florence Charter, paints that use inorganic pigments and natural binders have a low environmental impact, making them an ideal option for heritage conservation.

From the perspective of the Nara Document on Authenticity [31], traditional lime plaster meets the requirements for aesthetic, technical, and functional compatibility, ensuring that the appearance, cultural significance, and original protective functions of heritage buildings are preserved. Paints with inorganic pigments and different types of binders also demonstrate high compatibility in both aesthetic and technical terms; however, natural binders may have certain functional deficiencies that could jeopardize the protection of the original material. According to the principles of the Burra Charter [32], both lime plaster and paints with natural binders require minimal maintenance, which promotes their ongoing and long-term conservation. In contrast, paints with synthetic binders require moderate maintenance and entail intermediate costs [31] (Nara Document on Authenticity, 1994).

The analysis of reversibility requirements, according to the principles of Cesare Brandi's Theory of Restoration [33], indicates that both lime plaster and paints with inorganic pigments and natural binders possess a high degree of reversibility, allowing their removal without compromising the adobe substrate (Florence Charter, 1982). This characteristic preserves the material unity of the heritage asset and facilitates future restoration interventions. In contrast, paints with synthetic binders exhibit moderate reversibility, which implies a certain risk of substrate deterioration and limits their suitability for subsequent restoration processes. According to the guidelines of the Florence Charter [34], formulations with inorganic pigments and natural binders present a reduced environmental impact due to their low emission of pollutants and the use of sustainable materials, while formulations with synthetic binders present a moderate environmental impact, associated with higher emissions and greater resource consumption [32] (Burra Charter, 2013).

Regarding the mechanical properties, the adhesion evaluation according to the ASTM D3359 [28] standard shows optimal performance in all analyzed samples. Paints with natural binders achieved values between 3B and 4B, reflecting good adhesion with minimal loss, while formulations with synthetic binders obtained a grade of 5B, indicating excellent adhesion without significant detachment. Likewise, the lime and latex-based paints exhibited behavior similar to that of the formulations with natural binder, with removals below 5%, thus confirming their optimal adhesion.

Regarding hardness (ASTM D3363) [30], inorganic pigments demonstrated greater resistance compared to lime plaster. The samples formulated with natural binder, particularly M01, maintained high levels of hardness in all dosages, suggesting remarkable wear resistance. For its part, Sample M02, with synthetic binder, recorded higher values in all analyzed proportions, outperforming the lime paints, whose hardness level was in an intermediate range.

Regarding the drying time (ASTM D1640) [29], the results indicated that paints with in-organic pigments and different types of binders constitute an effective alternative to lime plaster. The formulations with synthetic binders exhibited fast and uniform drying times, while those with natural binders, although with some variability, also showed more efficient drying times than lime plaster, whose application required a considerably prolonged time per layer. Although the ANOVA did not reveal statistically significant differences between the samples, the experimental results suggest that paints with synthetic binders offer greater efficiency in terms of drying.

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Abbreviations

The following abbreviations are used in this manuscript:

ASTM	American Society for Testing and Materials
ICOMOS	International Council on Monuments and Sites

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