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# Evaluation of the Physical and Mechanical Properties of Handmade Paints with Inorganic Pigments from Cusco According to American Society for Testing and Materials' Standards for Architectural Applications

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**Abstract:** The artisanal production of paints using inorganic pigments from the Cusco Valley is considered a sustainable alternative to the use of synthetic industrial paints. This approach not only helps reduce the environmental footprint associated with the use of volatile organic compounds (VOCs) but also utilizes local materials. The present study evaluates the physical and mechanical properties of paints obtained from natural pigments through standardized tests based on the American ASTM standards, focusing on adhesion (ASTM D-3359), drying time (ASTM D-1640), surface hardness (ASTM D-3363), and the performance of the paints when exposed to the environmental factors of Cusco (under real conditions). In this regard, the pigments were extracted from traditional quarries and processed through the sedimentation method (MS) and ball milling (MG). The produced paints were formulated with the addition of polyvinyl acetate (PVA) as a binder and water as a solvent and were applied to standardized panels. The results show that all samples meet the requirements of the technical parameters, demonstrating good adhesion, appropriate drying times, and acceptable hardness for architectural coatings, Chromatic variations (ΔE*) were recorded depending on the processing method and the level of environmental exposure, with paints containing ground pigments (MG) being more resistant to fading. This study concludes that these artisanal formulations represent a technically viable and culturally relevant alternative to industrial coatings, especially in contexts of heritage restoration or sustainable architecture.

**Keywords:** paint durability; ASTM standards; adhesion test; drying time; hardness test

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## 1. Introduction

The current manufacturing of industrial paints involves the release of volatile organic compounds (VOCs), such as xylene, benzene, and toluene, which adversely affect human health and ecosystems [1]. In contrast, the use of natural inorganic pigments and water-based binders in artisanal paints positions them as paints with a lower environmental impact and reduced toxicological risk. This approach has been studied by recent research aimed at formulating more sustainable architectural coatings [2,3]. This study aims to technically evaluate artisanal paints using pigments from the Cusco Valley, following ASTM standard procedures to verify their viability as durable architectural coatings and for heritage conservation (see Figure 1).

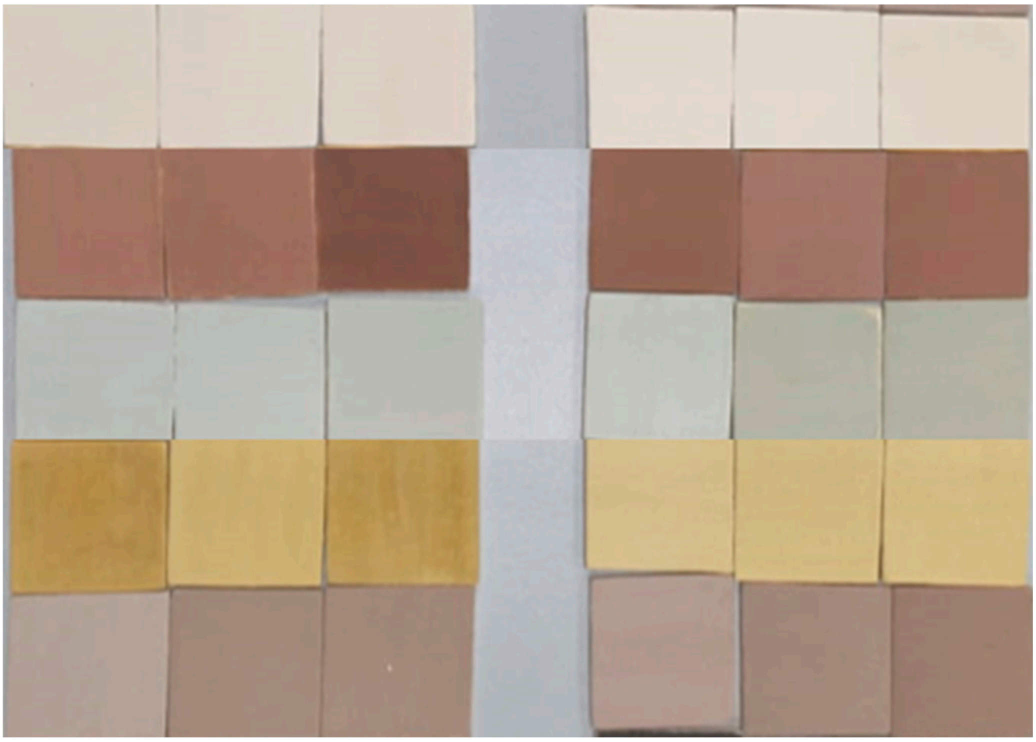

**Figure 1.** On the left are the paints (2, 6, 7, 11, and 12) formulated with pigments obtained through the sedimentation method (MS), and on the right are the paints (2, 6, 7, 11, and 12) obtained by the ball milling method (MG). Both have a dosage of 20%, 40%, and 60% of binder addition.

Researchers such as [4–6] are pioneers in studies aimed at producing environmentally friendly paints. As a result of these investigations, new technologies were developed that involved changes in the dosages of aromatic components, the replacement of pigments containing heavy metals, the transformation of solvents, and the creation of new water-based paints [7]. Some progress has been reported in the results presented by CETESB—Companhia Ambiental do Estado de Sao Paulo (2008)—which produces paints composed of two percent organic compounds and ninety-eight percent water, significantly reducing the emission of VOCs. One of the most challenging components to replace in latex paints is the various additives made up of formaldehyde and acetaldehyde; despite the substitution of other compounds, these still produce VOCs.

The production of paint based on earth pigments is currently being studied in depth, as seen in the experience of the "Earth Colors" project, which conducts research related to the industrial production of these paints at the Federal University of Vicosa. In this process, binders such as carpenter's glue or polyvinyl acetate (PVAc) are added, and these are evaluated against the standards of the American Society for Testing and Materials (ASTM) [8].

The origin of the natural inorganic pigment mainly comes from soil quarries through slow processes of modification of the elemental minerals in the molding rocks present in secondary minerals due to the phenomenon of weathering; this phenomenon results from the alloying of partially modified elemental minerals, as well as minerals with clay content known as secondary minerals [9].

According to [10], among the primary and secondary minerals, the clay minerals stand out as the source of the main pigments for paint production. The appearance of these pigments is due to the weathering actions on the rocks that modify the surface layer, which gradually leads to the exposure of layers known as "horizons". Their recognition is achieved through the analysis of the vertical profile that shows the different horizontal layers, referred to as the geological profile [9].

These clays consist of particles that exhibit stable chemical and physical properties across the surface of the planet. This stability provides the clays with enduring properties for their use as inputs in the construction sector, understanding that, throughout their useful life, they do not undergo significant changes in their internal properties such as colorimetry, dimension, and their chemical and mineralogical nature [9].

Within the characteristics of silicate clay particles, they present as laminar figures; therefore, they overlap through their faces, increasing the adhesion between each layer, forming a solid section that repels water. Considering soils exposed to weathering, they do not possess this property due to the high presence of gibbsite, which is introduced between layers characterized by a low level of compaction, as well as a high content of pores and high levels of permeability, thus resulting in lower resistance [11].

In Peru, and particularly in the region of Cusco, conventional industrial paints, such as acrylics and alkyds, are widely used in new constructions and in architectural maintenance processes. However, these paints contain volatile organic compounds (VOCs), such as xylene, benzene, and toluene, which negatively affect indoor air quality and are linked to an increase in respiratory diseases in urban areas. Furthermore, national production still lacks strict regulations regarding the disposal of hazardous waste associated with the paint industry, resulting in a significant environmental impact [12].

Despite regulatory advancements in other Latin American countries, Peru remains one of the few in the region where the use of lead in decorative paints has not been completely banned. In 2020, a study conducted by the NGO IPEN revealed that more than 40% of the paints analyzed in the Peruvian market exceeded internationally permitted lead levels, posing a severe risk to public health, especially for children and pregnant women [13].

In light of this situation, an alternative system is proposed based on handcrafted paints formulated with natural mineral pigments from the Cusco Valley and water-based binders such as polyvinyl acetate (PVA). These paints have little to no VOC content, which reduces their impact on health and the environment, and their local production contributes to strengthening regional economies and revaluing traditional knowledge [14].

Recent research has shown that these formulations not only meet technical standards regarding adhesion, hardness, and drying time, but also exhibit good performance against environmental exposure, making them suitable for application in heritage and sustainable architecture [15].

The research conducted by Tressmann et al. explores the utilization of marble waste as mineral fillers in artisanal paints based on earth pigments, as well as its performance as an active pigment in water-based architectural paints. The study evaluates physical–mechanical parameters such as adhesion, abrasion resistance, and surface durability under standardized conditions, demonstrating the technical viability of the waste as a functional component. The morphological and mineralogical characterization of the mixtures allowed for the establishment of relationships between the material's particle size and its behavior in architectural applications. The obtained formulations exhibited stability and competitive performance compared to commercial synthetic-based paints. The results support the use of mineral waste as sustainable inputs in the production of paints with favorable technical and environmental attributes [16].

Lopes and his team analyzed the impact of incorporating granite waste into paints formulated with earth pigments, focusing on key properties such as hiding power and abrasion resistance in architectural contexts. The research identified that the controlled addition of these wastes improves the optical and mechanical performance of the coating without compromising its stability. Through standardized tests, it was determined that certain proportions optimize opacity and durability against wear. The physicochemical characterization of the components revealed favorable interactions between the pigment matrix and the stone additive. The study supports the technical use of lithic waste as functional modifiers in sustainable mineral-based paints [17].

The same authors investigated the influence of granite residue on the weather resistance of paints made with soil pigments applied to architectural surfaces. The research included accelerated artificial aging tests and physico-chemical analyses to determine the chromatic stability and cohesion of the coating exposed to simulated weather conditions. The results showed that certain proportions of addition improve durability without compromising texture or adhesion capacity. The incorporation of the residue allowed for greater structural integrity against cycles of moisture and radiation. This study supports the use of mineral waste as a functional reinforcement in earth-based paints aimed at sustainable applications [18].

Lopes and another team conducted a comparative study between paints formulated with pigments derived from granite waste and those made with natural soil pigments, analyzing their technical performance in architectural applications. The research included standardized tests to evaluate adhesion, coverage, abrasion resistance, and durability against environmental factors. The results revealed significant differences in covering ability and color stability, depending on the mineral origin of the pigment. The paints with granite waste exhibited better mechanical resistance without compromising artisanal application. This comparative analysis contributes to the selection of mineral inputs based on their physical performance in sustainable coatings [19].

Quiteño developed a proposal for artisanal paint using local soils from the western region of El Salvador as a material for the surface protection of adobe walls in rural contexts; the study included the granulometric and mineralogical characterization of the samples, as well as the empirical evaluation of their adhesion, permeability, and behavior against weathering. The formulation was based on low-cost and easily accessible materials, prioritizing compatibility with raw earth substrates. Field tests demonstrated that the mixtures offer acceptable performance under variable climatic conditions, and this experience highlights the potential of earth-based paints as sustainable solutions in vernacular architecture [18].

Maulana and his team developed a technical procedure for the production of natural water-based paint using non-toxic inorganic materials and plant-based binders with stabilizing properties. The process included controlled dispersion of the pigment, optimization of viscosity, and evaluation of resistance to peeling on different porous surfaces. The final formulation exhibited good adhesion, environmental compatibility, and notable color coverage capability. The methodological design integrated safety criteria for use in inhabited interiors. This technological proposal demonstrates the potential of eco-friendly paints in artisanal and architectural application contexts [20].

Faria, Schmid, and Heringer de Miranda investigated the abrasion resistance of paints formulated with curcumin pigment and PVA resin, evaluating their performance under mechanical wear conditions; the tests demonstrated that the incorporation of curcumin improved the chromatic stability and durability of the paint film, although the wear resistance was lower than that of other formulations based on conventional inorganic pigments. The results suggest that while curcumin offers esthetic advantages, it is necessary to optimize the formula to achieve comparable performance in architectural applications; this study highlights the importance of adjusting the physical properties of paints to meet durability standards [21].

Xu and colleagues presented a data-driven approach for the development of materials intended for functional coatings, utilizing advanced methods of material analysis and optimization. The research combined computational analysis with experimental testing to evaluate the mechanical, adhesion, and durability properties of the coatings. The results highlighted the importance of precise material characterization in the formulation of functional paints with applications in various environmental conditions. This methodological approach allowed for the identification of key relationships between material compositions and their performance in high-performance coatings. The study provides a solid foundation for the research of new materials applied to architectural coatings [22].

Li and his team employed deep learning to analyze acoustic emission data in the assessment of cracks in welded joints of field bridges, developing a data clustering system to enhance the accuracy of inspections. Through this approach, a more efficient evaluation of structural integrity was achieved by identifying patterns in the acoustic data that indicated potential failures. The research highlights the potential of machine learning techniques in improving traditional material inspection methods, suggesting an application of these approaches in assessing the mechanical properties of materials in coatings. The adaptability of this methodology could optimize the classification of defects in architectural paints [23].

Xia and colleagues proposed an approach based on Building Information Modeling (BIM) and climbing robots for planning inspection routes of surfaces on cable-stayed bridge towers, enhancing coverage and accuracy in the assessment of structures; their research integrated path planning algorithms with automated systems, enabling more efficient and comprehensive inspections of hard-to-reach surfaces. This innovative system facilitated defect detection and continuous monitoring of structural integrity, suggesting potential applications in quality control and the durability of architectural coatings. The results demonstrated the effectiveness of the technology in conducting detailed inspections without direct human intervention [24].

## 2. Materials and Methods

### *2.1. Extraction and Processing of Pigments*

#### 2.1.1. Selection of Pigment Sources

The pigments were obtained from traditional quarries in the Cusco Valley, identified by their historical use in the production of natural paints. A stratified sampling was conducted to ensure the representativeness of the different tones and mineral compositions present in the area.

#### 2.1.2. Pigment Processing Methods

To assess the influence of the preparation method on the performance of the paint, the pigments were processed using two distinct techniques:

- Sedimentation method (MS): the extracted materials were suspended in water and left at rest to allow particle separation by density. The settled material was then filtered and dried;
- Ball milling method (MG): a high-energy ball mill was used, operating at 300 rpm for 2 h, with the aim of achieving a finer and more homogeneous particle size distribution.

### *2.2. Formulation of Paints*

#### 2.2.1. Components of the Paint

The paints were formulated considering pigments sourced from processed samples, polyvinyl acetate (PVA) as a synthetic binder due to its stability and compatibility with inorganic pigments, and water as a natural dispersing medium.

#### 2.2.2. Mixing and Preparation Process

Each paint was formulated with a ratio of 2:1:2 (pigment–binder–solvent, by weight). The mixture was homogenized using a mechanical disperser at 1500 rpm for 10 min to ensure uniform particle distribution. Afterwards, the samples were stored in airtight containers and aged for 48 h before application.

#### 2.2.3. Application on Test Panels

The paints were applied to standardized panels of cement–sand mortar (100 × 150 mm) using a 3 mil (75 µm) spatula to ensure a uniform thickness. Subsequently, the panels were cured under controlled conditions of 23 ± 2 °C and 50 ± 5% relative humidity for 7 days prior to quality testing.

The samples were placed on inclined easels at a 45° angle facing north, maximizing their exposure to solar radiation, rainfall, winds, and variations in temperature and humidity. Throughout this study, periodic recordings of the condition of the pictorial surfaces were made, documenting the appearance and progression of pathologies such as cracking, detachment, blistering, and discoloration. Visual and digital analysis methods were employed to quantify the deterioration at different intervals (15 weeks), allowing for the comparison of the resistance of the evaluated formulations.

### *2.3. Environmental Exposure Testing and Pathology Assessment*

#### 2.3.1. Atmospheric Factor Exposure Testing (Natural Durability)

To evaluate the physical behavior of paints against weather conditions, 28 samples (14 per processing method: sedimentation—MS—and grinding—MG) were exposed for 15 weeks under natural conditions in the city of Cusco (3400 m.a.s.l.), characterized by high UV radiation, thermal variation, and relative humidity. The samples were mounted on panels tilted at 45° facing north, according to ASTM D5722-22 [25]. (Practice for Environmental Exposure Testing). Visible changes were documented weekly through high-resolution photographic records and technical datasheets.

#### 2.3.2. Pathology Assessment: Cracking, Delamination, and Blistering

To quantify the pathologies, a standardized visual evaluation grid was applied, based on criteria adapted from ASTM D714-02 [26] (blistering), ASTM D661 [27] (cracking), and ASTM D662 [28] (flaking or detachment). A standard observation area of 5 × 5 cm was defined for each sample.

The pathologies were quantified as the number of visible deterioration units per area, considering cracks, detachments, or bubbles (blisters). Each deterioration unit was defined as a visible defect equal to or greater than 0.5 mm (crack or detachment) or 0.3 mm (blister), following criteria for digital optical measurement.

The quantification was carried out at weekly intervals, accumulating values up to S15. The data were expressed as a cumulative deterioration index, without physical units, but based on standardized and controlled counting.

#### 2.3.3. Measurement of Chromatic Discoloration

The decrease or loss of color was measured using a portable spectrophotometer X-Rite Capsure 2.0, which was adjusted and calibrated with a standard white reference according to ASTM D2244-16 [29] (Standard Practice for Calculation of Color Tolerances). Measurements were taken for each type of sample before exposure (week 0) and at intervals spaced 3 weeks apart (S3, S6, S9, S12, and S15).

The color system used was CIELAB, and the discoloration was quantified using the $\Delta E^*$ index (Delta E), which represents the difference between two color measurements in $L^*$, a*, and b* coordinates. A ΔE* ≥ 1 indicates a perceptible difference; ΔE* > 5 is considered severe discoloration.

The results were expressed as accumulated ΔE* values by samples and presented in graphs as temporal evolution. This value is a standardized dimensionless magnitude used in studies of chromatic stability.

#### 2.3.4. Design of the Exposure Test and Sample Coding (See Table 1)

To evaluate the behavior of the paints against environmental factors, 28 distinct samples were prepared, differentiated by the type of processed pigment (MS: sedimentation method; MG: ball mill method) and the internal numerical formulation code (e.g., 02, 06, and 14), which corresponds to the batch and proportion of pigment and binder. Thus, "MS-02" corresponds to sample 02, which was obtained by sedimentation, while "MG-14" refers to sample number 14, which was obtained by ball milling.

All samples were applied in the form of a homogeneous layer on cement–sand mortar panels measuring 100 × 150 mm and were exposed at a 45° angle facing north in the city of Cusco (3400 m above sea level). The exposure lasted for 15 weeks, and each week was coded as S1, S2, S3... up to S15, where S = week of continuous environmental exposure, allowing for a progressive evaluation of the pathologies.

**Table 1.** Details of paint samples and abbreviations used in the exposure test.

| Sample Code | Pigment Processing Method | Pigment Type | Binder Content (%) | Notes |
|---|---|---|---|---|
| MS-01 | Sedimentation (MS) | Natural ochre | 40 | Standard formulation |
| MS-02 | Sedimentation (MS) | Cusco red | 60 | High hematite content |
| MS-06 | Sedimentation (MS) | Yellow earth | 20 | Fine pigment |
| MS-14 | Sedimentation (MS) | Clayey brown | 40 | Variable granulometry |
| MG-02 | Ball Milling (MG) | Cusco red | 60 | High homogeneity |
| MG-06 | Ball Milling (MG) | Yellow earth | 20 | Medium dispersion |
| MG-14 | Ball Milling (MG) | Clayey brown | 40 | Well-ground pigment |

### 2.4. Quality Assessment According to ASTM Standards

The physical and mechanical properties of the paints were evaluated according to the applicable ASTM standards for architectural coatings.

#### 2.4.1. Adhesion Test (ASTM D3359—Cross-Cut Method) [30]

To measure adhesion, the cross-cut method was used, where cross cuts were made with a spacing of 1 mm on the painted surface. Adhesive tape was applied over the grid and removed at an angle of 180°. The classification was performed according to the ASTM scale, ranging from 5B (no peeling) to 0B (total peeling).

#### 2.4.2. Drying Time Assessment (ASTM D1640—Surface and Total Drying) [31]

The drying time was measured under controlled conditions:

- Surface drying: it is recommended to lightly press a dry cotton pad on the surface every 10 min until no residue remains;
- Total drying: this was evaluated by applying a standard weight of 100 g on the paint every 30 min until no marks were left.

#### 2.4.3. Hardness Test (ASTM D3363—Pencil Hardness Method) [32]

The resistance of the paint films to deformation was evaluated using the pencil hardness test. A series of calibrated pencils (from 6B to 6H) were applied with a force of 750 g at a 45° angle on the painted surface. The final hardness is determined as the hardest pencil that does not leave a mark on the paint film.

### 2.5. Ethical Considerations and Data Availability

This study does not involve human or animal subjects; thus, ethical approval was not required. All data, protocols, and materials used in this research will be available for consultation and replication upon request.

## 3. Results

### 3.1. Resistance to Atmospheric Factors in the City of Cusco

#### 3.1.1. Pathology of Cracking MS and MG (See Figure 2)

- Figure 2 shows the results of the presence of surface cracking pathology in paint samples produced with inorganic pigments obtained through the sedimentation process (MS) and ball milling (MG), respectively, exposed to real atmospheric conditions in the city of Cusco for 15 weeks (S1 to S15), which included rainy seasons (high humidity) and dry seasons (sharp temperature changes ranging from 23 °C in the morning to −3 °C at night), representing the most extreme atmospheric characteristics of this city;
- On the vertical axis, the cumulative cracking index is quantified, expressed as the total number of visible cracks per evaluated surface area. It is observed that the MS-05 and MG-05 samples exhibit the highest cracking values, with 39 and 106 cracks, respectively, at the end of the test, indicating a lower structural stability of the paint film;
- In contrast, samples such as MS-01, MS-03, MG-01, and MG-03 show a more stable response, with significantly lower cracking levels, below 20 cracks in MS and 50 cracks in MG, suggesting a greater compatibility between pigment, binder, and substrate;
- These results indicate that the choice of pigment processing method (MS-MG) has a direct relationship with the mechanical behavior of the paint samples exposed to atmospheric factors in the city of Cusco.

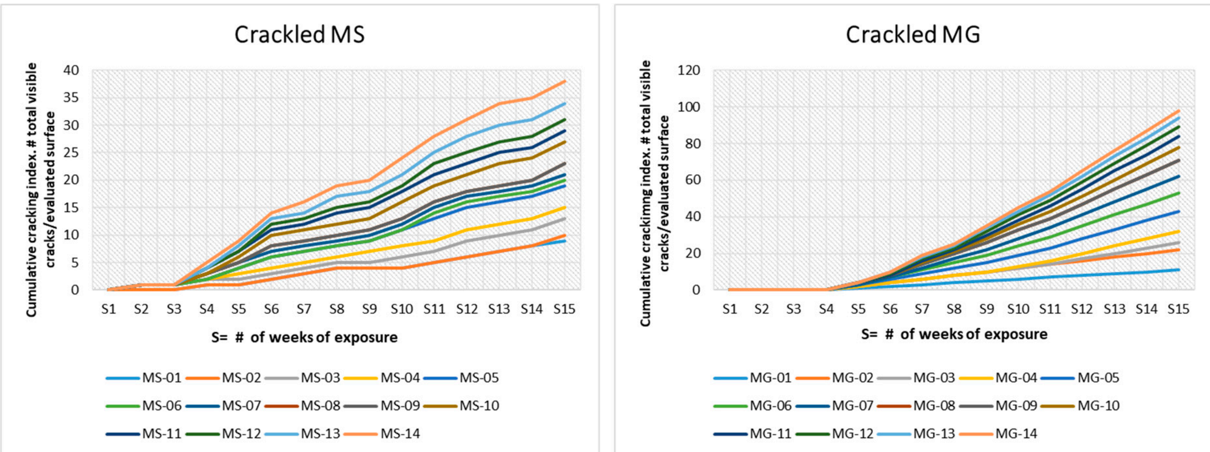


**Figure 2.** Pathologies of cracking due to exposure to atmospheric factors of paint samples made with sedimentation-derived pigment (MS) and ball milling (MG).

#### 3.1.2. Pathology of MS and MG Detachment (See Figure 3)

- Figure 3 illustrates the behavior of the paint samples in response to the delamination of paint film layers after progressive exposure to simulated environmental conditions over 15 weeks (S1 to S15), assessing the cumulative amount of delaminated areas per unit surface area. The vertical axis indicates the delamination index, measured in normalized units of affected area;
- In the samples with pigments processed by sedimentation (MS), delamination gradually increases starting from week 2, reaching a maximum of 21 units in MS-05, while the other samples remain between 11 and 19 units by the end of the test;

- On the other hand, the samples with pigments obtained through the ball milling process (MG) exhibit different behavior, as the detachment index reaches a value of 15 units from week 2 and remains almost constant until week 15 without significant increases, which demonstrates greater surface stability of the samples but with no evidence of progressive improvement;
- The milling process generates finer particles that favor effective initial adhesion, but without positive evolution against long-term environmental degradation. The method of obtaining the pigment through sedimentation shows greater variability and progression of deterioration related to the heterogeneous distribution of particle sizes, which compromises cohesion as the test progresses.

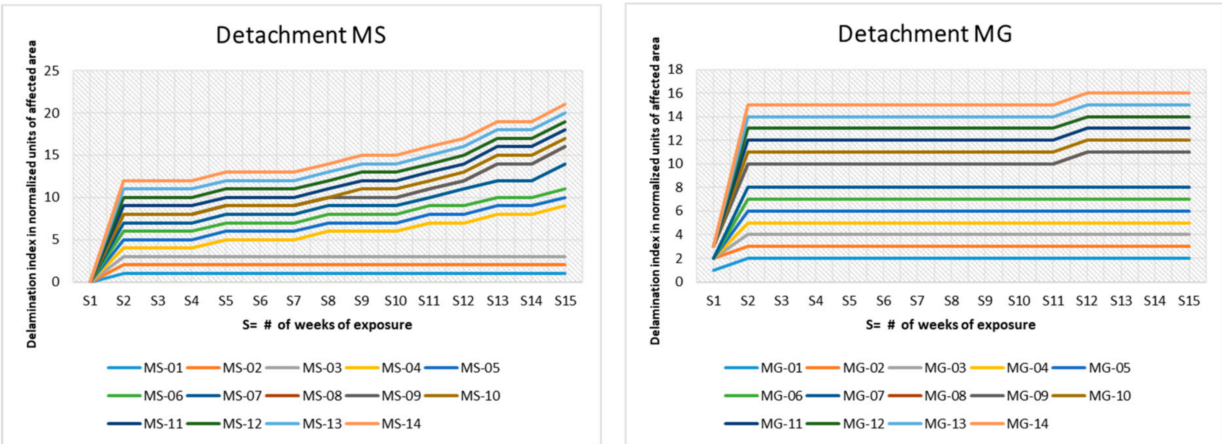


**Figure 3.** Pathologies of delamination due to exposure to atmospheric factors of paint samples manufactured with sedimentation pigments (MS) and ball milling (MG).

#### 3.1.3. Blistering Pathology MS and MG (See Figure 4)

- Figure 4 illustrates the evolution of blistering pathology in the paint films exposed to the environmental conditions of Cusco, differentiating between two methods of pigment extraction (sedimentation—MS—and ball milling—MG); the vertical axis presents a quantitative index of the number of blisters per unit area, while the horizontal axis (S1–S15) indicates the amount of exposure time (weeks);
- In the MS samples, a progressive increase in blistering is observed starting from week 2, reaching maximum values of 32 units in MS-01 and 30 in MS-05, while the less affected samples, such as MS-06 and MS-07, do not exceed 18 units;
- Additionally, the MG samples show similar evidence regarding the progression of the pathology, but with a more evident acceleration between week 5 and week 10; starting from this week, the values stabilize, reaching a maximum of 28 units in MG-01;
- On average, the MG samples exhibit blistering values between 15 and 27 units, with a standard deviation of $\pm 3.5$, suggesting greater homogeneity in response to exposure to atmospheric factors in Cusco compared to the MS samples, which record a standard deviation of $\pm 5.2$;
- The difference can be attributed to the greater granulation regularity of the pigments obtained by milling with balls, which improves the internal distribution of the coating but does not necessarily enhance its resistance to moisture accumulation; in contrast, the sedimentation technique generates more irregular surfaces with greater susceptibility to moisture accumulation, which intensifies the blistering pathology in certain samples.

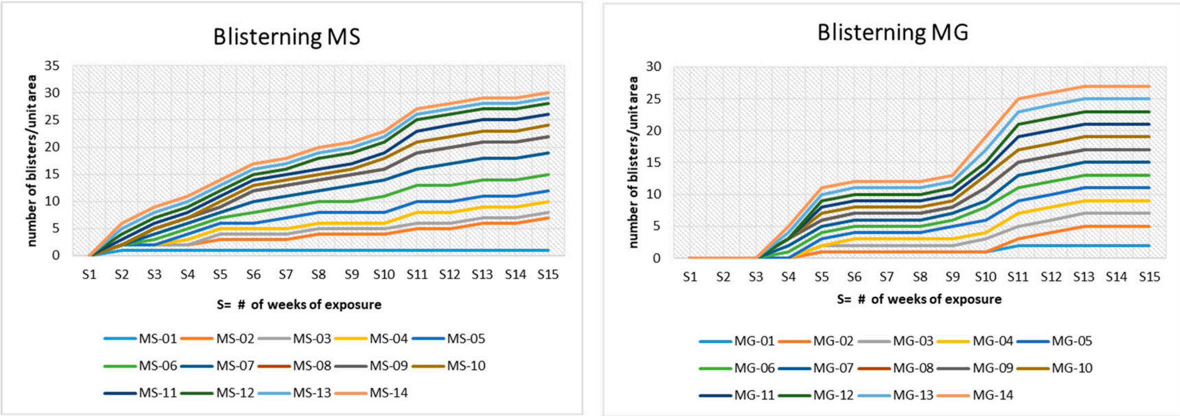


**Figure 4.** Pathologies of blistering due to exposure to atmospheric factors of paint samples manufactured with pigment obtained by sedimentation (MS) and ball mill grinding (MG).

3.1.4. MS and MG Color Degradation Pathology (See Figure 5)

- The graph shows the evolution of the decoration index ΔE* in architectural paint samples exposed to atmospheric conditions for 15 weeks, comparing inorganic pigments obtained by sedimentation (MS) and ball mill grinding (Mg);
- The MS samples have increased their initial ΔE* values from 10 to maximum values between 60 and 75 by week 15, indicating a dramatic and visually distinct color change. In contrast, the Mg samples maintained their low and stable results throughout the test, with a ΔE* varying from 10 to 14 units until week 10, slightly rising to 18 units by week 15, which is still considered moderate in terms of durability and color retention;
- Based on this result, the pigments obtained by ball mill grinding (Mg) exhibit greater resistance to photodegradation and better color stability, possibly due to improved particle size homogeneity and effectiveness in pigment dispersion within the binder; additionally, the low statistical dispersion of Mg samples compared to MS demonstrated greater reproducibility and reliability under real environmental conditions.

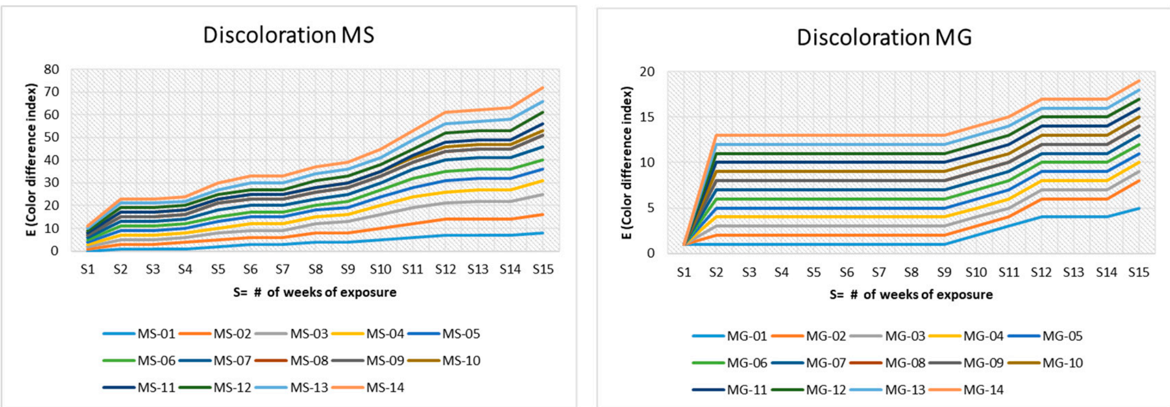


**Figure 5.** Pathologies of discoloration due to exposure to atmospheric factors of paint samples made with sedimentation pigments (MS) and ball mill grinding (MG).

3.1.5. ASTM D-1640 Drying Time 31 (See Figure 6 and Table 2)

- ASTM D1640 is a commonly used instrument that determines the drying and curing time of organic coatings at various stages, such as touch dry, hardening, and complete drying; the ASTM 1640 test investigated samples with different additions of PVA binder (20%, 40%, and 60%) applied in successive layers;

- The findings for samples M-02, M-06, M-07, M-11, and M-12 allow us to detect trends in the variation in drying time compared to the percentage of PVA and the number of layers applied; in general, the increase in the amount of PVA results in a gradual increase in drying time, as evidenced in all analyzed samples. M-07 had the highest drying times in the 60% range, with the fourth layer reaching 20 min. According to this behavior, the film produced on the surface takes longer to lose moisture due to its greater water retention and lower porosity;
- On the other hand, in samples M-02 and M-06, the drying time behavior is more variable. In M-02, the drying of the last layer for 20% PVA shows a sharp drop to 0 min, suggesting a possible complete absorption of the solvent or a difference in evaporation depending on the arrangement of the material. In contrast, sample M-06 shows a more uniform increase in drying times, highlighting the increasing trend of drying time with successive layers;
- Regarding sample M-11, a linear increasing behavior is observed in each of the layers, with drying time values depending on the accumulated thickness. This aligns with the behavior required for sample M-12, where a greater number of layers results in an average increase in drying time, with maximum values of 20 min at 60% in the fourth layer;
- Therefore, based on the results obtained, the formulation with the highest percentage of PVA and a greater number of layers dries in longer times, which should be considered when thinking about multiple layers during a coating process. On the other hand, variability was observed concerning the drying process in some of the samples; thus, it is possible to consider that factors such as substrate absorption, ambient humidity, and application uniformity can affect the solvent evaporation processes of the paint.

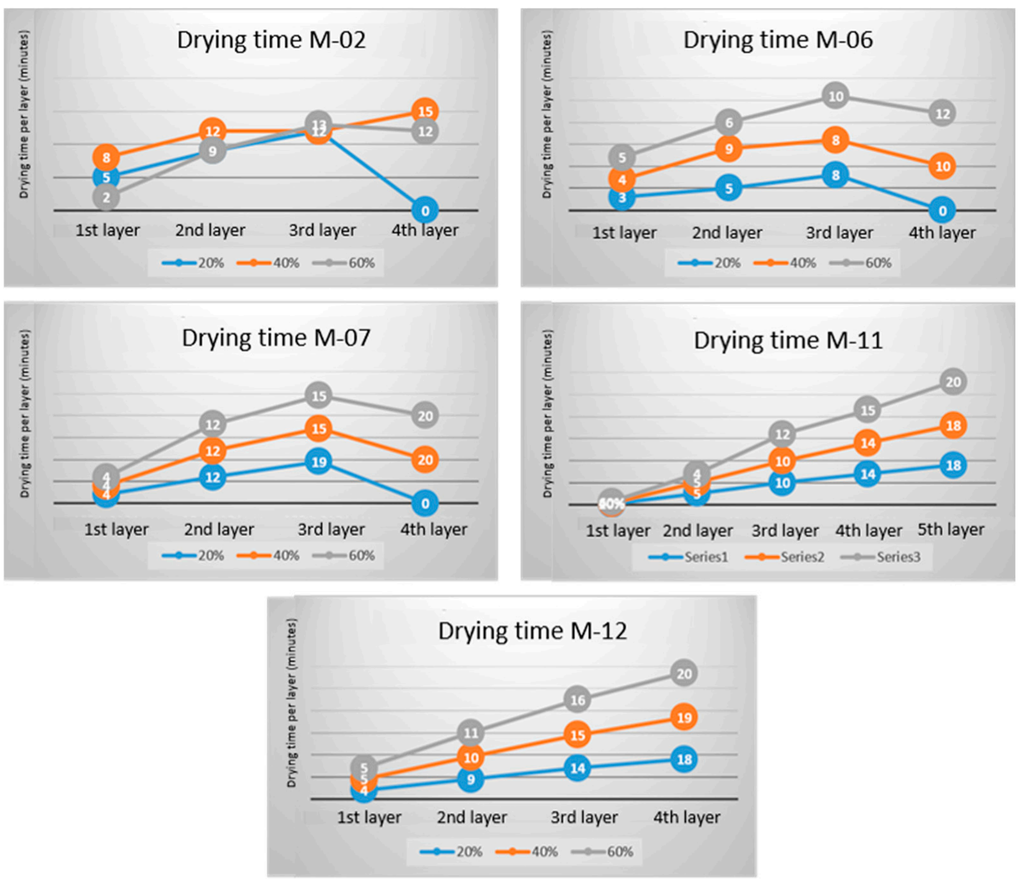


**Figure 6.** Test standard ASTM D1640 for paints produced with inorganic pigments.

**Table 2.** Comparison of drying time results of paint samples with a dosage of 60% PVA addition in samples of paints with inorganic pigments.

| | | Drying Time in Minutes | | | |
|---|---|---|---|---|---|
| | | **1st Layer (min)** | **2nd Layer (min)** | **3rd Layer (min)** | **4th Layer (min)** |
| M-02 | 20% | 5 | 9 | 12 | 0 |
| | 40% | 8 | 12 | 12 | 15 |
| | 60% | 2 | 9 | 13 | 12 |
| M-06 | 20% | 3 | 5 | 8 | 0 |
| | 40% | 4 | 9 | 8 | 10 |
| | 60% | 5 | 6 | 10 | 12 |
| M-07 | 20% | 4 | 12 | 19 | 0 |
| | 40% | 4 | 12 | 15 | 20 |
| | 60% | 4 | 12 | 15 | 20 |
| M-11 | 20% | 5 | 10 | 14 | 18 |
| | 40% | 5 | 10 | 14 | 18 |
| | 60% | 4 | 12 | 15 | 20 |
| M-12 | 20% | 4 | 9 | 14 | 18 |
| | 40% | 5 | 10 | 15 | 19 |
| | 60% | 5 | 11 | 16 | 20 |

#### 3.1.6. ASTM D-3363, Hardness [32] (See Figure 7)

- In this analysis, five samples have been considered: M-02, M-06, M-07, M-11, and M-12, with three binder dosages of 20%, 40%, and 60%, to study the applicability of such coatings as paint; generally speaking, the samples with a higher concentration of binder improve the hardness of the coating and reach optimal levels in some of them, although there are variations among the samples, reflecting different mechanical behaviors and surface resistance;
- Sample M-02: this sample shows variable hardness depending on the concentration of the binder. At 20%, the values range between 2B, 3H, and 6H, indicating low resistance at certain points. At 40%, there is an improvement reaching 5H and 6H, demonstrating an increase in resistance. At 60%, the hardness varies widely from B to 6H, suggesting inconsistencies in the formulation of the coating. Due to this variability, sample M-02 is considered optimal for manufacturing as paint by modifying the formulation to ensure uniformity in hardness;
- Sample M-06: a more stable behavior is observed compared to M-02. At 20%, the hardness is 3H, indicating acceptable resistance for basic applications. At 40%, it reaches 6H, showing significant improvement. With 60%, it presents values between HB and 6H, suggesting greater mechanical resistance. Overall, M-06 meets the hardness requirements to be considered suitable as paint, although it is recommended to evaluate the homogeneous distribution of hardness at higher concentrations of binder;
- Sample M-07: the hardness of this sample varies moderately. At 20%, it shows values ranging from 3H to 6H, indicating some resistance, although with slight variability. At 40%, it remains within a range of 3H to 6H, which indicates stability in surface hardness. With 60%, it improves slightly, reaching values between 4H and 6H. Although the sample shows a tendency to withstand a higher concentration of binder, the variability on the scale suggests the need for optimization in the formulation to ensure uniform hardness across the surface;
- Sample M-11: this sample demonstrates good stability in its hardness values. At 20%, it shows values between 2H, 5H, and 6H, which already indicates acceptable resistance. At 40% and 60%, it maintains a hardness of 6H, confirming excellent mechanical resistance and surface stability. Since the sample meets the required standards, it is

considered suitable for manufacturing as paint without the need for adjustments in its formulation;

- Sample M-12: it is the sample with the best performance in terms of hardness. At 20%, it already reaches a level of 6H, demonstrating superior resistance from the lowest concentration of binder. At 40% and 60%, it maintains the same value of 6H, suggesting excellent stability and uniformity in surface hardness. Due to its high performance, M-12 is fully suitable for manufacturing as a high-resistance paint without requiring modifications to its formulation;
- Samples M-12 and M-11 meet the requirements of the ASTM D-3363 standard and can be used for the production of paints with high scratch resistance. Sample M-06 is also suitable, although it could benefit from slight optimization. In contrast, samples M-02 and M-07 show variations in hardness that could improve their performance, so they require adjustments in their formulation to enhance their uniformity and mechanical resistance.

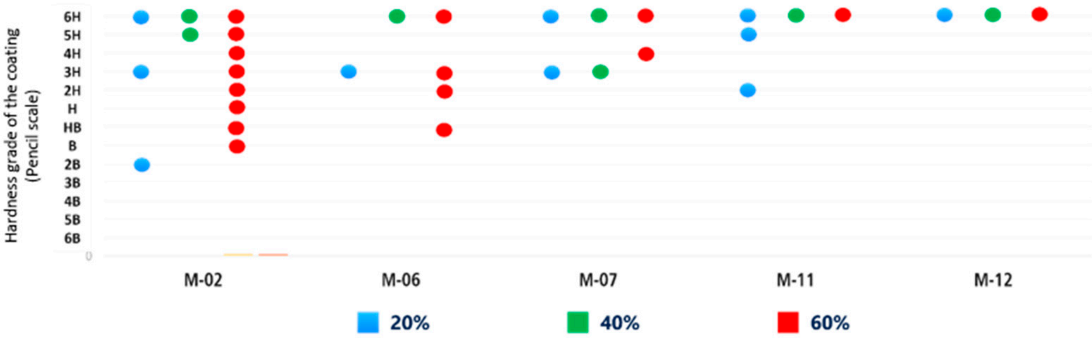


**Figure 7.** Hardness test results ASTM D-3363 (2197) for paint samples.

3.1.7. ASTM D-3359, Adhesion [30] (See Table 3)

- The ASTM D-3359 adhesion test allows for the classification of coating resistance concerning substrate separation based on a grid cut or "X" incision method (ranging from 0B to 5B, where 5B indicates maximum adhesion and 0B indicates complete failure). In this test, five samples (M-02, M-06, M-07, M-11, and M-12) with different concentrations of PVA (20%, 40%, and 60%) were used in three repetitions to determine their suitability for paint manufacturing;
- Sample M-02 shows an adhesion of 5B at all PVA concentrations (20%, 40%, and 60%), indicating that the cohesion of the coating with the substrate is very good, with no visible detachments observed in any of the repetitions; this behavior allows us to infer that the formulation of this sample is suitable for use in paint manufacturing without the need for adjustments;
- Sample M-06 also exhibits a presence of 5B at all concentrations, reaffirming the strong bond of the surface and the correct performance of the coating with stable behavior, making this sample suitable for use in paint manufacturing, meeting the requirements of the ASTM D-3359 standard;
- In the case of sample M-07, a slight variability is observed in the 20% concentration, with one repetition showing 4B, although it generally maintains values of 5B in most tests. At the 40% and 60% concentrations, the adhesion is uniform with 5B across all repetitions, indicating overall good adhesion. However, the slight variability at the lower concentration suggests the need for more precise control in the formulation;
- Sample M-11 exhibits behavior similar to M-07, with values of 5B in most concentrations; although, at the 20% concentration, a repetition shows 4B, suggesting a slight

decrease in adhesion under this condition. Nevertheless, the overall values remain high, making it suitable for paint manufacturing with reliable adhesion;

- On the other hand, sample M-12 shows the most variable results in the test. At 20% PVA, adhesion fluctuates between 2B and 3B, indicating a notable loss of cohesion between the coating and the substrate. At 40%, lower adhesion is detected with values ranging from 1B to 3B, demonstrating considerable detachment and compromising its performance. However, at 60% PVA, there is a consistent improvement in adhesion, reaching 4B, indicating a relative enhancement.

**Table 3.** Comparison of adhesion results between a paint sample with inorganic pigments.

| Sample | 1 | 2 | 3 |
|---|---|---|---|
| M-02-20% | 5B | 5B | 5B |
| M-02-40% | 5B | 5B | 5B |
| M-02-60% | 5B | 5B | 5B |
| M-06-20% | 5B | 5B | 5B |
| M-06-40% | 5B | 5B | 5B |
| M-06-60% | 5B | 5B | 5B |
| M-07-20% | 5B | 5B | 4B |
| M-07-40% | 5B | 5B | 5B |
| M-07-60% | 5B | 5B | 5B |
| M-11-20% | 5B | 5B | 4B |
| M-11-40% | 5B | 5B | 5B |
| M-11-60% | 5B | 5B | 5B |
| M-12-20% | 3B | 2B | 3B |
| M-12-40% | 1B | 3B | 3B |
| M-12-60% | 4B | 4B | 4B |

## 4. Discussion

The results obtained in this study confirm the technical viability of artisanal paints formulated with inorganic pigments from the Cusco valley when compared to what was reported by Tressmann and others, who demonstrated that mineral waste can be used as functional components in architectural paints, achieving adhesion and resistance levels comparable to commercial coatings. In both cases, the control of particle size and the compatibility between pigment and binder were crucial for achieving stable and resistant films, as reflected in this study with adhesion values of up to 5B according to ASTM D3359 standards. Furthermore, the use of polyvinyl acetate as a binder allowed for an adequate balance between internal cohesion and surface flexibility, which favored the mechanical response of the coatings under real environmental exposure conditions.

Regarding resistance to abrasion and weathering, the results align with the observations of Lopes and others, who found that the use of granite waste improves the performance of paints formulated with earth pigments by increasing their covering power and durability without compromising their surface integrity. In this study, the samples obtained by grinding balls (MG) showed a lower incidence of cracking and detachment compared to those obtained by sedimentation (MS).

The evolution of the color degradation index (ΔE*) showed that the MG samples retained their initial color better than the MS samples, which aligns with what Lopes described in his comparative study between natural pigments and granite residues, where the latter demonstrated greater stability against photodegradation due to their crystalline structure and ability to reflect ultraviolet radiation. In the present work, this color stability was attributed to the greater dispersion of the pigment within the binder in the MG samples, thereby reducing the heterogeneity of the paint film and decreasing the differential light absorption. This condition is essential in exposed architectural applications, where color permanence constitutes a criterion for visual quality and durability of the surface finish.

Regarding the drying behavior, the results revealed that the increase in binder content was associated with a longer drying time, which relates to what Yun Chi-gwan et al. described, who developed paints based on non-toxic inorganic materials and observed that the viscosity and water retention of the binder medium directly affect curing times. In the analyzed formulations, the higher percentage of PVA resulted in greater moisture retention, extending drying times without compromising the adhesion or final hardness of the coating.

## 5. Conclusions

The handmade paints formulated with inorganic pigments from Cusco comply with ASTM standards, making them a viable technical option for architectural applications. Adhesion tests, drying time, and hardness confirmed that formulations with higher PVA content exhibit better mechanical performance, although at the cost of increased drying time. It is shown that the processing method of the pigments significantly influences the stability of the coating, with ball milling being the technique that provides the best results in terms of compaction, crack resistance, and lower incidence of detachment.

The findings of this research suggest that paints formulated with pigments processed through ball milling and with an optimized proportion of PVA can be an effective alternative for heritage conservation and use in contemporary architectural coatings. However, it is recommended to continue with long-term studies to assess the durability of these coatings under extreme environmental conditions, as well as to explore the use of natural binders that may enhance the sustainability of these formulations.

In future research, it is recommended to analyze the impact of factors such as relative humidity, exposure to ultraviolet radiation, and the application of protective coatings to improve the durability of paints. Additionally, the integration of new characterization methods, such as infrared spectroscopy and advanced microscopy analysis, will provide a better understanding of degradation processes and optimize the formulation of these coatings for architectural and heritage applications.

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## Abbreviations

| Abbreviation | Meaning |
|---|---|
| ASTM | American Society for Testing and Materials |
| PVA | Polyvinyl acetate |
| VOCs | Volatile organic compounds |
| MS | Sedimentation method |
| MG | Ball milling method |
| S# | Stage number in the durability test (e.g., S1, S2, etc.) |
| UV | Ultraviolet |
| NCS | Natural Color System |
| HB | Hardness classification in pencil test (between H and B scales) |
| H | Hard (pencil hardness scale) |
| B | Black (pencil softness scale) |
| µm | Micrometer (micron) |
| RPM | Revolutions Per Minute |
| g | Gram |
| %RH | Percentage of Relative Humidity |
| C | Celsius (°C) |
| mm | Millimeter |
| µg/m³ | Micrograms per cubic meter |
| LD | Linear Dichroism |

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