



International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 03, March 2026)

Material intelligence in Ancient Mural Technology: Organic additives and Mineral aggregates in the Mud plaster of the Ajanta Caves

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Abstract-- The Ajanta Caves murals represent a amazing achievement of early Indian artistic and technical traditions. The colors and iconography displayed in these paintings are significantly more concentrated than the underlying mud plaster. The initial layers, which comprise a sophisticated blend of mineral aggregates and organic additives, have been instrumental in maintaining the durability and integrity of the mural surfaces for nearly two thousand years. This study systematically investigates the composition and functional importance of the Organic and In-organic additives used in Ajanta's mud plaster. Utilizing comprehensive review of prior scientific research and present state of the Painting. This work assesses how ancient artisans produced stable plaster bases by employing local geological resources, such as silty clay, zeolite, glauconite, calcite, and fibrous plant materials. Previous analyses using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) have demonstrated that Ajanta's plasters were deliberately enhanced with organic binding agents and mineral stabilizers, improving cohesion, tensile strength, and moisture regulation (Singh & Arbad, 2013b). Nonetheless, the technical rationale and broader implications of these additive practices for conservation and materials science require further exploration. This paper contextualizes Ajanta's plaster techniques within the wider framework of traditional building, binding materials and conservation science. This paper highlights the sophistication of historical material solutions developed from locally sourced resources. The study suggests that a deeper understanding of organic–mineral interactions is essential not only for the effective preservation of the Ajanta

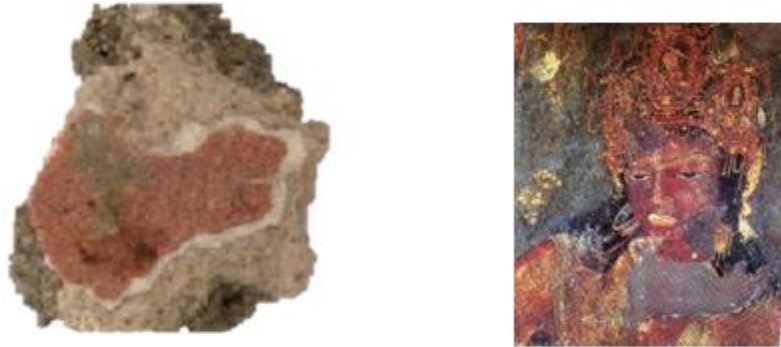
murals but also for advancing sustainable practices in contemporary conservation strategies.

Keywords-- Ajanta Caves, Mud plaster, Organic additives, Mineral aggregates, Mural conservation, and Traditional material technology.

I. INTRODUCTION

In historical mural practices, the longevity of murals depends not only on pigment stability but also on the sophisticated construction of underlying plaster layers. These foundational strata are generally comprised of advanced material systems that synthesize geological resources with organic additives, thereby improving structural integrity, adhesion, and environmental adaptability (Singh & Arbad, 2012). They focused on the conceptual frameworks and methodologies for information retrieval systems, emphasizing the critical role of user interaction and the dynamics of information seeking behavior. It discusses the evolving nature of search technologies and the importance of understanding user contexts to improve retrieval effectiveness.

Together, these studies contribute to a refine understanding of how users interact with search systems, emphasizing the integration of behavioral insights into technological designs for optimized information retrieval experiences.



Stratigraphy of Ajanta Mural Painting & Conservation Experiment source: Journal of Heritage Tourism, & Parimoo, Ratan

Figure 1 source: (Singh & Arbad, 2012).

The Ajanta Caves in Maharashtra, India, dating from the second century BCE to the sixth century CE, exemplify such technical sophistication. Carved into basalt cliffs along the Waghura River valley. These caves house extensive Buddhist, Jataka, and Bodhisattva murals (W. Spink, 2018). The remarkable preservation of which over nearly two millennia is primarily attributed to the intrinsic properties of the mud plasters underlying them Figure :1

To achieve optimal performance, support layers for murals must achieve a balance among mechanical strength, porosity, and compatibility with both pigments and the native rock substrate. Durable plasters should resist cracking, withstand environmental variability, and maintain their performance over extended periods. Attaining these criteria is particularly complex in contexts such as Ajanta, where the stone substrate consists of uneven basalt exposed to fluctuating humidity and temperature conditions(W. M. Spink, 2007). Ideally, plasters would incorporate regionally sourced clays, selected mineral aggregates, and organic binders to enhance cohesion and mitigate shrinkage(Singh & Arbad, 2013c). Nevertheless, fully explicating how ancient artisans realized this equilibrium remains a sophisticated challenge, as the apparent simplicity of mud plasters often secretes intentional and informed choices in material selection.

Initial archaeological assessments suggested that historic mud plasters were typically composed of minimally modified local clays(Somathilake, 2022;Singh & Arbad, 2014c). However, recent scientific investigations have studied this view.

Analytical studies have demonstrated that Ajanta's plaster comprises a deliberately engineered blend of silty clay, mineral aggregates, and organic elements, collectively imparting distinctive physical characteristics (Singh and Arbad, 2014;(Singh & Trambake, 2012). Granulometric analysis(Grainulograph) confirms the dominance of silt particles, constituting over 70% of the mixture, while lower proportions of clay and sand yield a medium-textured, non-plastic composition that minimizes shrinkage and upholds structural stability (Singh & Arbad, 2013d). These findings indicate purposeful selection and modification of raw materials rather than incidental usage.

Subsequent mineralogical research has identified a spectrum of aggregates, including quartz, feldspar, calcite, zeolite, and glauconite, reflecting the area's basaltic geology. These inclusions serve as more than inert fillers; they stabilize the plaster matrix. For instance, calcite may reduce shrinkage and function as a binder by forming chemical linkages among clay particles (A. Rodriguez-Navarro, 2000);(Kiyuna et al., 2011). The detection of zeolite and glauconite, which are rare in other historic plasters, further suggests strategic material selection aimed at optimizing structural attributes and moisture regulation (Singh & Arbad, 2014b);(Ozino-caligaris et al., 2008). Such evidence underscores an advanced level of material knowledge and challenges oversimplified interpretations of ancient building methods.

A significant but less thoroughly examined aspect of Ajanta's plaster technique involves the use of organic additives.



Scientific studies have identified traces of proteinaceous substances and plant fibers in the plaster matrix. Over time, these organic materials have largely decomposed, leaving detectable residual calcium oxalate through spectroscopic methods (C. Rodriguez-Navarro et al., 2007); (Singh & Arbad, 2014a). Historical research has also documented fibrous plant components, such as rice husks and plant fibers, which likely enhanced the tensile strength and minimized cracking in the plaster layers (Paramasivan, 2013). Additionally, these additives may have promoted chemical interactions with clay minerals, facilitating flocculation and improving cohesion within the mixture (Theng, 2012); (Petit, 2023). These findings indicate that ancient artisans intentionally incorporated organic materials to modify both the mechanical and chemical properties of the clay plaster, potentially reducing its overall weight.

Despite these advancements, several critical questions remain unsorted. Much of the existing research centers involved in identifying the mineral composition of the plaster or addressing conservation challenges associated with murals. While such research provides valuable technical information, it often focuses on isolated components rather than their functional relationships. Consequently, the interaction between mineral aggregates and organic additives is not fully understood. In essence, while the materials present are known, a comprehensive understanding of the rationale and methodology behind their combination is lacking. This gap limits the ability to recover the technical expertise underlying the original construction techniques.

This deficiency has implications that extend beyond historical inquiry. Conservation activities at Ajanta necessitate the development of repair materials that closely replicate the physical and chemical attributes of the original plaster. Without a thorough understanding of the interplay between organic additives and mineral aggregates, contemporary conservation materials may prove incompatible with the historical substrate. Such incompatibility can result in uneven shrinkage, moisture retention, or mechanical stress, thereby accelerating mural deterioration. Thus, elucidating the fundamental material principles governing Ajanta's plaster is crucial for both accurate historical reconstruction and effective long-term preservation. Continued research guided by ancient texts will be instrumental in advancing this understanding.

Within the broader discipline of heritage science, this issue is closely associated with the increasing interest in traditional material technologies. Ancient construction methods frequently utilized locally sourced materials with a level of sophistication that remains only partially understood by present-day engineers.

Mud plasters found at Ajanta exemplify such practices. The analytical examination of the interactions between organic binding agents, mineral aggregates, and clay mixtures facilitates an understanding of how craftsmen skillfully adapted natural materials to achieve robust structural performance. These findings have valuable implications for ongoing discussions regarding environmentally sustainable construction and conservation materials.

Considering this context, the current study investigates the functional importance of organic additives and mineral aggregates in Ajanta's mud plaster. The research adopts a holistic perspective, considering these elements as components of an integrated material system designed to satisfy specific structural and environmental criteria.

II. OBJECTIVES OF THE STUDY

This study pursues the following objectives.

- Analysis of the composition and properties of mineral aggregates in Ajanta mud plaster.
- To investigate the types and functional roles of organic additives incorporated into the plaster matrix.
- To explore the interactions between organic and mineral constituents and their contributions to mechanical stability and durability.
- To assess the influence of these traditional material strategies on contemporary conservation practices.

By addressing these objectives, this research seeks to elucidate the technical principles underlying the preparation of Ajanta plaster and demonstrate how historical knowledge systems developed effective material solutions using locally available resources.

III. LITERATURE REVIEWS

This review synthesizes current research on the material composition, execution techniques, conservation strategies, and historical significance of Ajanta's mural paintings. The study is integrating insights from scientific analysis, conservation documentation, and art historical studies. The technical complexity of historic plaster systems has attracted attention in interdisciplinary fields, such as conservation science, archaeology, and materials engineering. Clay plasters are complex composites in which a clay matrix, mineral aggregates, and organic additives combine to form surfaces that are both structurally strong and responsive to decorative finishes. Understanding these systems is crucial not only for heritage conservation but also for understanding the technical knowledge underlying traditional building practices.



In the context of the Ajanta Caves, studying the composition of plaster is particularly important because the preservation of the famous murals directly depends on the stability of the underlying layers of plaster.

Publication Trend and Growth Research in Conservation of Ajanta has evolved through three distinct "waves". First was Historical Phase (1819–1950s) Dominated by descriptive reports, artist copies (John Griffiths, Lady Herringham), and early interventions (Italian restorers Cecconi and Orsini). Second phase was Scientific Consolidation (1953–2000). This phase were focus shifted to the chemical composition of pigments and binders, spearheaded by the Archaeological Survey of India (ASI) Science Branch. Third phase is Multidisciplinary & Digital Phase (2000–2026). This phase focused on High-growth period utilizing non-destructive testing (NDT), AI-driven digital restoration, and environmental monitoring.

A co-occurrence analysis of keywords in the literature highlights the different primary clusters on Ajanta's Material Science wherein concentrated on Tempera technique, Mud plaster, Earth pigments, Lapis lazuli, Organic binders. Deteriorating agents of Ajanta painting is Micro-climatic fluctuation, Relative humidity, Bat excreta, Bio-deterioration, Shellac varnish (past interventions). Conservation Methodology of Ajanta were Chemical cleaning, Consolidation, Laser cleaning, Nanotechnology, Micro-emulsions. Now focusing on 3D Scanning, Infrared Reflectography, AI-based pixel restoration.

Literature is centered around a few key institutional hubs and prolific authors role and Impact Archaeological Survey of India (ASI) The primary governing body; responsible for the majority of technical field reports. Manager Rajdeo Singh One of the most prolific Indian authors; focuses on the chemistry of preservation and material analysis. Walter Spink is an art historian, his chronological research (Ajanta Archive) provides the structural framework for conservation timelines. Istituto Centrale per il Restauro (Italy) Key international collaborator on technical documentation and Non Destructive Technique. Research is typically found in specialized conservation and heritage journals Studies in Conservation (IIC), International Journal of Conservation Science (IJCS), Journal of Archaeological Science and Heritage (MDPI) Journal of Cultural Heritage

Archaeologists contextualize these scientific findings within historical construction practices, shedding light on the evolution of building technologies and their relationship to artistic developments. Materials engineers investigate the mechanical properties of the plaster, such as compressive and tensile strength, to inform restoration approaches and ensure the structural integrity of the murals.

A concrete illustration of these collaborative efforts is provided by recent X-ray diffraction studies, which have identified the presence of calcium carbonate in Ajanta plasters. Calcium carbonate not only enhances the durability of the plaster but also influences the selection of conservation materials and techniques. Moreover, innovations in plaster technology such as the deliberate inclusion of mineral aggregates and organic additives have been linked to shifts in mural styles and techniques at Ajanta across various historical periods (Dighe & Singh, 2025); (Kiyuna et al., 2008). By integrating scientific analyses with historical and archaeological insights, researchers can trace how technical advancements in plaster preparation supported both the preservation and evolution of Ajanta's artistic legacy. Understanding these interdisciplinary contributions is essential for heritage professionals, researchers, and students seeking to preserve and interpret the material and artistic achievements of the Ajanta Caves.

The logic of traditional mud plaster and composite materials

Mud plasters have historically been produced by combining locally sourced clay with sand, crushed stone, and organic fibers. The earthen plaster of Ajanta is characterized by deliberately selected materials indicating sophisticated understanding of construction materials. Studies reveal that the plaster contains high silt (>75%), low clay content, and raw materials likely sourced from the Waghura River bed adjacent to the caves (Singh & Arbad, 2015). The composition includes high percentages of silt with specific gravity ranging from 2.70–2.90 and deliberately added lime (calcite) to enhance cementing characteristics (Singh & Arbad, 2014c). Notably, Proteic materials mixed with vegetal fibers and seeds were incorporated into the plaster composition. The presence of calcium oxalate detected in FTIR spectra indicates these organic binding materials and their oxidative decomposition products. Unique aggregates including gluconites and zeolites were also incorporated, with sepiolite addition likely intentional to improve flexural strength and performance (Singh & Arbad, 2013c); (Singh, 2011); (Elenga et al., 2011). From a materials science perspective, these blends act as natural composites, with each ingredient serving a distinct structural function; for example, clay ensures cohesion, mineral aggregates mitigate shrinkage and bolster compressive strength, and organic fibers enhance tensile resistance and control cracking (Singh, 2011); (Ozino-caligaris et al., 2008); (Houben and Guilloud, 1994).

The inclusion of organic additives, such as straw, husk, or plant fibers, is particularly critical, as they facilitate stress distribution during drying and exposure to environmental

changes. The absence of such reinforcements often results in mud plaster surfaces exhibiting cracking and detachment due to shrinkage Table -1.

Table 1:
Function of Ajanta plaster Composition

Organic Component	Function in Plaster	Chemical Status (Modern)
Rice Husk / Paddy Skin	Reinforcement / Reduction of Weight	Partially carbonized / embedded ³
Grass Seeds / Fibers	Prevents shrinkage cracks	Fibrous remnants identified ³
<u>Proteic</u> Materials	High-adhesion binder	Transformed to Calcium Oxalate ³
Cow Dung	Antiseptic / Plasticity agent	Mineralized inclusions ³

Recent advancements in sustainable construction research have revisited these principles. Investigations into fiber-reinforced clay materials have indicated that organic components substantially improve the mechanical properties of clay composites, increasing both the tensile strength and durability (Kanth & Singh, 2019). These outcomes demonstrate that ancient builders possessed applied knowledge of composite material behavior before modern engineering concepts were formally introduced.

Early scientific investigation of the Ajanta plasters

The first comprehensive analysis of Ajanta plaster composition was carried out by S. Paramasivan in the 1930s. Employing chemical and microscopic techniques, Paramasivan identified ferruginous clay, sand, rock fragments, and substantial organic matter within the clay plaster layers (Paramasivan, 1939). The organic component, estimated to be between 1% and 14%, primarily originated from vegetable fibers and rice husks integrated into the matrix (Singh & Arbad, 2014c). These materials likely functioned as reinforcements, enhancing structural cohesion and minimizing cracking.

Paramasivan further documented the multi-layered complexity intrinsic to the plaster system. Microscopic examination revealed that fresco foundations generally comprised three to four distinct plaster layers separated by visible joints.

The initial base layer was thick and coarse, engineered to address the uneven basalt substrate, with subsequent layers displaying increased refinement, culminating in a thin lime plaster suited for painting (Singh & Arbad, 2014c); (Sharma et al., 2022); (Paramasivan, 1939).

Later investigations substantiated many of Paramasivan's findings and broadened the perspective on the particle size distribution within the plaster. Singh and Arbad (2013) observed considerable variability in aggregate sizes in the rough plaster layer, ranging from fine clay particles to larger silica and laterite fragments (Singh & Arbad, 2013d). This gradation improved the packing density and significantly reduced shrinkage during drying. According to their research, smaller particles, chiefly composed of clay and fine silica, promoted cohesion, whereas larger aggregates provided additional structural stability.

Pigments, Bonding Media, and Their Interaction with Plaster, Although the plaster serves as the structural foundation of the murals, its interaction with pigments and binding media is also pivotal to the conservation of the paintings (Singh & Arbad, 2013b); (Singh & Arbad, 2013a). Analytical studies indicate that most pigments at Ajanta were derived from minerals, such as red and yellow ochre, terre verte, and kaolin, and carbon was employed for black coloration (Lal, 1967); (Sharma et al., 2022); (Singh & Arbad, 2014c). The paint layers were applied using the tempera technique, utilizing water-soluble binding media, possibly animal glue or plant gum.



The longevity of an artwork depends on compatibility between the pigments and the underlying plaster. Mineral-based colors adhered efficiently to lime surfaces; consequently, a thin lime layer provided an optimal painting substrate. Additionally, the porous quality of the clay plaster facilitated moisture regulation, thereby reducing the likelihood of peeling or blistering. This stratified construction illustrates the advanced understanding of material interactions inherent in composite wall systems.

Conservation research and materials challenges

Although the original materials of the Ajanta murals are notably robust, the site has encountered significant conservation challenges since its rediscovery in the nineteenth century. Early preservation and replication efforts often involved the application of varnishes to augment color visibility. However, according to Singh and Arbad (2013), the repeated use of shellac and similar varnishes resulted in undesirable outcomes, such as darkening the surface and causing entrapment in plaster cracks, thereby complicating later restoration (Singh & Arbad, 2013b); (Garg et al., 1995).

In addition to human intervention, environmental variables, such as water infiltration, microbial activity, and insect infestations, have contributed to deterioration. Italian conservation campaigns conducted in the early 20th century identified biological threats arising from organic matter present in the plaster as a critical stability concern. This finding underscores the inherent paradox of employing organic additives, while they offer certain structural advantages, they can introduce biological vulnerabilities under specific environmental conditions (Uno & Shimazdu, 2012); (Singh & Arbad, 2014c).

Contemporary conservation science endeavors to balance effective preservation with minimal intervention. Advanced analytical methods, including cross-sectional microscopy and non-destructive testing, have been utilized to investigate the stratigraphy of painted plasters and determine their constituent materials (Mathur, 2005); (Singh & Arbad, 2014c). Although these techniques have enhanced our understanding of mural construction, uncertainties regarding the functional contributions of organic additives within the plaster matrix remain.

Knowledge gaps in existing literature

Although current research offers important insights into the composition and conservation of the Ajanta murals, several key gaps persist. First, many studies tend to treat organic additives as incidental inclusions rather than purposeful components of the plaster matrix, with insufficient investigation into whether ancient artisans deliberately designed these mixtures for tailored mechanical properties.

Second, much of the available literature examines individual material constituents such as pigments or binders without adequately considering how the overall plaster system functions as an integrated structural whole. Greater emphasis should be placed on the interactions among organic fibers, mineral aggregates, and lime finishing layers to fully understand the durability of mural substrates.

Third, there is a paucity of comparative analyses between traditional plastering techniques and modern materials. Such studies are essential for elucidating how historical practices achieved sustainability using locally sourced and renewable resources.

Implications of the Current Study

Given these limitations, this research re-evaluates Ajanta mud plasters using composite material theory and traditional knowledge systems. By synthesizing prior conservation studies and material analyses, this study intends to clarify the roles played by organic additives and mineral aggregates in enhancing the structural integrity of the plaster layers.

Furthermore, this investigation supports wider discussions on sustainable construction practices and heritage conservation. Ancient building methods typically incorporated renewable resources and locally sourced materials, offering valuable perspectives for contemporary initiatives aimed at developing environmentally responsible construction technologies. Understanding the ingenuity embedded in Ajanta's plaster systems informs both art conservation efforts and modern architectural science.

IV. METHODS

A qualitative research methodology was employed to examine the composition and functional significance of organic additives and mineral aggregates used in the mud plaster of the Ajanta Caves. This approach was selected because the primary objective was not the empirical measurement of material properties, but rather the interpretation of historical evidence, conservation documentation, and scientific analyses to discern the technical rationale underlying traditional plaster techniques. Such a methodology facilitates the integration of archaeological records, conservation science, and materials research, resulting in a comprehensive understanding of historic construction practices.

This research comprised a systematic review and analysis of the literature pertaining to Ajanta mural painting methods, conservation studies, and traditional mud construction materials. The focus was primarily on the Ajanta Cave complex in Maharashtra, India, which dates back to approximately the 2nd century BCE to the 6th century CE (Owen, 2010); (W. M. Spink & Yaguchi, 2017).



Over the past century, numerous conservation expeditions and material assessments have contributed to the preservation of these caves, producing an extensive collection of documents detailing the composition, layering, and degradation of the plaster substrates supporting the murals.

This study utilized a range of data sources, including published conservation reports, peer-reviewed journal articles, archaeological records, and material analysis studies. Notable emphasis was placed on foundational works, such as Paramasivan's scientific investigation into Ajanta mural techniques and subsequent conservation research by the Archaeological Survey of India. Additional references included contemporary heritage science publications examining traditional building materials and mixed clay methods. These documents were carefully selected for their detailed accounts of plaster composition, stratification, and conservation practices.

To ensure both relevance and reliability, an intentional document selection strategy was adopted. Priority was given to academic articles and reports published within the last decade to reflect current advancements in conservation science and materials analysis, while earlier seminal studies were incorporated for their unique analytical observations critical to the understanding of Ajanta plaster technology. The study analyzed a body of scholarly publications, conservation reports, and technical assessments that collectively documented the physical properties of Ajanta's plaster layers.

The analytical approach involved qualitative content analysis, which enabled a systematic examination of textual and descriptive information. Relevant sections from the chosen documents were identified and extracted, encompassing descriptions of the plaster composition, references to organic additives, observations on mineral aggregates, and evaluations of the structural behavior. Each excerpt was coded according to thematic categories such as organic reinforcement, aggregate structure, stratification, stability mechanisms, and conservation outcomes.

Repeated reviews and cross-comparisons revealed recurring patterns throughout the literature. For instance, multiple studies consistently noted the presence of plant fibers and rice hulls within clay plaster layers, indicating purposeful incorporation rather than incidental inclusion. Similarly, detailed accounts of graded mineral aggregates appeared across various conservation reports, suggesting a deliberate technique to enhance the mechanical integrity of the plaster matrix.

A comparative analysis with current materials science research on clay composites was also conducted. Studies of modern fiber-reinforced clay materials have provided insights into the influence of organic constituents on mechanical properties, facilitating an informed comparison with historical documentation regarding the composition of Ajanta plaster. This approach sought to elucidate the functional significance of the materials employed by ancient craftsmen.

Furthermore, conceptual evaluation framed Ajanta plasters as composite materials. Composite theory posits that combining substances with diverse physical attributes can yield structures with superior mechanical performance. Employing this framework, we assessed the interaction between organic fibers, clay matrices, and mineral aggregates to produce a robust plaster system capable of supporting murals over extended periods. To uphold scholarly accuracy, the findings were corroborated through source cross-validation. Where feasible, details from one study were compared with evidence reported in other literature, thereby enhancing consistency and minimizing reliance on isolated interpretations.

Although direct laboratory experiments or field sampling were not undertaken, a qualitative synthesis of historical and scientific literature offers substantive insights into the technical foundations of Ajanta plaster production. By integrating conservation reports with advanced knowledge of clay composites, this research contributes to a more comprehensive understanding of the roles played by organic additives and mineral aggregates in sustaining the structural strength of these renowned frescoes (Ghosh, 1996); (W. M. Spink, 2007).

V. DISCUSSION

A review of historical records and conservation literature demonstrates that the mud plasters employed in the Ajanta Caves were highly advanced composites rather than simple earthen mixtures. These plasters were meticulously engineered with deliberate incorporation of organic additives and mineral aggregates to form a resilient and stable foundation for murals. Such findings underscore the substantial empirical expertise possessed by ancient craftsmen who applied natural materials with a level of sophistication comparable to many modern construction methodologies.

One notable finding from the literature is the intentional inclusion of organic fibers and plant residues within successive layers of clay plaster.

Early microscopic analyses detected vegetable fibers, rice husks, and other plant matter embedded in the plaster matrix (Paramasivan, 1939). These organic constituents were purposefully integrated, not incidental impurities, as they appear to have been selected to enhance the mechanical properties of the final material.

Contemporary research on clay materials confirms the reinforcing effects of organic fibers. Their presence facilitates stress distribution throughout the clay matrix, mitigates the development of shrinkage cracks during drying, and increases the overall tensile strength (Dighe & Singh, 2025);(Singh & Arbad, 2014b);(W. Spink, 2014);(Walker et al., 2016). Accordingly, the organic additives observed in Ajanta's plasters can be interpreted as natural reinforcement agents, likely contributing to the system's resistance against thermal expansion, humidity fluctuations, and internal movements within the rock substrate.

This interpretation aligns with global traditional building practices, in which materials such as straw, animal hair, and various plant fibers are routinely added to mud plasters to improve durability. The application of similar techniques at Ajanta suggests that ancient Indian artisans had a practical understanding of these principles, even in the absence of contemporary scientific articulation.

Additionally, the careful selection and grading of mineral aggregates is a significant aspect of the Ajanta plaster system. Conservation analyses frequently report the presence of sand, silica fragments, and laterite particles within the coarser plaster layers (Singh and Arbad, 2013), with aggregate sizes ranging from fine grains to coarse inclusions. Such grading is critical for minimizing shrinkage and promoting structural stability.

In present-day materials science, the employment of graded aggregates is recognized as an effective means to increase composite density. Mixtures of varied particle sizes allow smaller grains to occupy the voids between larger grains, resulting in denser and more mechanically robust materials. The identification of such gradation in Ajanta's plasters indicates that ancient craftsmen consciously selected, processed, and combined local resources to achieve optimal performance.

The stratified configuration of the plaster system lends credibility to this interpretation. Historical documentation reveals that successive layers of plaster were applied, starting with a substantial clay base intended to eliminate inconsistencies in the basalt rock substrate. Each subsequent layer exhibited increased refinement, culminating in a thin application of lime plaster designed to serve as an ideal ground for painted decorations(Singh & Arbad, 2014b).

This systematic arrangement offered not only structural reinforcement but also optimized the surface for fresco work.

Notably, the interaction between the uppermost lime layer and the underlying clay contributes significantly to the durability of the murals. The lime stratum is relatively hard and exhibits chemical compatibility with mineral pigments, making it particularly suitable for painting methods such as tempera(Singh & Arbad, 2014a). Conversely, the clay sublayers retain a degree of flexibility and porosity, enabling the wall structure to accommodate environmental variations without incurring severe cracking(Agrawal et al., 1988);(Archaeological Survey of India, Aurangabad Circle, 2025),.

Nevertheless, the incorporation of organic materials introduces certain vulnerabilities. Conservation assessments have reported that organic components within plaster can attract insects or facilitate microbial growth under conducive conditions. Early 20th-century investigations at the Ajanta Caves documented insect infestations linked to organic residues embedded in the plaster (Singh & Arbad, 2014c);(Singh & Arbad, 2013e). These observations underscore a fundamental paradox: although organic additives enhance mechanical properties, they simultaneously elevate biological risks if environmental parameters are inadequately regulated.

Modern conservation interventions raise further considerations regarding material compatibility. Previous restoration efforts frequently employed synthetic agents, such as shellac varnishes or chemical consolidants, to stabilize mural surfaces. Although these measures aimed to safeguard the artwork, they occasionally produced adverse outcomes, including surface darkening and diminished vapor permeability of the plaster layers.

Such experiences highlight the necessity of thoroughly understanding the original composition of heritage materials. The introduction of conservation substances that are chemically or physically discordant with historic plaster can disrupt moisture dynamics, induce stress, or exacerbate deterioration. In contrast, restorations employing analogous traditional materials are more likely to sustain the inherent performance characteristics of the wall system.

From a theoretical perspective, current research affirms the relevance of composite materials theory in analysing historical building practices. The Ajanta plaster technique exemplifies how blending materials with complementary attributes yields systems that balance robustness with adaptability. Clay serves as the cohesive matrix, mineral aggregates bolster compressive strength, organic fibers enhance tensile properties, and lime finishing layers establish an optimal surface for artistic work.



International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 03, March 2026)

Despite these advances, significant knowledge gaps persist. Most existing studies rely on limited sample analyses and descriptive reports rather than exhaustive material testing. Consequently, the quantitative impact of organic additives on the mechanical integrity of the plaster matrix remains insufficiently characterized. Moreover, ongoing environmental challenges, including humidity variations and visitor-related stresses, continue to affect mural preservation (Singh et al., 2025).

Further research utilizing advanced analytical methodologies, such as microstructural imaging, spectroscopic techniques, and rigorous mechanical testing, can offer deeper insights into the composition and behavior of historical plasters. Experimental reconstructions of traditional mixtures may elucidate the functional contributions of specific ingredients. Such endeavors will advance scientific understanding of historical material technology and inform the development of improved conservation approaches.

VI. CONCLUSION

This study investigated the influence of organic additives and mineral aggregates in the mud plaster used at the Ajanta Caves, with a focus on understanding their contributions to the strength and longevity of one of the world's most distinguished wall painting traditions. Through a comprehensive analysis of historical documentation, conservation literature, and recent research on mud aggregates, this study highlighted the technical proficiency underpinning the manufacture of Ajanta's plasters.

The findings indicate that the plasters employed by Ajanta were meticulously engineered composites rather than mere layers of mud. The intentional inclusion of organic materials, such as plant fibers and rice husks, enhanced the mechanical properties of the plasters by increasing their tensile strength and mitigating shrinkage-induced cracking. Additionally, the incorporation of graded mineral aggregates contributed to the structural integrity by optimizing density and minimizing deformation during the drying process. Collectively, these elements produced a durable substrate capable of supporting mural paintings for over 15 centuries.

The stratified configuration of the plaster system demonstrates an advanced understanding of material behavior. Substantial base layers accommodated the caves' irregular basalt surfaces, whereas successively finer layers provided a suitable ground for artistic application. The terminal application of lime plaster established a chemically favorable interface for mineral pigments, facilitating the tempera technique.

This multilayered approach enabled the wall system to achieve an optimal balance between strength, flexibility, and surface quality. Beyond its historical value, this research informs the theoretical discourse on traditional construction knowledge systems. The material strategies observed at Ajanta reveal that ancient craftsmen possessed sophisticated practical knowledge of composite materials well before the advent of modern engineering principles. Their capacity to synergistically combine organic and mineral constituents underscores the potential of traditional practices to provide sustainable solutions in contemporary construction.

The findings also have significant implications for heritage conservation practices. Previous interventions utilizing synthetic materials have occasionally disrupted the physical and chemical performances of historic plaster layers. Accordingly, a thorough understanding of original material compositions and their functional rationale is critical for guiding effective conservation strategies. In many contexts, the reinstatement of traditional materials may offer superior compatibility compared to modern alternatives.

Notwithstanding these contributions, the study has certain limitations. The analysis predominantly relies on secondary sources and previously published reports, with minimal direct laboratory investigation of plaster samples. Consequently, interpretations regarding the mechanical behavior of the plaster components are inferred from qualitative comparisons with modern soil studies rather than empirical data.

Future research should prioritize experimental replication and laboratory-based characterization of traditional plaster compositions, including microstructural and mechanical analyses. Such work would enable a quantitative assessment of the roles played by organic and mineral constituents in the overall performance of plasters. Furthermore, interdisciplinary collaboration among archaeologists, conservation experts, and materials scientists is essential to advance the understanding of technological innovations in historic construction.

In summary, the mud plasters of Ajanta exemplify extraordinary ancient material craftsmanship. The deliberate integration of organic and mineral components within a layered architecture facilitated the preservation of extensive murals over many centuries. Continued investigation of these time-tested techniques offers valuable insights into historical art and architecture and can serve as a foundation for developing more sustainable building and conservation practices.

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International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 03, March 2026)

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