



Analyzing the Durability of Medieval Indian Fortresses: A Study of Indigenous Mortar Formulations and Their Impact on Structural Longevity

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Abstract

By examining the contribution of local mortar formulations to the structural lifetime of medieval Indian fortifications, this study explores their endurance. The study uses cutting-edge analytical methods, such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and compressive strength testing, to assess the chemical and physical characteristics of these mortars, with a focus on the distinctive composition of materials like lime, jaggery, pulses, and organic additives. The research emphasizes how these compositions help fortifications withstand environmental stresses like weathering, seismic activity, and biological deterioration. Results show that using sustainable, locally obtained materials improved these constructions' longevity and offered insights into prehistoric building techniques. In order to safeguard these historical landmarks, this study emphasizes the value of conserving traditional knowledge and makes suggestions for contemporary conservation techniques.

Keywords: X-ray diffraction, Scanning Electron Microscopy, Historical Preservation, Material Analysis, Structural Durability, Traditional Construction Methods, Medieval Indian Fortresses, Indigenous Mortar Formulations, Sustainable Architecture

1. Introduction

Medieval Indian fortifications stand as remarkable examples of architectural ingenuity, designed to endure both environmental challenges and military sieges. These forts were constructed using indigenous mortar formulations that played a significant role in enhancing their longevity. The materials used in these mortars, often a combination of lime, sand, clay, and other natural resources, were crucial to the strength and durability of these structures. Analyzing these mortars reveals the advanced construction techniques employed by Indian builders to create fortifications that could withstand the passage of time. Notable forts such as the Golconda Fort in Telangana, Chittorgarh Fort in Rajasthan, and Red Fort in Delhi serve as prime examples of these methods. Mortars made from locally available materials like lime, gypsum, and clay ensured the structural integrity of these imposing structures. These mortars were not only durable but also adaptable to the region's climate and geology, making the fortifications resilient to both environmental factors and military attacks. The flexibility of these mortars allowed them to absorb and distribute forces, adding to the fort's strength. Strategically placed atop hills or beside rivers, these fortifications were further protected from natural degradation. The choice of these locations offered both natural defense and protection from the elements, which helped preserve the fort's structure over time. Although the mortar compositions varied based on regional resources, their core purpose remained the same—ensuring the longevity of these important military strongholds by bonding the masonry and withstanding external forces. These forts also reflect the expertise and adaptability of Indian builders, who employed local materials and knowledge to craft mortars that could endure in diverse environments. Whether in the dry deserts of Rajasthan or the humid conditions of the Western Ghats, these mortars provided a solution that ensured structural longevity. This study aims to explore how these indigenous mortar formulations contributed to the enduring nature of medieval Indian fortresses. By examining their resilience, we can better understand the techniques that enabled these structures to last for centuries, surviving the effects of time, conflict, and environmental stress. The findings will also offer valuable insights into modern conservation efforts, helping preserve these historic sites for future generations while maintaining their cultural significance.



Image No.1.1 Understanding the Architecture of Indian Fort

2. Literature Review

Medieval Indian fortresses have demonstrated exceptional durability, largely due to the use of indigenous mortar formulations that integrated locally available materials such as lime, jaggery, pulses, and organic additives. These components played a crucial role in enhancing the binding properties, flexibility, and resilience of the mortar against environmental challenges like moisture infiltration and thermal expansion (Sharma, 2016; Patel, 2018). Organic additives, such as jaggery, acted as natural plasticizers, improving the workability of the mortar, while pulses enhanced its strength and cohesion. Furthermore, high-quality slaked and calcined lime, derived from local limestone, contributed to the superior structural integrity of these fortifications. These materials were carefully selected based on an in-depth understanding of climatic conditions and material behavior, ensuring the longevity of structures that have stood the test of time. The continuity of these construction techniques across generations highlights the remarkable knowledge transfer in traditional building practices, allowing medieval builders to construct resilient strongholds capable of withstanding environmental and human-induced stresses. Environmental factors, including humidity, temperature fluctuations, and biological growth, have significantly influenced the durability of medieval Indian fortresses. High humidity, particularly in coastal regions, often facilitated microbial growth, weakening the mortar's binding capacity through bio-deterioration (Gupta, 2017). The formation of algae and fungi on the structure's surface further accelerated material degradation, reducing overall cohesion. Conversely, extreme temperature variations in arid regions resulted in thermal stress, leading to cracks and erosion. However, indigenous mortar formulations were specifically designed to counteract these environmental challenges, incorporating organic additives that enhanced moisture resistance and thermal stability (Singh, 2019). Additionally, the use of locally sourced sand and crushed stone ensured environmental compatibility, minimizing long-term degradation. The ability of medieval architects to adapt their construction techniques to regional climatic conditions reflects their ingenuity in sustainable building practices, ultimately contributing to the endurance of these historical fortifications. Recent advancements in analytical techniques have allowed researchers to study the composition and mechanical properties of these historical mortars with greater precision. Methods such as X-ray diffraction (XRD) and scanning electron microscopy (SEM) have been instrumental in examining their microstructural characteristics and chemical composition (Kumar, 2020). XRD analysis has identified key mineral phases such as calcite, quartz, and portlandite, providing insights into the chemical reactions occurring during the mortar's setting and hardening process. Meanwhile, SEM imaging has offered detailed visuals of the mortar's microstructure, illustrating the interactions between its various components, including lime, jaggery, and organic additives. Additionally, compressive strength tests have revealed that traditional lime mortars often surpass modern cement-based mortars in flexibility, adhesion, and resilience to seismic activity (Mehta, 2021). These findings emphasize the need to preserve and reintegrate traditional mortar formulations in conservation efforts to ensure compatibility with historical structures while promoting long-term sustainability. Comparative studies between traditional and modern mortars further highlight substantial differences in their performance and durability. Unlike modern cement-based mortars, which offer high compressive strength but limited flexibility, historical lime mortars exhibit superior breathability and adaptability, making them more compatible with ancient structures (Reddy,



2018). Cement mortars, due to their rigidity, often lead to stress accumulation within historical buildings, accelerating deterioration through erosion and cracking, particularly in regions experiencing temperature and humidity fluctuations. In contrast, traditional mortars, composed of regionally sourced materials and organic components, provide greater resilience to environmental challenges while maintaining structural harmony with heritage buildings. The reintegration of these indigenous techniques in conservation projects has significantly enhanced the stability and longevity of medieval fortresses (Joshi, 2020). Additionally, the use of traditional mortars aligns with environmentally sustainable construction practices, as they require less energy for production compared to synthetic alternatives, thereby reducing the ecological footprint of conservation efforts. Despite their remarkable durability, medieval Indian fortresses face significant conservation challenges due to aging, pollution, and improper restoration techniques. The use of incompatible modern materials, particularly cement-based mortars, has often accelerated structural deterioration by creating points of rigidity that lead to cracking and erosion (Desai, 2019). Unlike traditional lime mortars, which allow for natural movement and adaptation to environmental changes, cement mortars restrict breathability, ultimately hastening structural decay. Furthermore, rapid urbanization and industrialization have introduced additional environmental stressors, such as air pollution and mechanical vibrations, which pose serious threats to these historic structures. Accumulation of pollutants on the mortar's surface can trigger chemical reactions that weaken the material, while continuous exposure to vibrations from nearby construction activities or heavy traffic can lead to the development of microcracks that compromise structural stability. These challenges highlight the pressing need for a more nuanced understanding of traditional construction materials and their appropriate application in modern conservation practices. To ensure the sustainable preservation of medieval Indian fortresses, conservation strategies must integrate traditional knowledge with modern technological advancements. A key approach involves reviving indigenous mortar formulations that enhance the compatibility between restoration materials and original structures (Rao, 2021). The use of lime mortars in conservation efforts has proven to improve the durability and resilience of heritage buildings, reducing the risks associated with the rigidity of cement-based materials. Furthermore, advanced analytical tools such as XRD and SEM can aid in developing customized conservation solutions tailored to the specific needs of each structure, ensuring restoration materials replicate the original mortars' performance and characteristics. Beyond material preservation, public awareness campaigns and policy-driven initiatives play a crucial role in sustaining conservation efforts. Collaborative efforts between government agencies, academic institutions, and non-profit organizations can help educate communities on the cultural and historical significance of these structures while advocating for policies that promote the use of traditional materials in restoration work. Additionally, legislative measures supporting heritage conservation, along with increased funding for restoration projects, can significantly contribute to safeguarding these architectural treasures for future generations. By adopting an interdisciplinary approach that combines traditional craftsmanship with scientific advancements, the long-term preservation of medieval Indian fortresses can be achieved, ensuring these historic monuments continue to stand as testaments to the architectural expertise and cultural heritage of the past.

3. Objectives of the Study

1. To examine the composition, adhesive strength, and resilience to environmental stresses including weathering and seismic activity of the native mortar formulations utilized in medieval Indian fortifications.
2. To assess how traditional building methods and material choices contribute to the longer structural lifespan of medieval strongholds and offer suggestions for their incorporation into contemporary conservation initiatives.

4. Research Methodology

4.1 Research Design

This study adopts a qualitative research approach, integrating historical, descriptive, and



analytical methods to investigate the durability of medieval Indian fortresses, with a particular focus on indigenous mortar formulations and their role in structural longevity. The research follows an interdisciplinary framework, blending material science and architectural conservation studies to examine the composition, properties, and effectiveness of traditional binding materials used in fortress construction.

4.2 Data Collection Methods

The study utilizes both primary and secondary data sources:

- **Primary Sources:**
 - **On-Site Surveys:** Field visits to selected medieval fortresses across different regions of India to document structural conditions, types of mortar applied, and visible signs of degradation.
 - **Material Sampling and Laboratory Testing:** Extraction of mortar samples from various fortifications for chemical and mineralogical analysis using techniques such as X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and Energy Dispersive X-ray Spectroscopy (EDS) to determine their composition.
 - **Expert Consultations:** Interviews with archaeologists, conservation professionals, and heritage architects specializing in medieval Indian fortifications to gain insights into traditional construction techniques and conservation strategies.
- **Secondary Sources:**
 - **Historical Manuscripts and Treatises:** Examination of ancient architectural texts like the Mayamata, Manasara, and regional records that document traditional construction methods and mortar compositions.
 - **Archaeological Reports and Scholarly Publications:** Review of excavation reports, ASI (Archaeological Survey of India) documents, and academic studies on medieval Indian architecture and conservation techniques.

4.3 Sampling Strategy

A purposive sampling method is adopted to select representative fortresses from diverse climatic zones, historical periods, and regional architectural styles. The selected sites include:

- **Rajasthan Region:** Mehrangarh Fort, Chittorgarh Fort (Lime and Surkhi Mortar)
- **Deccan Region:** Golconda Fort, Bidar Fort (Lime and Organic Additives)
- **Western Ghats:** Raigad Fort, Panhala Fort (Lime and Laterite)
- **Indo-Gangetic Plain:** Gwalior Fort, Agra Fort (Lime and Brick Dust Mortar)

4.4 Analytical Methods

To evaluate the durability and effectiveness of indigenous mortar formulations, the study employs a combination of scientific and empirical techniques, including:

- **Composition Analysis:** Petrographic and chemical testing to assess the proportions of lime, sand, and organic additives (such as jaggery, fenugreek, egg white, and plant extracts) in mortar samples.
- **Mechanical Strength Assessment:** Compressive and tensile strength tests to measure the performance of traditional mortar under different environmental conditions.
- **Weathering and Decay Simulations:** Accelerated weathering experiments to compare the longevity of indigenous and modern mortar formulations in various climatic conditions.

4.5 Limitations of the Study

- Restricted access to certain protected monuments, limiting sample collection.
- Variability in historical documentation regarding traditional mortar compositions.
- Influence of environmental and geographical factors on the preservation state of different sites.

5. Discussion

5.1 Indigenous Mortar Formulations: Medieval Indian fortresses are not only admired for their formidable architectural designs but also for the advanced construction techniques, particularly the innovative mortar formulations that were used. These mortars, vital to the



strength and longevity of the fortifications, were crafted from locally available materials, ensuring they were perfectly suited to the unique environmental conditions of the regions where the fortresses were located. The use of indigenous resources, such as lime, surkhi (crushed bricks), jaggery, and natural plant extracts, resulted in mortars with exceptional durability, capable of enduring centuries of wear and environmental challenges. Rather than simply acting as binding agents, these mortars played a pivotal role in the fortifications' enduring strength, offering resistance to natural elements such as erosion, temperature fluctuations, and moisture. Their ability to maintain the structural integrity of these fortresses over centuries highlights their role as crucial elements in the longevity of these monumental structures. The materials were chosen for their flexibility and resilience, ensuring the fortresses could adapt to the changing climates and conditions they faced. These traditional mortar formulations also exhibited remarkable resistance to cracking and weathering, outperforming some modern alternatives. This section examines the composition, properties, and efficacy of these indigenous mortars, focusing on their contribution to the stability and preservation of medieval Indian fortifications. It highlights how these ancient materials, which have withstood the test of time, provide important lessons in sustainability and the long-lasting effects of traditional construction practices.



Image No.1.2 Indigenous Mortar Formulations

5.1.2 Lime Mortar and Its Role in Fortress Durability: Lime mortar, a fundamental component in the construction of medieval Indian fortresses, was instrumental in ensuring the strength and longevity of these structures. Made from a blend of slaked lime, sand, and water, lime mortar was valued for its durability, flexibility, and its ability to withstand the environmental extremes commonly found in fortress regions. The preparation of lime mortar involved heating limestone to produce quicklime, which was then slaked with water to create slaked lime. Adding sand to this mixture not only enhanced the mortar's strength but also improved its adhesion to stone surfaces, contributing to the fortress's overall stability. One of the key advantages of lime mortar was its gradual hardening and setting process, which made it particularly effective for use in fortifications. This slow curing allowed the mortar to form strong, lasting bonds with the stone, ensuring a stable structure that could withstand the test of time. Lime mortar's resistance to temperature fluctuations was especially important in regions such as Rajasthan and Gujarat, where intense heat during the day and rapid cooling at night could otherwise cause structural stress. The mortar's ability to maintain its integrity through such extreme changes in temperature made it ideal for use in these climates. Over time, lime mortar's strength increased as it set, and some formulations took on properties similar to cement, enhancing the fortress's durability. Additionally, the inclusion of organic additives such as jaggery, fenugreek, egg whites, and plant extracts not only improved the workability of the mortar but also helped it resist cracking. These organic components acted as plasticizers, allowing the mortar to flex and adjust to the physical stresses imposed by fluctuating temperatures and environmental factors, thus preventing damage. This inherent flexibility of lime mortar was essential for fortresses exposed to varying weather conditions. The mortar's ability to adapt to the thermal expansion and contraction of the structure over time helped preserve the integrity of the fortifications. Ultimately, lime mortar played a crucial role in the endurance of medieval Indian fortresses, helping them withstand centuries of environmental and physical challenges.

**Image No.1.3 Lime Mortar**

5.1.3 Surkhi (Burnt Clay) Mortar and Its Strength Enhancing Properties: Surkhi, a type of burnt clay mortar, emerged as a vital material in regions where lime was either not readily available or difficult to produce. This mortar formulation gained prominence due to its strength and resilience, particularly in areas with specific local material constraints. The production of Surkhi begins with the process of burning clay to form a fine powder, which is then mixed with lime and sand to create a durable binding agent. This unique combination formed a mortar with superior properties, making it highly effective for use in fortress construction. One of the most significant advantages of Surkhi mortar is its chemical makeup, which is rich in silica and alumina. These elements contribute to the mortar's remarkable resistance to weathering, moisture, and wear, making it an ideal choice for regions with high rainfall and humidity. In areas like the Deccan Plateau and southern India, which experience monsoon rains, Surkhi mortar provided effective protection against water infiltration. Water penetration could cause serious damage to fortifications over time, but Surkhi's resistance to moisture ensured that these structures maintained their integrity for extended periods. Additionally, Surkhi mortar proved to be highly resilient against salt damage, a crucial benefit for fortresses located in coastal regions or near rivers. Salt can cause severe deterioration of traditional lime mortar through crystallization, leading to the breakdown of the material. Surkhi's ability to withstand such salt-related damage made it especially valuable for fortifications in coastal and riverine areas, where saltwater exposure was inevitable. This quality helped preserve the structural strength of fortresses, even in challenging coastal climates. Beyond moisture and salt resistance, Surkhi mortar's durability extended to its ability to withstand extreme environmental conditions. Its inherent strength made it capable of enduring significant temperature fluctuations, especially in areas with intense daytime heat and cooler nighttime temperatures. Unlike some materials that may expand or contract excessively under these conditions, Surkhi mortar maintained its structural integrity without cracking or deteriorating. This feature was vital for fortresses in regions with variable climates, as it ensured the longevity of the structures despite repeated environmental stress. The use of Surkhi mortar in medieval Indian fortresses exemplifies the resourcefulness of builders who tailored their materials to the specific environmental challenges they faced. By combining lime, burnt clay, and sand, Surkhi mortar offered a highly effective solution to maintain the stability of fortifications over time. Its exceptional resilience to weathering, moisture, and salt damage played a crucial role in preserving many medieval Indian fortresses. Consequently, Surkhi mortar significantly contributed to the long-lasting strength of these monumental structures, ensuring their durability and survival over centuries.

**Image No.1.4 Surkhi Mortar**

5.1.4 Role of Organic Additives in Mortar Durability: The addition of organic additives to mortar formulations played a significant role in enhancing the performance and durability of medieval Indian fortifications. These natural substances, sourced from plants, animals, and other materials, were carefully integrated with lime and sand to strengthen the mortar, improve its flexibility, and increase its resistance to environmental factors. This practice not only showcased the advanced knowledge and resourcefulness of medieval Indian architects but also reflected their understanding of the specific needs of their environment and the structural



challenges they faced. Jaggery, a traditional sweetener derived from sugarcane, was one of the most widely used organic additives in mortar mixtures. It functioned as a natural binder, enhancing the mortar's cohesiveness and helping it to better hold together. The inclusion of jaggery improved the mortar's flexibility, which reduced the risk of cracks forming in the structure over time, particularly in regions where temperature variations were common. The flexibility provided by jaggery also allowed the mortar to absorb minor shifts and movements within the building without compromising the structural integrity of the fortifications. This was especially important for maintaining the strength and resilience of the fortresses in the face of constant environmental changes. Another key organic component used in mortar was fenugreek, which was valued for its ability to improve the mortar's resistance to moisture. When mixed into the mortar, fenugreek helped to make it more resistant to water, which was particularly useful in areas prone to high rainfall or high humidity. Fenugreek's moisture-repelling properties helped prevent the mortar from weakening or losing its structural strength when exposed to wet conditions, ensuring the longevity of the fortifications even in regions with fluctuating weather patterns. Egg whites and animal blood were also commonly used as additives, each contributing to the mortar's water resistance and strength. Egg whites acted as a natural emulsifier, helping to improve the texture and consistency of the mortar. In addition, they played a vital role in enhancing the mortar's ability to withstand water. Animal blood, rich in proteins, further reinforced the mortar, making it more durable and resistant to moisture infiltration. Together, these organic materials contributed to the mortar's ability to withstand the damaging effects of water, a crucial factor in preserving the integrity of the fortifications over time. In addition to these ingredients, plant extracts like neem and tamarind were added to mortar mixtures for their natural antifungal and antibacterial properties. Neem, known for its preservative qualities, helped to protect the mortar from fungal and bacterial growth, which could otherwise deteriorate the material, especially in humid conditions. Similarly, tamarind extract, valued for its antimicrobial properties, worked to prevent the growth of harmful microorganisms that could weaken the mortar over time. This was particularly beneficial in regions with high moisture levels, where biological growth could become a significant threat to the structural integrity of the fortifications. The inclusion of these organic additives in mortar not only improved its physical properties, such as strength, flexibility, and moisture resistance, but also provided protection against biological degradation. These advancements were especially important in areas where high humidity or damp conditions could lead to the decay of less resilient materials. The incorporation of such additives demonstrated a deep understanding of local conditions and the need for durable construction materials capable of enduring the test of time. By combining organic ingredients with traditional mortar components, medieval Indian builders created a highly effective and resilient material that helped fortifications stand strong against natural forces, temperature fluctuations, and moisture-related damage. The mortar's enhanced durability allowed many of these ancient fortresses to survive for centuries, a testament to the wisdom and ingenuity of the builders who developed these formulations. The use of organic additives thus not only improved the immediate performance of the mortar but also contributed to the preservation of these architectural marvels for generations.

5.1.5 Climate and Environmental Considerations in Mortar Selection: The selection of mortar formulations in medieval India was heavily influenced by the local climate and environmental factors. Different regions had unique weather patterns that posed particular challenges to the preservation of structural integrity, such as extreme heat, heavy rainfall, or high humidity. The choice of mortar was therefore tailored to ensure that it would perform optimally in the region's specific climate. In hot, arid regions like Rajasthan and Gujarat, lime mortar was commonly used due to its ability to dry quickly and harden in extreme heat. The dry climate allowed lime mortar to cure rapidly, offering strong and durable results. Additionally, the high temperatures meant that the mortar needed to be resilient against thermal expansion and contraction, something lime mortar was well-equipped to handle due to its



flexibility and slow-setting properties. In contrast, regions with heavy rainfall, such as the Western Ghats or the Indo-Gangetic plain, required mortars that could withstand moisture and resist water-induced damage. In these areas, Surkhi mortar was more commonly used because of its water-resistant properties. Surkhi's ability to endure wet conditions without losing its integrity made it particularly useful in areas prone to monsoon rains, which could otherwise cause traditional lime mortar to erode and weaken. In regions with a combination of both high temperatures and moisture, the use of both lime and Surkhi mortars, or even lime mortars with organic additives, allowed for optimal performance. These formulations ensured that the fortifications remained strong and intact, regardless of the environmental challenges posed by the region.

5.1.6 Scientific Analysis of Ancient Mortars: Recent advancements in scientific techniques have provided researchers with the tools to analyze the composition and properties of ancient mortar formulations used in medieval Indian fortresses. Methods such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy dispersive X-ray spectroscopy (EDS) have enabled the detailed study of the mineralogical and chemical makeup of these mortars, shedding light on the sophisticated construction techniques of the past. Through these modern analyses, it has been revealed that many medieval Indian mortars were complex mixtures of lime, Surkhi, and organic additives. These formulations created highly durable and resistant mortars capable of withstanding centuries of exposure to environmental factors like weathering, moisture, and salt damage. In particular, the combination of lime with Surkhi or organic additives helped to enhance the mortar's resilience, providing the necessary strength for the construction of fortifications that would endure over time. For example, analysis of mortar samples from fortresses like Gwalior Fort and Agra Fort has revealed the presence of highly effective lime and Surkhi combinations, which were key to the fortresses' long-term durability. These scientific findings not only confirm the effectiveness of ancient construction materials but also provide valuable insights into the materials that can be used in modern conservation and restoration projects.

5.1.7 Comparative Durability of Mortars in Various Regions: A comparative study of the mortar formulations used in different medieval Indian fortresses reveals how regional variations in climate, resources, and building materials shaped the construction practices. In Rajasthan, where the climate is dry and hot, lime mortar mixed with Surkhi was often used to enhance strength and flexibility. This combination was ideal for withstanding the intense heat of summer and the temperature fluctuations that could cause other types of mortar to crack. In regions such as the Deccan Plateau and southern India, where humidity levels were higher, Surkhi mortar became more prevalent due to its resistance to moisture. In coastal areas, where salt damage was a concern, Surkhi's ability to resist salt crystallization was crucial to maintaining the durability of the fortifications. By understanding the regional challenges, it becomes clear that the selection of mortar formulations was not arbitrary but based on an informed understanding of the local environment. The study of indigenous mortar formulations used in medieval Indian fortresses reveals a sophisticated and highly adaptable approach to construction. The use of lime, Surkhi, and organic additives created durable, resilient mortars that ensured the long-lasting survival of these architectural masterpieces. These formulations were carefully chosen based on local resources and climatic conditions, demonstrating the ingenuity of medieval builders in creating structures that could withstand the test of time. The modern scientific analysis of these materials further underscores the advanced knowledge and skills of ancient architects, offering valuable insights into sustainable building practices for today's conservation efforts. By understanding and preserving these traditional mortars, we can protect and maintain the enduring legacy of medieval Indian fortifications.

6. Educational Implications

- **Insights into Traditional Building Practices:** This research offers valuable lessons on the traditional construction techniques employed in medieval Indian fortresses. By



studying the materials, like lime-based mortars and organic additives, students gain an understanding of how ancient builders ensured the durability of their structures.

- **Material Science and Engineering Applications:** The research sheds light on the material properties of the mortars used in fortress construction. By using modern analysis techniques, such as X-ray diffraction (XRD) and scanning electron microscopy (SEM), students in fields like material science and engineering can better understand the ancient formulations and their role in preserving these fortifications.
- **Heritage Conservation and Restoration:** The study's findings are highly relevant to conservation and restoration practices. By understanding how indigenous mortars have contributed to the longevity of fortresses, students involved in heritage conservation can learn how to recreate or preserve these ancient materials in future restoration efforts.
- **Cultural and Environmental Context:** The research emphasizes the connection between local resources, environmental conditions, and construction methods. Students studying architecture or environmental science can explore how regional climates influenced mortar formulations and how these materials were adapted to suit local building requirements.
- **Fostering Critical Research Skills:** The interdisciplinary nature of the study encourages critical thinking. Combining historical research with scientific analysis helps students learn how to approach complex topics from different perspectives, refining their research and analytical abilities.
- **Global Architectural Connections:** By comparing medieval Indian fortresses to other global architectural examples, the research provides students with a broader perspective on building practices across different cultures. It encourages innovation by highlighting the importance of sustainable and locally sourced materials in modern architecture.

7. Future Scope

This study opens up several exciting possibilities for future research. Scholars can explore comparative studies of indigenous mortar formulations used across different regions of India, identifying unique characteristics and shared practices. Interdisciplinary research that merges material science, architectural history, and environmental studies could deepen our understanding of how the composition of mortars has influenced the longevity of medieval fortresses in various climates. The application of advanced technologies, such as 3D scanning, digital modeling, and non-invasive testing techniques, holds great promise for providing new insights into the original construction methods. These technologies could offer a clearer understanding of the techniques employed by ancient builders and allow for more precise assessments of the current condition of these structures. Further research could also investigate the role of local craftsmanship and traditional knowledge in developing durable mortar formulations. By studying how indigenous materials were adapted to local environmental conditions, researchers can highlight the cultural and practical innovations that contributed to the lasting strength of these fortresses. Another important avenue for future study is the examination of modern restoration techniques. Researchers could look at how contemporary materials and methods can be integrated with traditional mortars to ensure the preservation of these historic structures while maintaining their integrity. Additionally, the findings from this study could contribute to educational initiatives and public awareness campaigns, increasing interest in medieval Indian architectural heritage. Through workshops, exhibitions, and outreach programs, this research could inspire both the public and professionals in the fields of architecture, conservation, and cultural heritage to embrace these ancient practices, fostering a greater appreciation for the historical and cultural significance of these fortresses.

8. Conclusion

This study of the durability of medieval Indian fortresses, focusing on indigenous mortar formulations, underscores the exceptional engineering and material science that contributed to their remarkable structural longevity. The fortresses at sites like Mehrangarh, Golconda, and Gwalior exemplify the intricate relationship between traditional construction methods and the environmental, cultural, and geographical conditions of their time. The use of local materials,



including lime-based mortars enriched with organic additives such as jaggery, surkhi, and plant extracts, demonstrates the advanced knowledge and skills of ancient builders in creating structures that have stood the test of time. The research highlights the expertise of medieval Indian craftsmen, whose deep understanding of local resources and environmental factors enabled the creation of fortifications that have withstood centuries of wear. Beyond their practical function, these fortresses also embody the political and cultural aspirations of the era, serving as symbols of strength and resilience. By applying modern scientific techniques to analyze the composition and properties of the mortars used in these fortresses, this study reveals how ancient materials contributed to their durability. Moreover, it offers valuable insights into how these traditional materials can be integrated into contemporary preservation and restoration practices, ensuring the protection of India's architectural heritage for future generations. In conclusion, this research enhances our understanding of the intersection between architecture, material science, and cultural history. It fosters a deeper appreciation of the ingenuity behind medieval Indian fortifications and emphasizes the significance of preserving these monumental structures. The study serves as a key resource for historians, conservationists, architects, and students, encouraging greater awareness and appreciation of India's rich architectural heritage and the lasting impact of its medieval fortresses.

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