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Traditional lime craftsmanship in China's built heritage: craft knowledge, transmission, and intangible cultural heritage conservation

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Lime was an enduring and versatile material in ancient China, widely applied in medicine, dyeing, shipbuilding, and notably in architecture as a binding agent for masonry, earthen structures, and decorative finishes. Its recognition as Intangible Cultural Heritage (ICH) stems from both its profound historical significance and its capacity to meet UNESCO's five criteria for ICH: sustaining cultural identity, embodying systematic knowledge, ensuring community continuity, stimulating creativity, and addressing contemporary challenges. This study employs a multidisciplinary approach, integrating historical, archeological, and anthropological research with experimental and scientific analysis, to establish a comprehensive knowledge framework. This framework is structured around six technical stages: material selection, calcination, slaking, formulation, construction, and curing. By reconstructing the embodied knowledge and socio-technical practices of artisans, we reconceptualize lime craftsmanship as a living, active, and productive form of ICH. This research offers valuable theoretical and practical insights for architectural heritage conservation and the promotion of sustainable cultural development.

Building materials constitute the foundation of spatial and architectural form. In China's traditional building construction system, structural and esthetic outcomes largely depend on the properties of primary materials, such as wood, clay, bricks, and stones. The inherent performance of these materials established the baseline of architectural performance, while their processed or enhanced capabilities defined the upper limit of potential improvements. Within this spectrum, the final architectural expression emerged from the appropriate application of materials, thereby optimizing the performance of each building component. This principle is eloquently captured in the ancient Chinese architectural classic *Yingzao Fashi* (《营造法式》), Treatise on the Construction Methods, 1103 CE, during the Song Dynasty), which advocates *taking materials as ancestors*, a principle that asserts all systems of building houses are based on materials¹. The inherent properties, application techniques, and cultural practices associated with traditional building materials reflect profound wisdom in architectural creation. Moreover, they inform value-based judgment in the conservation of architectural heritage today.

Lime has long served as a vital cementitious material in traditional Chinese construction, extensively employed in foundations, walls, roofs,

finishes, and other building elements. Portland cement was introduced to China in the late 19th century and began to be produced on a large scale with standardized application in the early 20th century². Following its widespread adoption, lime was gradually displaced as the primary binding material. By the 1970s, its use had been largely reduced to that of an admixture. However, in recent years, advancing theory and growing practical experience in architectural heritage conservation, various guiding documents have emphasized the importance of using traditional materials in preservation efforts, particularly highlighting the detrimental effects of cement in the restoration of architectural heritage.

This concern was raised as early as the 1980s when Sir B. M. Feilden (ICCRROM) advised UNESCO against the use of cement in cultural heritage restoration projects^{3,4}. In the conservation and restoration of cultural relics and historic structures, lime is not merely a direct replacement but a critical material essential for maintaining structural health, extending service life, and preserving historical value. As a traditional building material, lime exhibits strength and properties that align with the principles of architectural heritage conservation, thereby establishing it as a functionally and materially compatible choice for restoration projects. Its vapor permeability,

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flexibility, compatibility, resistance to salt crystallization, and ability to integrate with traditional craftsmanship render it irreplaceable in addressing common pathologies in historic buildings, such as moisture ingress, salt weathering, and cracking, as well as in protecting vulnerable historical fabric (Figs. 1 and 2). Neglecting the specific characteristics of lime and resorting to incompatible modern materials such as Portland cement can accelerate deterioration and result in irreversible damage to historic structures.

Current academic research on the application of lime in ancient architecture is predominantly concentrated in three domains: historical investigation, scientific analysis of traditional mortar, and its utilization in conservation engineering. The first domain, historical investigation, has traced the history of lime use in construction prior to the Song and Yuan dynasties based on archeological evidence, including developments such as the formation of *White Ash Surface* (白灰面) in prehistoric periods⁵⁻⁷. A second major domain involves the scientific analysis of traditional mortar, where modern analytical techniques are employed to investigate the composition, properties, and curing mechanisms of historic mortars⁸⁻¹³. Lastly, the integration of traditional lime technology into contemporary conservation practice has gained increasing prominence, demonstrating its practical value in the restoration and preservation of architectural heritage¹⁴⁻¹⁹.

Despite these thematic advances, research on traditional building lime remains fragmented and lacks a unified theoretical framework. Significant gaps persist in several areas: a systematic knowledge system of lime as a historical scientific and technological theory; effective models for safeguarding and transmitting lime technology as intangible cultural heritage (ICH); and a coherent value system guiding the applicative of traditional lime techniques in contemporary conservation practice. For instance, although existing studies have identified lime production and construction techniques described in historical texts, they often fail to interpret their underlying scientific principles. Furthermore, decontextualized interpretations of historical records have occasionally led to misinformed conservation strategies.

From the perspective of ICH, lime technology embodies significant technological value, artisanal lineage, and regional characteristics, reflecting the agricultural-era wisdom of utilizing local materials and adapting techniques to local conditions. Although lime-related crafts, such as traditional boat-making, plaster sculpting, and regional construction techniques, are included in China's national ICH list, lime craftsmanship itself often remains implicit and supportive rather than explicitly recognized. Yet, it constitutes an irreplaceable component of traditional construction processes and is essential to the holistic preservation and continuity of traditional building techniques.

Without a comprehensive understanding of traditional lime works, its application in architectural heritage conservation cannot be scientifically grounded and may instead cause further damage. Examples include blistering of lime coatings on walls and localized collapses in recently restored

sections of the Ming Great wall at over 20 locations in recent years, failures largely attributable to inadequate research into traditional lime materials and incorrect repair behavior.

Supported by modern scientific research, including experimental reconstructions of traditional processes analyzed to elucidate reaction mechanism, and grounded in textual and historical studies, this paper systematically examines traditional lime technology through six integrated perspectives: raw materials (石, *shi*), calcination fuel and methods (煨, *duan*), slaking processes (解, *jie*), formulation design (方, *fang*), construction techniques (工, *gong*), and curing characteristics (固, *gu*). By reconstructing variations in materials, fuels, firing techniques, slaking methods, mortar formulations, and processing technologies, this study aims to establish a comprehensive research framework to support future heritage conservation (Fig. 3).

Simultaneously, the value of lime technology extends beyond technical utility. From the perspective of ICH and traditional craftsmanship, it represents not only a fusion of materials science and engineering, but also a holistic system of living practical knowledge, social networks, and cultural significance. Research on its value is thus evolving from a narrow focus on skill preservation toward a multidimensional intersection of culture, science, and ecology. Drawing on archeological history, anthropological fieldwork, and materials science experimentation, this study seeks to strengthen the synergy between heritage science and community development, establish a cross-disciplinary, cross-regional, and cross-cultural collaborative network, and revitalize traditional lime technology within the contexts of sustainable construction and ecological civilization.

Methods

This study employs an integrated, multidisciplinary methodology to investigate traditional lime techniques in China's architectural heritage. By combining qualitative and quantitative approaches, the research bridges the domains of cultural heritage studies and materials science. It is designed to systematically document, analyze, and interpret both tangible and intangible aspects of lime craftsmanship, facilitating a holistic understanding of its historical development, technical processes, and contemporary relevance.

Historical and documentary analysis provides the foundational context for this research. A systematic review of ancient texts, technical manuals, and local records was conducted to trace the historical evolution of lime production and application. This archival research offers critical insights into the socio-technical evolution of lime use across various dynasties and regions in China. Complementing this historical inquiry, archeological field investigations were undertaken at traditional production sites, including historical kiln structures and quarries. Material samples collected from heritage structures were analyzed to correlate textual descriptions with physical evidence, helping to validate chronological developments and regional variations of lime-based materials.

Fig. 1 | Moisture circulation at masonry mortar interfaces.

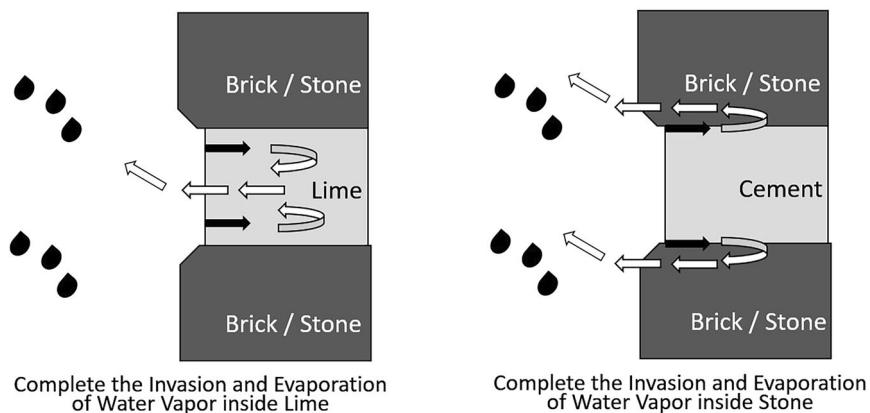


Fig. 2 | Carbonation cycle in pneumatic lime.

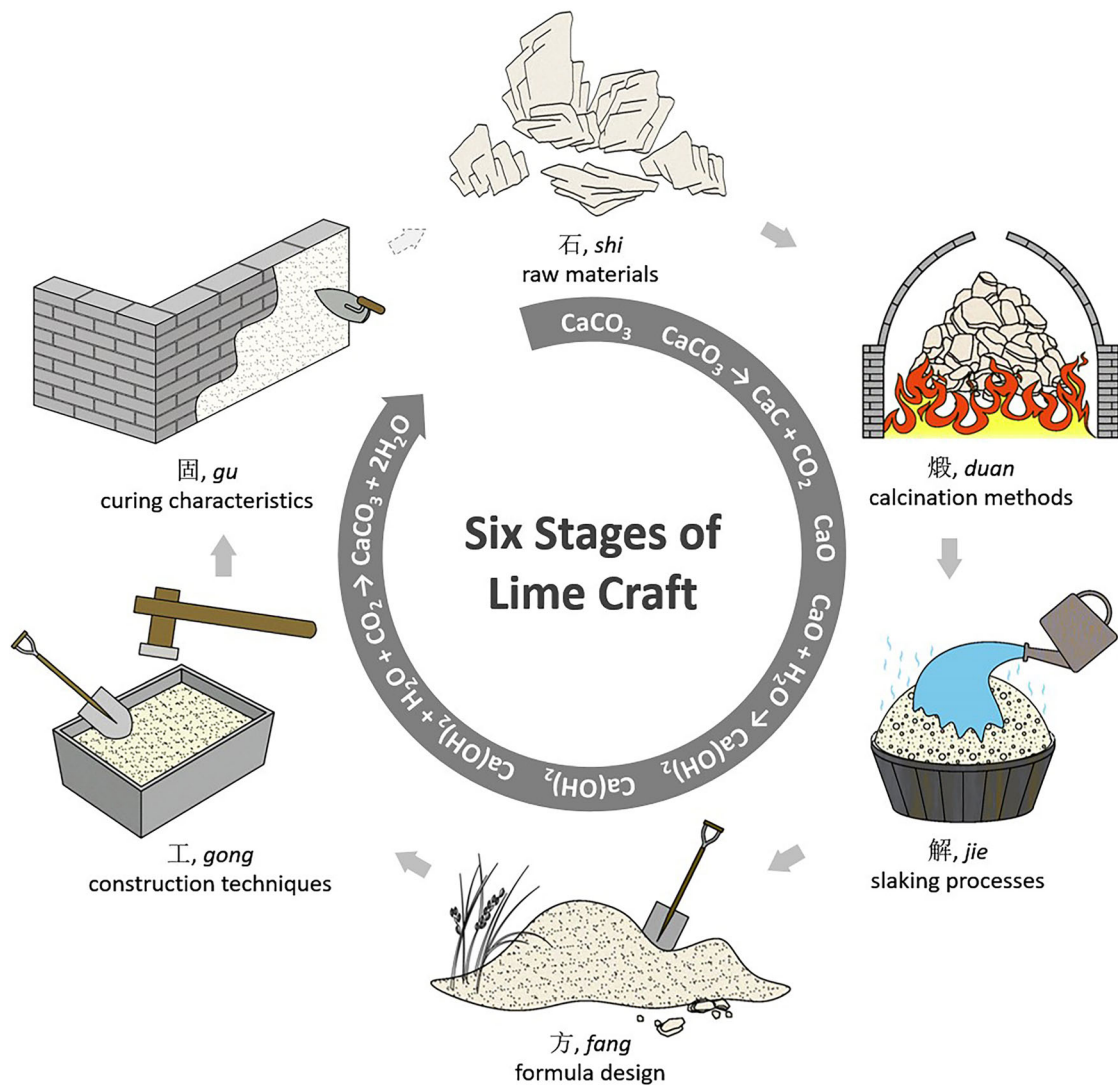
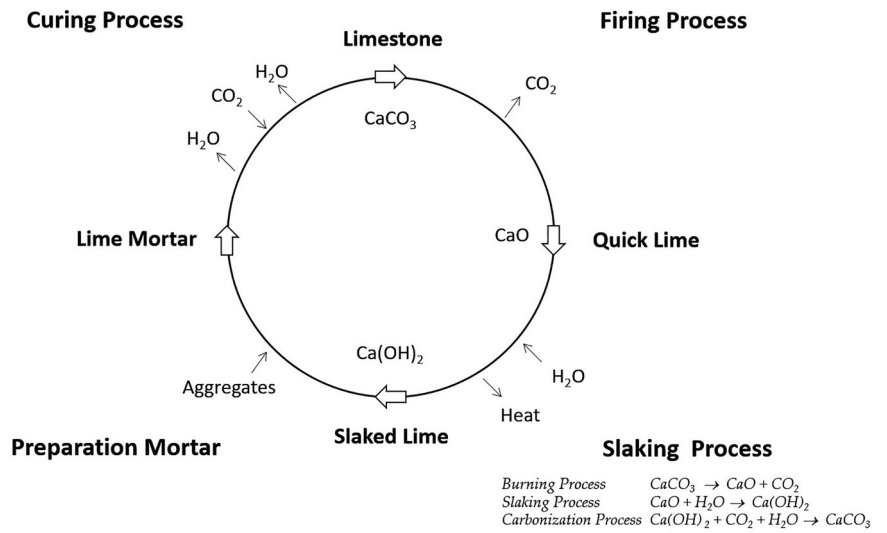


Fig. 3 | Schematic diagram of the lime crafts system.

Anthropological methods, including participatory observation and in-depth interviews with practicing artisans, were essential for capturing tacit knowledge and socio-cultural dimensions of lime techniques. Fieldwork focused on documenting operational sequences, ritual practices, and community-based knowledge transmission, highlighting the living tradition of lime craftsmanship.

Laboratory analysis utilizing materials characterization techniques—such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and chemical composition testing—provided quantitative data on the microstructure and performance characteristics of traditional lime materials. Experimental reproductions of key processes, including carbonation, hydration, and weathering were conducted to compare traditional lime with modern alternatives such as cement and industrial limes (e.g., CL90, NHL). These experiments assessed comparative compatibility, durability, and sustainability.

The technical investigation is structured around six core stages of lime production and application: raw material selection, calcination, slaking, formulation, construction techniques, and curing. Each stage is examined through an integrative approach combining historical documentation, anthropological data, and scientific experimentation to construct a comprehensive technical narrative.

Finally, from an ICH perspective, the study synthesizes its findings to discuss cultural value systems, knowledge transmission mechanisms, and conservation strategies. The multidisciplinary framework—incorporating historical, archeological, anthropological, and experimental evidence—not only reconstructs traditional lime technology but also informs its potential application in contemporary conservation practice and sustainable development.

Raw materials for lime production

According to ancient documents, two primary raw materials were utilized for firing lime in Chinese construction: limestone and oyster shells.

The practice of quarrying mountain rocks to produce lime emerged no later than the middle of the Yangshao culture, during which *jiang-shi* (姜石), a type of ginger-shaped stone, was predominantly used²⁰. By the Longshan culture period, limestone had become a standardized material for lime production. For instance, a kiln unearthed in 2004 at the Xiaweiluo site in Xunyi, Shaanxi (2900–2100 BC), contained masses of lime, lime powder, fragmented bluestone, and calcined siliceous limestone²¹, indicating that lime burning using limestone was already a mature technology during this era. Since then, the use of lime has served as key evidence for identifying ancient human settlements, and natural stones along with calcite, or dolomite-bearing organisms became the principal raw materials for lime making from this period onward²².

The earliest explicit documentary record of limestone calcination for lime in China appears in *Bowu Zhi* (《博物志》, Records of Myriad Things), compiled around 290 CE by Zhang Hua during the Western Jin Dynasty: “By calcining white stones, one obtains white ash. When the firing is complete and the ash is heaped on the ground, it cools entirely after a day. If rainwater is poured upon it, the pile flares up again, emitting smoke and flames.”²³ This passage indicates that lime (white ash) was produced by firing white stone and subsequently slaking it with water, a process that releases considerable heat and steam.

A similar account is found in *Commentary on the Classic of Materia Medica* (《本草经集注》), compiled around 500 CE by Tao Hongjing during the Southern Liang Dynasty: “Nowadays, near the hills, one finds a bluish-white stones. After firing in a kiln, if water is poured upon it, the mass steams, heats intensely, and crumbles into powder... Commonly known as *shi-e* (lime), it has been used since antiquity in constructing tombs, for its properties in waterproofing, repelling insects, and inhibiting decay.”²⁴ The description of lime calcination and slaking is consistent with that in *Bowu Zhi* and highlights its functional applications in moisture prevention, sterilization and pest control.

An earlier reference to lime use appears in the *Rites of Zhou* (《周礼》, *Zhouli*, compiled late Warring States period, ca. 4th–3rd century BCE), in

the section “Autumn Official: Minister of Crime”, which describes an official method for eliminating aquatic insects: “(The office) is in charge of eliminating aquatic vermin: they roast the stones (lime-rock) and cast them into the water.”²⁵ This practice was later elucidated by the Qing scholar Wu Hao in *Dubia on the Thirteen Classics* (《十三经义疑》, late 18th century): “*Fen-shi* (焚石, roasted stones) is what we now call lime (*shihui*, 石灰). When the calcined stones encounters water, it crackles, and the resulting sound and heat drive away aquatic pests.”²⁶ Thus, by the Northern and Southern Dynasties, the functional properties of lime, initially recorded for pest control, were conventionally employed in tomb construction for its waterproofing and insect-repelling properties.

Notably, both the *Records of Myriad Things* and *Commentary on the Classic of Materia Medica* describe limestone colors such as white or bluish-white, reflecting early mineral selection criteria. *Tiangong Kaiwu* (《天工开物》, The Exploitation of the Works of Nature, 1637) by Song Yingxing further noted that stones used for lime primarily blue, though occasionally yellow or white²⁷. Limestone is primarily composed of calcite (calcium carbonate) and typically appears gray-white; impurities may yield shades of dark gray, light red, or light yellow. Although ancient practitioners lacked modern mineralogical knowledge, empirical observations enabled them to identify bluish or yellowish-white stones as producing high-quality lime, a conclusion corroborated by contemporary scientific research.

Since the pre-Qin period, coastal regions of China have maintained a tradition of producing lime by calcining oyster shells. Ancient texts refer to lime derived from these biological sources as shell-lime (蜃灰, *shi-hui*) or, when mixed with charcoal, as clam-charcoal (蜃炭, *shi-tan*)²⁵. According to the *Rites of Zhou*, this mixture was applied to repel pests and control moisture, and it was used in the construction of buildings and tombs for purposes such as wall plastering, disinfection, and insect prevention. The origin of shell-lime and clam-charcoal is likely associated with the Shandong Peninsula, then part of ancient Qi State. Known as Dongyi during the Xia and Shang dynasties. Strategically located with less developed agriculture than the Central Plains, Qi leveraged its coastal resources by engaging in salt production and promoting industry and commerce, rapidly ascending to prominence during the Spring and Autumn Period. It is highly probable that the shell-lime and charcoal mixture used in Zhou palaces construction was supplied from Qi. Similar use of shell-lime has also been identified in the palace remains of the Bohai Kingdom (Goguryeo)²⁸.

The traditional method of lime making from oyster shells persisted for millennia and only declined in the 20th century. As recorded by Song Yingxing in *Tiangong Kaiwu*: “Along the coasts of Wenzhou, Taizhou, Fujian and Guangzhou, where local stone is unsuitable for lime production, nature provides oysters and mussels to serve as substitutes.”²⁷ An illustration in his work (Fig. 4) clearly indicates that oyster shells were the primary raw material. The production process involved stacking oyster shells in open areas to rinse them with rainwater or to wash them manually to reduce salt content. Workers then layered alternately with charcoal in kilns and fired at high temperatures. The resulting calcined material was cooled, sieved into powder, and sometimes further sprinkled with water or pounded to refine it into what was known as oyster-shell lime. In some cases, fine coral reefs were used as an alternative to oyster shells. This traditional technique matured no later than the early Ming Dynasty and became well-established among artisans in the southeastern coastal regions. By the 16th century, the method of firing oyster-shell lime had been transmitted to various regions in the Philippines and Southeast Asia, reflecting its significant role in technological exchange and cultural diffusion²⁹.

Limestone, a sedimentary rock predominantly composed of calcium carbonate (CaCO₃), is one of the most abundant mineral resources on Earth. Global limestone reserves are substantial, with estimates exceeding two billion tons. China ranks among the world’s richly endowed countries in terms of limestone resources and is also a leading global producer³⁰.

Fig. 4 | Lime production from oyster shells in *Tiangong Kaiwu*²⁷.

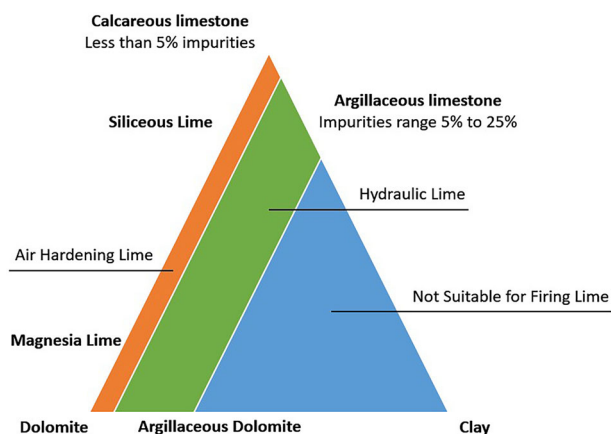
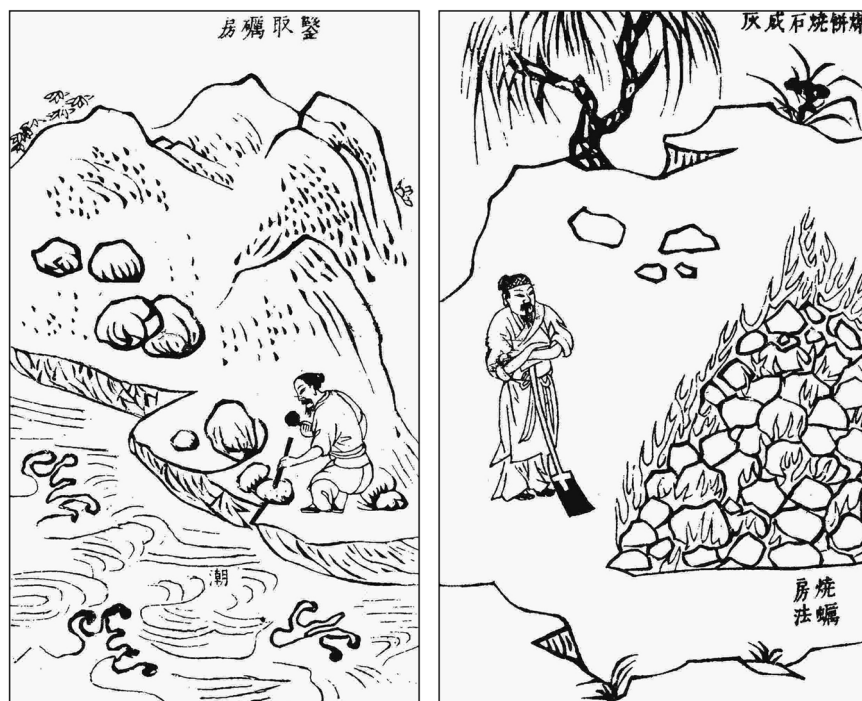


Fig. 5 | Relationship between raw materials and lime types.

According to current Chinese national standards, lime is categorized into two types based on calcium and magnesium content: calcareous lime and magnesian lime, the latter defined as containing more than 5% magnesium oxide (MgO). Both types are air-hardened limes, meaning they set and harden upon exposure to air. The blue limestone mentioned in *Tiangong Kaiwu* has been confirmed through modern practice to be primarily calcareous limestone, suitable for producing calcareous lime or lime with low hydraulic activity. In contrast, most yellow-white limestone is dolomitic or magnesium-rich, yielding magnesian or high-magnesium lime after calcination.

The production of high-purity lime generally requires that the clay content in the raw materials remains below 5%. When the clay content ranges between 5% and 25%, the resulting lime exhibits hydraulic properties due to the formation of dicalcium silicate (C₂S, 2CaO·SiO₂), which enables hardening under water. This variety is classified as hydraulic lime. The correlation between raw material composition and lime type is summarized in Fig. 5.

Owing to a lack of explicit historical documentation, it remains difficult to confirm whether hydraulic lime was intentionally produced or used in

ancient China. However, raw materials such as certain natural limestone, oyster shells in coastal areas, or *Aga earth* in Xizang contain inherent siliceous and argillaceous components³¹. Lime calcined from such materials likely exhibited partial hydraulic characteristics, resulting in enhanced binding properties, compressive strength, dimensional stability, water resistance, and freeze-thaw durability compared to those of air-hardening lime.

Processes and methods of calcining lime

Under the traditional labor system in ancient China, the production of building materials was an exceptionally arduous undertaking³². Tasks such as mining, material handling, firing, and processing were conducted under some of the most challenging working conditions and involved high labor intensity. Among these processes, calcination was essential for lime production, and the use of vertical kiln represents one of the earliest mastered methods historically. The calcination temperature for ordinary lime generally does not exceed 900 °C, a range achievable with ancient firing techniques.

Experienced artisans accumulated and transmitted practical knowledge such as the Fire Formula: “White smoke rises, yellow smoke falls, green smoke remains still.” This empirical rule was used to estimate furnace temperature and determine optimal firing duration based on the color of emitted smoke. Additional techniques included raking ash inside the kiln with long-handled iron tools to prevent agglomeration and ensure even burning.

A Neolithic lime kiln unearthed at the Xiaweiluo site in Xunyi, Shaanxi, exemplifies early vertical kiln structures. Its firing chamber is nearly circular in plan, with curved walls situated directly below the kiln superstructure. An opening at the top was likely used for loading raw materials (Fig. 6). The vertical kiln design remained the predominant method for lime burning throughout ancient Chinese history. A Tang Dynasty kiln site in Gongyi, Henan, displays a similar structure, consisting of a vertical circular chamber and a basal firebox³⁴ (Fig. 7). Even after the establishment of the People’s Republic of China, this kiln type continued to be used in rural areas, such as in Dagu Village, Mabugang Town, Longchuan County, and Heyuan County, Guangdong Province (Fig. 8).

Fig. 6 | Lime kiln excavated at Xiaweiluo, Xunyi County, Shaanxi Province³³.

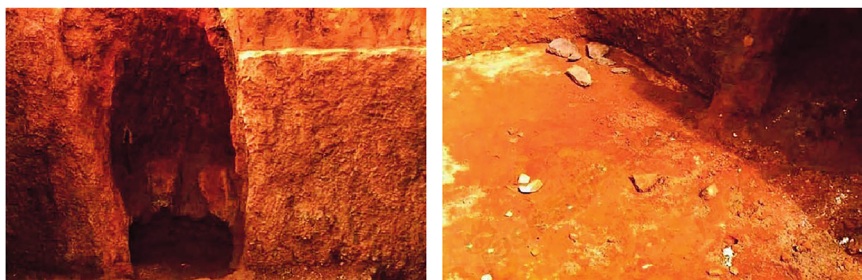


Fig. 7 | Tang-Dynasty lime-kiln site at Gongyi, Henan Province³⁴.



Fig. 8 | Lime kiln at Dagu Village, Mabugang Town, Heyuan, Guangdong Province.



Fig. 9 | Nineteenth-century lime kiln at Clints Wood, England³⁵.

However, due to its labor-intensive nature of its operation and associated environmental impacts, traditional kilns were largely supplanted by mechanical vertical kilns after the 1990s. This kiln type was not exclusive to China; similar structures were used in the West, as evidenced by a 19th-century British lime kiln (Fig. 9) and a traditional kiln site in west-central Scotland (Fig. 10).

Owing to limited textual and material evidence, it remains uncertain whether lime produced in such simple vertical kilns originated from high-purity limestone or stone mixed with clay and other impurities. The quality of lime produced in these kilns varied considerably, influenced by raw material quality, calcination temperature, and firing duration.

Typically, calcareous limestone requires calcination temperature between 900 °C and 1000 °C, while the ideal range for producing high-quality quicklime is 950–1150 °C, except when raw materials contain mud or silicon. Inadequate temperature or insufficient firing duration resulted in poor-quality lime. Dolomitic or yellow-white limestone decomposes at ~730–900 °C. Quicklime produced from dolomite at temperatures exceeding 900 °C is generally unsuitable for construction purposes³⁷.

Lacking precise temperature measurement, ancient craftsmen relied on experience to control the firing process, judging completion through visual cues such as furnace color and firing time. For instance, during the Qing Dynasty, lime production in Chenmu Town (Suzhou) differed significantly from that in Yixing (Wuxi). In Yixing, hardwoods were used as fuel, with firing completed within five to six days. The intense, rapid process often resulted in lime that was less suitable for wall construction or fine plastering. In contrast, Chenmu Town employed rice straw or vegetable stalks as fuel, with firing lasting fifteen to twenty days. The slower, milder process yielded a finer and more workable lime, highly valued for various application³⁸.

These differences suggests that Yixing's high-temperature, short-duration firing risked overburning, whereas Chenmu's lower-temperatures,

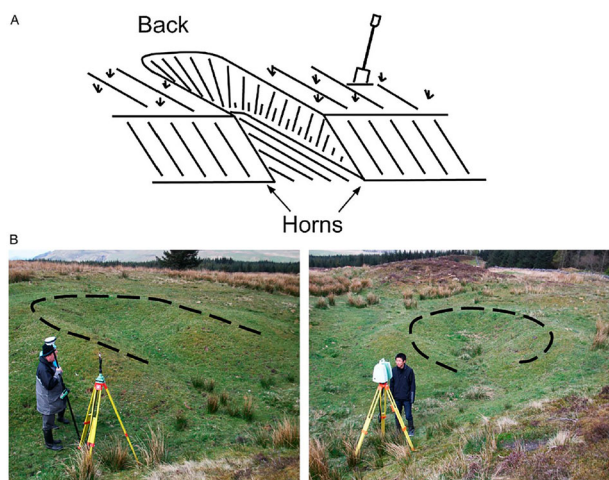


Fig. 10 | Eighteenth-century lime kiln at Blairskaitth Trig, Baldernock, Scotland³⁶. A Sketch of clamp kiln redrawn by Bishop from Nisbet, S.; B Degraded remains of clamp kilns at Blairskaitth Trig, Baldernock (left: U-shaped kiln, and right: adjacent horseshoe-shaped kiln).

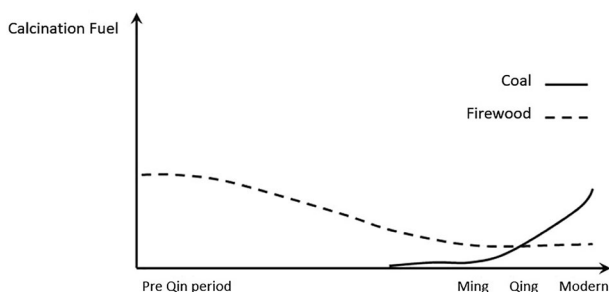


Fig. 11 | Trend for the use of lime calcination fuel.

prolonged firing enhanced product quality. Alternative methods were also employed, such as the pile-firing technique illustrated in *Tiangong Kaiwu* (Fig. 4), particularly for oyster shells, which require less fuel due to their thinness. This traditional method continues to be practiced in certain coastal regions such as Wenzhou.

Throughout much of Chinese history, firewood was the primary fuel for lime burning. *Yingzao Fashi* (Volume 27) records the use of reeds and weeds (茭草, *shancao*) in kiln operation. By the Ming and Qing dynasties, population growth in North China resulted in firewood shortages, leading to a gradual shift toward coal as an alternative fuel. In the more forested regions of South China, however, firewood remained the dominant fuel until the 1970s (Fig. 11).

Tiangong Kaiwu offers one of the few detailed pre-modern descriptions of lime calcination technology: “First, take coal and mud to make coal cakes. Place each layer of coal cakes alternating with a layer of stone. Ignite from the bottom. The best ash is called *mineral ash*, and the poorest is called *kiln slag ash*. When the firing is complete, the stone’s properties are transformed.”²⁷ When firewood was used instead of coal cakes, continuous feeding is required, consuming substantial quantities of wood. According to *Ming Huidian* (《明会典》, the Collected Statutes of the Ming Dynasty), each kiln of lime, ~16,000 kg, required about 178 bundles of reeds and firewood, each measuring approximately five *chi* in length³⁹.

Lime production was also accompanied by ritual practices, especially before the Republican period. In region such as Jiangning (present-day Nanjing), quarrying and lime burning involved ceremonial activities. An annual mountain sacrifice was held on the fifth day of the lunar new-year, featuring offerings, firecrackers, and incantations intended to ensure safety



Fig. 12 | Gray clay used in Ming Dynasty mural tombs in Loudi, Hunan⁴¹.

and success. Kiln ignition ceremonies required offerings of three types of animal sacrifice and incense to the Kiln God, reflecting a tradition shared with stove and furnace worship, typical of craft-based deity worship in traditional Chinese industry.

Slaking processes of lime

As a fundamental building material, quicklime must undergo slaking before it can be used in construction. Historical records indicate that structural failures occasionally resulted from the use of un-slaked (“new”) lime in tombs construction. A Ming Dynasty folk account describes such incidents: “It is now common among moderately wealthy families to heap lime around the brick burial chamber. The lime must be sieved and left to lose its *fire-qi* (火气) before it is placed in the tomb; after a long time it sets and becomes hard. I once heard of a family who packed fresh lime outside the coffin to keep out moisture. Unaware that lime, when it lies close to wood and is acted upon by the damp earth vapors, can ignite and destroy itself, they found the outer coffin burnt and the tomb vault collapsed.”⁴⁰

Although explanations involving *fire-qi* and interactions among the Five Phases reflect traditional beliefs, the technical rationale for avoiding fresh lime is clear: after the tomb is sealed, groundwater infiltration triggers a reaction in the un-slaked lime, releasing heat and causing volumetric expansion. This process can corrode wooden coffins, exert pressure on brick walls, and ultimately lead to structural collapse of the tomb (Fig. 12).

As indicated in historical texts, watering was a common method for slaking lime as early as the Northern and Southern Dynasties. This process involves the reaction of calcium oxide (CaO) with water to form calcium hydroxide [Ca(OH)₂], releasing significant heat²⁴. By the Tang Dynasty, the weathering method, whereby quicklime was exposed to air for a period before use, had also been developed. Ancient practitioners recognized that weathered lime exhibited distinct properties, leading to its specific application in various contexts, including traditional Chinese medicine recipes⁴².

The *Bencao Tujing* (《本草图经》, Illustrated Classic of Materia Medica, 1061) of the Song Dynasty differentiated between lime slaking methods: “Lime is produced in the valleys of the Zhongshan region; today it is found everywhere near mountainous areas. It is made by burning blue-stone and is also called stone forging. There are two kinds: wind-slaked and water-slaked. Wind-slaked lime is obtained by taking the already-burned stone and exposing it to the wind, where it disintegrates of itself; this is the stronger variety. Water-slaked lime is produced by drenching the stone with water; steam rises as it breaks apart, and its strength is somewhat inferior.”⁴³ Thus, traditional medicine considered wind-slaked (weathered) lime more potent than water-slaked lime.

Which method was more common in ancient practice? *Tiangong Kaiwu* states: “(Lime) left in the wind will, in time, be blown into powder of itself, if it is needed at once, water is poured on it and it likewise breaks up spontaneously.”²⁷ This suggests that atmospheric weathering was the conventional method, with water used only in cases of urgency. Studies indicate



Fig. 13 | Surface morphology of weathered lime and natural limestone.

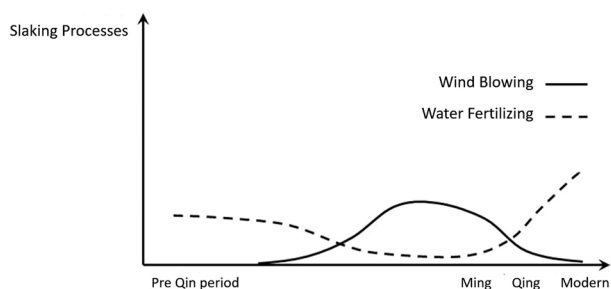


Fig. 14 | Historical trends in slaking methods for quicklime.

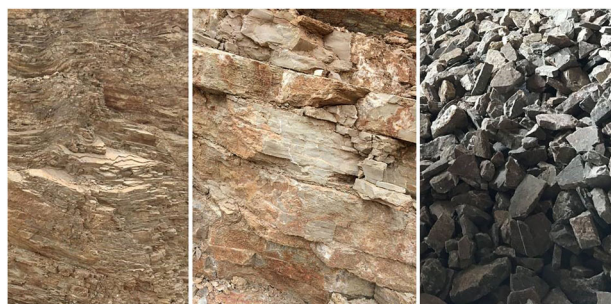


Fig. 15 | Lime mines, raw stone materials, and crushed limestone before firing from the Zhejiang-Anhui border region.

that although wind-slaked lime develops strength slowly initially, it carbonizes faster, shortening construction timelines, and ultimately achieves higher long-term strength⁴⁴. By the Ming Dynasty, weathering was the primary method for producing construction lime (Fig. 13).

During the Qing Dynasty, however, the use of lime paste for wall plastering increased. Hydration was found to improve the workability, fineness, and shelf life of lime paste, making it more convenient for storage and application. Consequently, hydration gradually supplanted weathering as the mainstream slaking method, nearly leading to the disappearance of the traditional weathering process (Fig. 14).

With growing interest in traditional materials such as hydraulic lime for heritage conservation, this study investigates the early hydration mechanisms and compositional stability of weathered lime. The goal is to improve material performance, broaden application potential, and identify suitable raw materials for restoring historic structures.

Variations in lime composition with different weathering durations were examined, and the effect of weathering time on mineralogical changes was analyzed. The early slaking mechanism and stability of weathered lime were evaluated based on composition and microstructure at different curing ages. Mechanical properties and stability were assessed by monitoring changes in physical and chemical characteristics over time.

The Zhejiang and Anhui border region is rich in high-quality limestone (Fig. 15) and has a long history of lime production. Three types of limestone were studied: block limestone (reddish-brown with a bluish fresh surface), strip limestone, and flake limestone (both bluish-gray) (Fig. 16). These



Fig. 16 | Three types of limestone used in lime calcination.

correspond to the high-quality raw materials documented in *Tian-gong Kaiwu*.

Chemical analysis showed that limestone from this region contains argillaceous silica, with acid-insoluble content ranging from 2.17% to 8.46% (Table 1). Block limestone is characterized by low acid-insoluble residue, whereas flake and strip limestone exhibit higher values, reaching 7–8%. Further chemical analyses indicate that these lithotypes are enriched in SiO₂, Al₂O₃ and Fe₂O₃. The hydraulic index (CI) of flake and strip limestone ranges from 0.37 to 0.54, meeting the compositional requirements for natural hydraulic lime (Tables 2 and 3).

Lime samples weathered for different durations were dried, sieved, and crushed for testing. Their physiochemical indices and morphologies are summarized in Table 4 and Fig. 17, respectively. Material properties including bulk density, stability, setting time, mechanical strength, and carbonization depth were evaluated under both laboratory and field conditions.

Under natural ventilation, quicklime blocks underwent slow disintegration without significant heat release (Fig. 18). Some samples rapidly powdered, while others cracked or remained largely unchanged. The rate and extent of pulverization were influenced by factors such as CaO content, hydraulic components, and firing temperature.

X-ray diffraction (XRD) analyses revealed mineralogical change during weathering: CaCO₃ increased over time, while CaO decreased. The hydraulic component 2CaO • SiO₂ gradually diminished, and Ca(OH)₂ content initially increased before declined (Fig. 19).

Lime weathered for 20 days exhibited an initial setting time of 1 h and a final setting time of 3 h, significantly shorter than the 70-h initial setting time of water-slaked lime (Fig. 20). Mechanically, weathered lime demonstrated high compressive strength, especially in air-cured specimens: 1 MPa at 7 days and 1.55 MPa at 28 days. This performance is comparable to that of NHL2 natural hydraulic lime per European standards, and superior to both water-slaked lime and modern industrial hydrated lime CL90 (Fig. 21).

Formula of building lime

Significant progress has been made in the scientific study of traditional building lime, particularly in the reconstruction of historic mortar formulations. However, research remains limited regarding the impacts of material properties on processing techniques and overall performance. In accordance with the principle of employing authentic materials and techniques in heritage conservation, the optimization of lime-based formulations has become an important research focus in recent years.

In historic construction, lime formulations varied considerably depending on their specific application and the incorporation of admixtures. Ancient texts document numerous recipes categorized by use, including masonry, plastering, flooring, and waterproof sealing. Artisans from different regional schools developed unique proprietary formulations and techniques, accumulating specialized expertise in processes such as

Table 1 | Acid-insoluble content of limestone raw materials (wt%)

Mining terminology	Characterization	Content (%)
Flaky limestone	The fresh surface is a gray mudstone with a thickness of several millimeters mixed with calcareous mudstone.	7.72
Striped limestone	Muddy limestone with a thickness of several centimeters.	8.46
Block limestone	The weathered surface is brown, and the fresh surface is dark to light gray block limestone.	2.17

Table 2 | Chemical composition of limestone samples (oxide weight percentage)

Oxide type	Flaky limestone	Striped limestone	Block limestone	Proportion of raw materials (%)
CaO	45.26	46.88	48.04	
SiO ₂	7.38	4.96	2.99	4–16
Na ₂ O	5.69	7.02	8.32	
K ₂ O	0.36	0.22	0.14	
Al ₂ O ₃	3.25	2.76	1.89	1–8
SO ₃	0.86	0.63	0.52	
Fe ₂ O ₃	0.50	0.39	0.14	0.3–6
MgO	0.49	0.14	0.09	
Cl ^a	0.54	0.37	0.218	0.3–1.1

^aCl is the hydraulic index.

Table 3 | Performance characteristics of hydraulic lime

	Types of natural hydraulic lime		
	NHL-2 weak hydraulic	3.5 medium hydraulic	5 strong hydraulic
7-day intensity (Ma)	–	≥1.5	≥2
28-day intensity (Ma)	2–7	3.5–10	5–15
Cl ^a	0.3–0.5	0.5–0.7	0.7–1.1

$$Cl = \left[\frac{(2.8 * SiO_2\%) + (1.1 * Al_2O_3\%) + (0.7 * Fe_2O_3\%)}{CaO\% + (1.4 * MgO\%)} \right]$$

Table 4 | Physical and compositional data of weathered lime samples

Group	Weathering time (days)	Date	Notes
FC20	20	2022-4-5	Crush and grind, use after passing through a 120 mesh sieve
FC30	30	2022-4-14	
FC40	40	2022-4-24	
NHL-2		Germany Standard	

foundation compaction, brickwork, wall finishing, and seepage prevention. These practices, which are both locally adapted and sustainable, form an integral part of regional architectural traditions. Customized lime mortars were produced through the incorporating aggregates (e.g., sand or clay), fibers (e.g., hemp, straw, cotton), and organic additives (e.g., glutinous rice, tung oil).

For masonry applications, lime was sieved to remove unburnt core material and mixed with clay to form earthen lime, or combined with water to produce mortar. Lime-earth mixtures were used for rammed-earth foundations as early as the Shang and Zhou dynasties⁴⁵.

The Song Dynasty treatise *Yingzao Fashi* (Volume 13, *System of Earth-Plastering Works*) provides detailed specifications: “First, use coarse mud to fill uneven areas and allow to partially dry; then apply medium mud to level the surface, again allowing it to dry slightly; finally, apply a fine mud under-

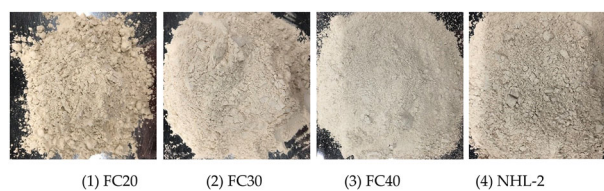


Fig. 17 | Raw materials used in weathering lime process.

layer. After applying lime mud, allow the water to settle and compress five times until the surface becomes glossy.”⁴¹ The text systematically classifies lime mortars by color, texture, application, additives, and mix proportions, forming a comprehensive specification system for traditional plastering crafts (Table 5).

Since the Song Dynasty, building foundations were commonly stabilized using *san-he-tu* (三合土, trinity mixture earth), a mixture of lime, clay, and sand. This material provided solidity, moderate impermeability, and cost effectiveness due to the local availability of materials. Chemical analysis of earth samples from site such as the Dagongmen River Site and the Old Summer Palace’s Ruyuan indicate that SiO₂ and CaO are the main components, consistent with traditional composite earth formulations⁴⁶ (Fig. 22).

Artisans also experimented with organic additives such as egg whites, glutinous rice, tung oil, animal blood, and brown sugar, creating organic–inorganic composite mortars with specialized functions. These

formulations were preserved and refined over time due to their superior performance.

A common masonry mixture incorporating glutinous rice is recorded in *Tiangong Kaiwu*. “For lining tombs and water-cisterns, mix one part slaked lime with three parts river-sand plus loess; bind the whole with a

liquor of glutinous rice (*Oryza sativa* var. *glutinosa*) and *Actinidia rufa* sap. Tamped lightly, the blend sets into a hard mass that will never decay; it is called *San-he-tu*.”²⁷ The use of glutinous rice mortar dates to the Northern and Southern dynasties. Analysis of a brick tomb from that period excavated in Dengzhou, Henan Province, revealed starch residues likely from glutinous rice mortar⁴⁷. During the Tang and Song dynasties, glutinous rice-lime mortar was used in city walls, such as those discovered in Nanchang dating to the 14th year of the Zhenguan reign (640 AD). These walls were constructed with gray bricks, jointed with glutinous rice slurry, bearing inscriptions such as “Great Tang, Gengzi Year”⁴⁸.

The Qing Dynasty text *Qinding Da Qing Huidian Zeli* (《钦定大清会典则例》, Imperially commissioned precedents and regulations of the Great Qing, 1764) formalized the use of glutinous rice in *san-he-tu*: “For three-component earth: one *dan* lime, six *sheng* of rice paste, one *dan* rice, and twenty bundles of firewood.”⁴⁹ The detailed process involved boiling glutinous rice into a thin, long-cooked congee until the grains completely disintegrated. This was mixed with lime, loess, and aggregate in specific proportions and worked thoroughly with a toothed rake. Consistency was critical: the mixture should not be too watery, yet must be fully blended to achieve firmness⁵⁰ (Fig. 23)

Such composite mortars were widely used in critical structural elements including city walls, foundations, tombs, and bridges. For example, the Ming Dynasty Nanjing city wall was bound with glutinous rice mortar and remains structurally sound after over 600 years. Similarly, lime-based composite shells in tombs at Tongwan city and from the Southern Song Dynasty exhibit high strength and durability. Without such materials, brick and timber structures would deteriorate rapidly, losing both functional and cultural value. Even in the late Qing Dynasty, glutinous rice lime mixtures were used in coastal fortifications⁵¹.

To this day, traditional artisans preserve techniques and mnemonic such as the “three boils and three filters” for preparing glutinous rice gel: boil glutinous rice → filter residue → boil again → filter again → repeat until the gel is clear. Another mnemonic for the mortar mixing sequence is, “Ash first, sand second, collect clay.” This ensure that the aggregate is evenly coated and the mixture is well homogenized (Table 6).

Lime-based materials constitute the principal inorganic binding system in traditional construction, fulfilling structural, protective, and decorative functions. A refined lime putty, produced through prolonged slaking, decantation, and elutriation, is reinforced with cellulose or fibrous

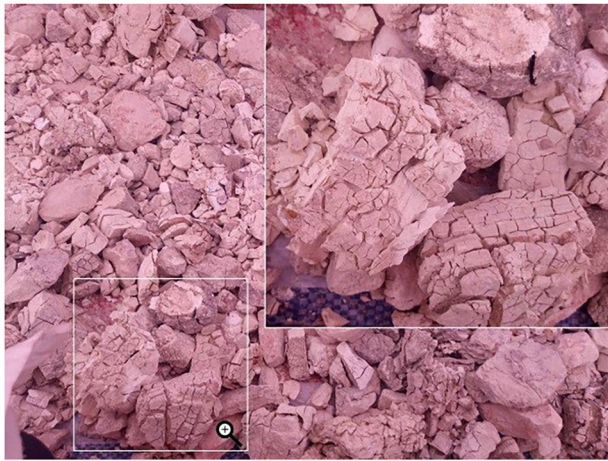


Fig. 18 | Physical state of quicklime after varying durations of weathering.

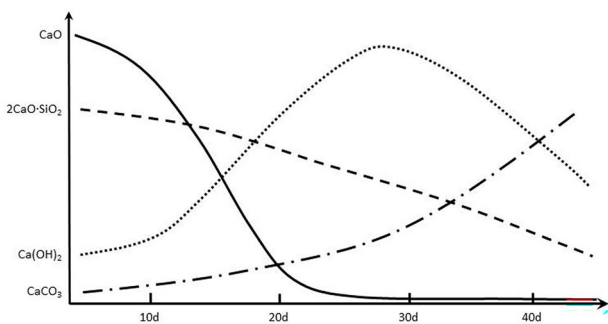


Fig. 19 | Evolution of mineral composition in lime during the weathering process.

Fig. 20 | Setting time of limes under different slaking methods compared with standard industrial lime.

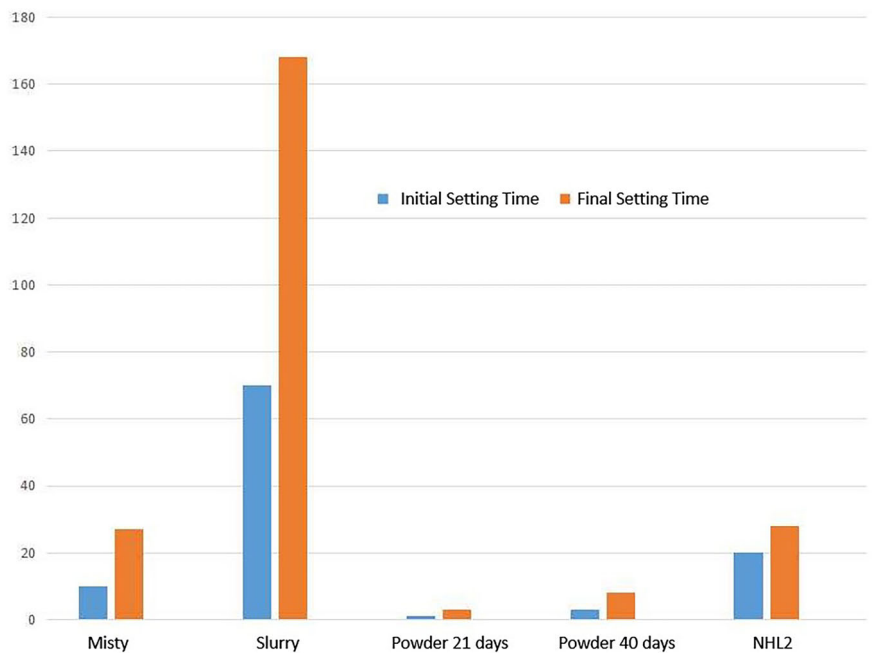


Fig. 21 | Compressive strengths of limes prepared with different slaking methods compared with standard industrial building lime.

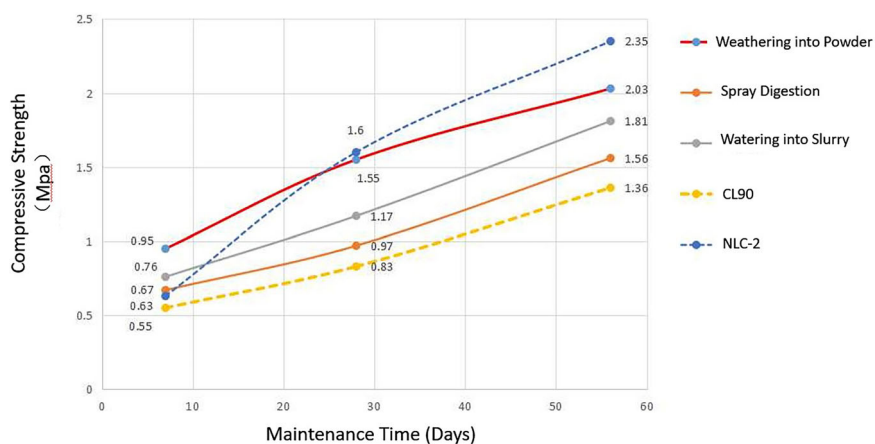


Table 5 | Lime plaster formulations documented in *Yingzao Fashi*

Type	Aggregate	Proportion	Notes
Red-doped Lime Plaster (合红灰)	Quick-lime : earth-cinnabar : red-earth	15 : 5 : 11.8	If not used for palace building, 17 : 3 : 11.8
Blue-gray-doped Lime Plaster (合青灰)	Quick-lime : soft coal dust	1 : 1	if soft coal is unavailable
	Quick-lime : coarse graphite : glue	10 : 1 : 0.07	
	Quick-lime : graphite coal : glue	10 : 1.1 : 0.07	
Yellow-doped Lime Plaster (合黄会)	Quick-lime : yellow earth	3 : 1	
White-doped Lime Plaster (合破灰)	Quick-lime : white-stem earth	1 : 4.8	lime : wheat straw 10 : 9
Fine Earth Coat (细泥)			1 square adds 15 jin wheat straw
Coarse Earth Coat (粗泥)			1 square adds 8 jin wheat straw
Two-Coat Earth Plaster (粗细泥)			for city walls & common houses

For every 30 jin quick-lime add 1 jin hemp tow (麻刀, *ma-dao*); if slaked-lime employed, 8 jin of lime add 1 jin hemp tow.

additives to produce finishing mortars characterized by high ductility and strong adhesion. In multi-layer coating systems, such as render, mural grounding, stucco, terrazzo, and exterior plaster, lime provides an alkaline and microporous substrate that enhances pigment stability and ensures compatibility with underlying materials.

Traditional application protocols are codified through generations of artisanal experience. For example, the thirteen-step *you di zhang zuo* (油灰地仗作, intonaco cycle work) technique in Qing-dynasty official architecture employed a composite of tung oil, lime, and hemp fibers applied to timber, forming a breathable and weather-resistant shell. This intermediate layer mediates the modulus transition between wood and finish coats, thereby enhancing overall durability. Ancient craftsmen summarized the complexity of these mixtures with the saying “*nine pastes and eighteen lime*”, reflecting the wide range of formulations tailored to specific technical requirements, as summarized in Table 7. An analogous materials strategy is observed in *Sanhetu*, a composite of lime, clay, and organic additives deployed in Jiangsu seawalls and sections of the Great Wall. Within this matrix, pozzolanic reactivity and fiber reinforcement contribute to exceptional resistance against freeze–thaw cycling and salt crystallization.

The macro-porous structure of calcium carbonate-based mortars provides high vapor permeability while retaining capillary activity. This hygrothermal functionality reduces interfacial condensation, limits salt accumulation, and prevents spalling and efflorescence, pathologies commonly associated with non-breathable Portland cement coatings that trap moisture. Therefore, even when concealed beneath masonry or tile finishes, lime-based interlayers and mortars remain essential to the long-term preservation and structural integrity of historic buildings.

Waterproof lime mortars were prepared through sedimentation, filtration, and fiber reinforcement, and applied in multi-step processes that included base treatment, priming, coating, compression, and brushing. Mix proportions were carefully adjusted according to specific applications requirements⁵². For moisture-resistant flooring, a compacted mixture of lime, sand, and earth was typically employed. In cases requiring higher moisture resistance, a putty made with tung oil or fish oil was applied. These lime-based systems effectively inhibited groundwater capillary rise, resisted atmosphere moisture, and prevented surface water infiltration. The stable, compact lime-earth layer provided both effective waterproofing and structural reinforcement, ensuring long-term resilience against natural erosion.

Tung oil was particularly significant in hydraulic engineering and application demanding water resistance, such as tomb construction. The Northern Song Dynasty text *Hefang Tongyi* (《河防通义》, Comprehensive Precedents for Yellow River Flood Control, 1048) records a mix ratio for embankments construction: “80 catties of tung oil, 240 catties of lime, 3 catties of lime and 1 catty of oil serve as joint reinforcement agents.”⁵³ Qing Dynasty records for the Yongding River dikes further specify: “Each seam is 5 *chi* wide, 1 *zhang* long, 1 loop of white lime, and 4 catties of tung oil.”⁵⁴ Thus, the tung oil to lime ratio during the Qing Dynasty was approximately 1:4, largely consistent with the 1:3 ratio documented in *Hefang Tongyi* (Fig. 24).

Construction techniques for building lime

The durability of traditional masonry hinged on two inseparable factors: the intrinsic quality of the materials and the logical rigor of their construction methods. Lime, the ubiquitous binder and finishing medium, exemplified this interdependence. Its final strength, porosity and adhesion were



Fig. 22 | Remains of the Haiyantang Reservoir site, Old Summer Palace, Beijing.



Fig. 23 | External wall structure of the earthen building in Longyan, Fujian.

determined long before the application, governed by the petrology of the source limestone, the temperature profile within the kiln, the completeness of slaking, the intensity of fiber incorporation, and the precision of placement. On site, these variables were systematically intergrated into a six-step craft sequence: stone selection, firing, slaking, pounding, plastering, and layered ramming. Among the various traditional lime application techniques, plastering and ramming are particularly representative. Together they transformed lime into a versatile technical interface capable of uniting timber, brick and stone into a coherent and durable fabric. The following sections examine these methods and their material specificities.

The performance of lime-earth and mortar slurries is highly dependent on the construction process. Improper techniques can compromise even well-formulated material. For instance, historical records from the Qing Dynasty note: “Lime-earth does not initially bind well with rice paste; however, without adequate mixing and curing time, the use of rice paste, though beneficial in theory, may lead to cracking.”⁵⁵

This underscores the importance of compaction. Lime-earth achieves structural strength only through sufficient ramming, especially in foundations. In imperial mausoleum projects of the Qing Dynasty, the *Xiaohang Zuofa Guiju* (看小夯作法规矩, a codified procedure for high-density earthen construction) was employed. The construction of Huiling during the Guangxu reign documented a rigorous lime ramming process, including material standards, quality inspections, and precise compaction sequences. The *dry work* phase, conducted before the introduction of water, involved a meticulously ordered procedure: laying and smoothing a bottom cushion; spreading an initial half step lift of lime-earth; removing loose particles through careful dust absorption; perforating form-board joints with vent

holes; drilling supplementary meteor relief openings through the full thickness; and repeating the half-step lime-earth placement to complete the dry assembly before moisture was introduced⁵⁶.

Beyond the officially codified procedures, vernacular variants evolved regionally for the construction of *San-he-tu* structures. Taking Fuzhou as a representative case, filed investigation and geotechnical testing of extant traditional dwellings have allowed the following construction sequence to be reconstructed: First, loess was stirred in water to form a homogeneous paste into which fully hydrated lime was gradually incorporated. Refined tung oil was then introduced, and the mixture vigorously worked with a hoe until it cohered into coherent lumps. An 8–10 cm deep groove was pre-cut into the subgrade to receive the material. The prepared compound was laid in three successive lifts, each compacted evenly before the next was added. After two or three courses had been built up to the required thickness, a hardwood tamper shod with iron was used to pound the surface to perfect plane. Finally, a wooden float was drawn across the floor until a slight oily sheen was emerged, indicating full consolidation and curing⁵⁷.

Plastering involved multiple steps from substrate preparation to finishing, using differentiated mortars such as base-coat lime, hemp-reinforced lime, and finish lime. A typical process included: substrate treatment (wetting, crack filling, nailing or pressing hemp fibers), base coating, covering, and polishing⁵². Substrate conditioning began with controlled pre-wetting, encapsulated in the vernacular adage “water is the bricklayer’s glue”, which ensured a uniformly saturated wall to supply the moisture for portlandite carbonation and provided a clean, micro-rough surface for optimum mortar-adhesion. When replastering existing masonry, the protocol was extended: cracks and voids were first raked out and filled, after which hemp fibres are mechanically anchored through nailing and pressing (压麻, *ya-ma*), forming a three-dimensional reinforcement grid that integrated old fabric with new render.

A base-coat of hemp-fiber lime plaster was then applied and screeded with a large steel float to achieve a level surface and to establish a strong bond for subsequent layers. The levelling coat was allowed to dry until approximately 70% firm (surface dull but firm to thumb pressure) before the finishing coat is applied; premature or delayed application risked hollow drumming, blistering and visual defects.

The timing of final troweling and compacting (赶扎, *gan-zha*) was governed by the evolving rheology of the lime plaster. Traditional practice referred to *three grouts and three ties* (三浆三扎, *san-jiang san-zha*), a cyclic process of light wetting and recompaction originally developed for bedding joints but equally applicable to rendering. Empirical evidence indicates that repeating the cycle beyond three passes further expels residual water, refines surface pore structure, and increases final bulk density, thereby extending service life.

A detailed technological note appears in *Yuanye* (《园冶》, The Craft of Gardens, 1631), the earliest extant Chinese treatise devoted exclusively to garden design and landscape esthetics, compiled by the Ming-dynasty master Ji Cheng. In the section *Bai-fen Qiang* (White Powder Wall) Ji records an upgraded plaster formulation: “Traditionally, walls were lime-washed over paper pulp; yet a finer, glossy surface may be obtained. Those in former times polished the coat with white wax; today river sand from Jianghu is mixed with a small portion of good lime for the base, then lightly dusted with additional lime and rubbed with a hemp broom to produce a wall naturally bright and mirror-like. Should dirt, it can be rinsed away, hence the name *mirror wall*.”⁵⁸ From a materials perspective, the substitution of well-graded river sand for clay fines produced a mortar of higher compressive strength and reduced drying shrinkage, while the lime-silica interface offered excellent adhesion and a smooth substrate for painting. A similar procedure is documented in *Yingzao Fayuan* (《营造法原》, Principles of Construction, 1933), the most comprehensive record of late-Qing and early-Republican building craft in the Suzhou region, confirming the continuity of this refined lime-sand rendering technique in Jiangnan vernacular practice⁵⁹.

Pounding mortar (捶灰, *chui-hui*) was a traditional Chinese preparation technique that transformed hydrated lime, fine charcoal ash, and

Table 6 | Types, formulations, and production techniques of traditional lime mortars in modern practice

Name	Primary use	Composition & processing method	Special notes
I. Classification by lime processing methods			
Sprinkled lime (泼灰)	Making various mortars	Quicklime is repeatedly and evenly sprinkled with water to form powder, then sieved	For lime-earth, it should not be used after 3–4 days; for exterior plastering, it should not be used after 3–6 months
Sturried lime (泼浆灰)	Making various mortars	After passing through a fine sieve, it is sprinkled with greyish slurry layer by layer and steeped for at least 15 days before use. Quicklime: Greyish lime = 100: 13	It is not suitable for exterior plastering after more than half a year
Boiled lime mortar (lime paste) (煮浆灰/灰膏)	Making various mortars; interior white lime plastering	Quicklime is mixed with water to form a paste, sieved through a fine sieve, and allowed to swell	It can only be used after more than 5 days; generally not suitable for exposed exterior areas or roofing under layer
Old slurry lime (老浆灰)	Silk-jointed wall masonry	Greyish slurry and quicklime are sieved through a fine sieve and allowed to swell. Greyish lime: Quicklime = 7:3, 5:5, or 10:2.5 (depending on color requirements)	A dark gray boiled lime mortar
II. Classification by hemp-fibers addition			
Plain lime mortar (蒸灰)	Whitewashed wall; knife-jointed wall; glazed masonry	Pure lime paste without additives	No hemp fibers in the mortar
Hemp-fiber mortar (麻刀灰)	Roofing underlayment; pointing for small-scale stonework	Sprinkled paste lime is mixed with water or greyish paste, then hemp cut is added and stirred evenly. Lime: Hemp = 100: 5	
Medium-chopped hemp-fiber mortar (中麻刀灰)	Ridge adjustment; tile laying; plaster filling in wall masonry; plastered wall surface; piled and plastered wall coping	Various lime mortars are mixed evenly, then hemp cut is added and stirred. Lime: Hemp = 100: 4	Used for plastering surface layer, Lime: Hemp = 100: 4
Fine-chopped hemp-fiber mortar (小麻刀灰)	Finishing pointing	Hemp cut is processed to be no more than 1.5 cm in length. Sprinkled paste lime is mixed with water or greyish paste, then hemp cut is added and stirred evenly. Lime: Hemp = 100: 3	
III. Classification by mortar color			
Pure white lime (纯白灰)	Gold brick flooring; rough brick wall masonry; indoor plastering	Mix slaked lime with water, or use lime paste. Hemp fibers can be added if needed	
Light Moon-white lime (浅月白灰)	Ridge adjustment; tile masonry; rough brick wall masonry; outdoor plastering	Mix grout lime with water. Hemp fibers can be added if needed	
Dark Moon-white lime (深月白灰)	Ridge adjustment; tile masonry; smooth white wall masonry; outdoor plastering	Mix grout lime with greyish grout. Hemp fibers can be added if needed	
Red lime (葡萄灰)	Red plaster finishing	Mix slaked lime with water, then add red earth powder and hemp fibers. Quicklime: Red earth = 1: 1; Lime: Hemp = 100: 3–4; If iron oxide red is used, Lime: Iron oxide = 100: 3	
Yellow lime (黄灰)	Yellow plaster finishing	Add golden earth to slaked lime after adding water, then add hemp cuttings. Quicklime: Golden earth: Hemp = 100: 5: 4	If no yellow earth is available, floor yellow can be used, with the dosage halved
IV. Special-purpose mortars			
Hump-back mortar (驼背灰)	Placed under round tiles, above mortar	Commonly moon-white medium hemp mortar	
Joint-filling mortar (扎缝灰)	Joint filling in tile laying	Moon-white coarse or medium hemp mortar	
Head-holding mortar (抱头灰)	Holding the ridge head	Moon-white coarse or medium hemp mortar	
Node mortar (节子灰)	Hook and plaster tile faces in tile laying	Plain lime paste	
Bear-head mortar (熊头灰)	Hanging and plastering bear-head when laying round tiles	Fine hemp mortar or plain lime. For yellow glazed tiles, mixed with red earth powder, for other glazed tiles, mixed with greyish lime	
Flower mortar (花灰)	Lining tiles, laying base bricks, piling and plastering valleys in tile roof ridge raising	Slurry mortar with a little water or a little greyish paste, not uniformly mixed	

Table 6 (continued) | Types, formulations, and production techniques of traditional lime mortars in modern practice

Name	Primary use	Composition & processing method	Special notes
Stir-fried mortar (爆炒灰)	Making pure white lime backing; palace ground	Sifted lime, prepared one day before use, relatively hard, no hemp added	Used for roof slope finding and increasing cushion thickness in backing
Protective board mortar (护板灰)	The first layer in the bedding cushion	Moon-white hemp-cut mortar, relatively thin, Lime: Hemp = 100: 2	
Sandwiched mortar (夹垫灰)	Round tile sandwich; tile sandwich	Slurry mortar or boiled mortar with appropriate water or greyish paste, uniformly mixed with hemp and stirred. Slurry mortar: Boiled mortar = 3: 7 or 5: 5, Lime: Hemp = 100: 3	
Base mortar (打底灰)	Wrapping tiles in round tile laying	Boiled mortar mixed with greyish lime and hemp. Lime: Hemp = 100: 3–4	
Surface-finishing mortar (抹面灰)	Wrapping tiles in round tile laying	Boiled mortar mixed with greyish lime and hemp. Lime: hemp = 100: 3–4	

Data source: Liu Dahe, *Wa Shi Ying Fa of Chinese Historic Architecture*, 1993.

chopped hemp into a dense, fiber-reinforced composite. Raw materials were proportioned by empirical rules, mixed by hoe, and then placed into a mortar pit where they were repeatedly pounded with hardwood rams until a homogeneous, plastic putty was achieved (Figs. 25 and 26). Archeological evidence indicates that this technique was already widespread by the Tang dynasty and remained in use throughout later periods of Chinese building construction history⁶⁰.

Extensive remnants of pounding lime mortar are preserved in the Leshan Giant Buddha scenic area. The spiral hair coils of the Buddha’s head are finished with a 5–15 mm skin of black-gray mortar composed of lime, coal ash and finely chopped hemp fibers. The ear, which were not carved directly from the bedrock, were constructed using timber frameworks sheathed in the same hammered mixture. Similarly, the projecting bridge of the nose and the concealed horizontal drainage gutter above the forehead were formed with wooden armatures and finished with tamped lime-ash renders⁶¹. Even bricks inserted into the cliff-core were externally coated with this material. Analytical samples indicate that the binder was produced by mixing lime, charcoal ash, and hemp in specific ratios, pounded the mixture in a mortar pit, soaking it to improve workability, and then rammed it directly onto the roughened stone substrate. Impact compaction forced the fresh paste into surface irregularities, creating a strong, micro-porous bond that has remained intact for over twelve centuries⁶². Samples indicate that the mixture was soaked after pounding to enhance workability and adhesion.

Pounded lime exhibits reduced air and moisture contents along with finer particle size compared to conventionally hydrated lime, enhancing its suitable for carbonization. Previous research has shown that the mortar prepared through traditional ash beating possesses high porosity, minimal shrinkage deformation, moderate strength, good water stability, and good freeze–thaw resistance⁶³. These characteristics contributed to the superior durability and widespread use of hammered ash mortar in traditional construction.

Experimental studies have quantitatively evaluated the performance of hemp-reinforced lime mortar. Results indicated that the incorporation of hemp fibers reduce shrinkage during drying and mitigate volumetric changes under thermal variation. The addition of lime and hemp not only improves mechanical strength and ductility but also enhance permeability, disperses stress, inhibits crack propagation, and improves erosion resistance.

The experimental materials were prepared by mixing lime with hemp fibers of controlled lengths and proportions, processed using traditional pounding methods. Mix proportions and visual characteristics of the samples are provided in Table 8 and Fig. 27, respectively.

XRD analysis of five pounded lime-hemp samples elucidated the effects of fiber length, content, and moisture on composition. Further analyses included morphological examination and qualitative strength tests to evaluate the binding performance and interfacial compatibility of hemp fibers within the lime matrix.

Carbonation depth as a function of curing time for five lime pastes is shown in Fig. 28. Sample C1 exhibited the slowest carbonation rate, while C2 and C5 carbonated at comparable, intermediate rates. Samples C3 and C4 demonstrated the most rapid carbonation. Although C1 and C2 shared the same initial moisture content, the lower water-to-binder (w/b) ratio and higher hemp fiber content in C2 increased the specific surface area and resulted in incomplete water coating of lime particles. The consequent higher porosity facilitates CO₂ diffusion and accelerated carbonation.

Samples C3, C4 and C5 possessed identical water content and broadly similar phase composition (as confirmed by XRD); differing primarily in hemp-fiber length and dosage. At the higher w/b ratio used in these mixes, increased fiber content raised the solid surface area but also refined the pore structure through mechanical restraint and water retention, thereby impeding CO₂ transport. As a result, the overall carbonation rate decreased with increasing fiber content from C5 to C3 to C4. Despite having the highest fiber content, C4 exhibited the fastest carbonation among the three

Table 7 | Formulations and craft techniques of admixtures in traditional lime-based mortars

Name	Primary use	Composition & processing method	Special notes
I. Organic-modified systems			
Glutinous rice mortar (江米灰)	Construction of glazed floral ornaments; clamping of glazed tiles	Mix lime slurry with green pulp, add hemp cuttings, then mix in glutinous rice pulp and alum water. Lime : Hemp: Rice juice : Alum = 100: 4: 0.75: 0.5	
Oil-ash mortar (油灰)	Fine rammed floor tiles	Mix fine white lime powder, flour, glue paste and tung oil. White lime : Flour : Glue : Tung oil = 1: 2: (0.5–1): (2–3)	A small amount of alum water can be added
	Installation of brackets on column tops; pointing of balustrade stone works	Mix lime slurry with flour and tung oil. White lime : Flour : Tung oil = 1: 1: 1	Should be harder for padding; should be thinner for pointing
	Caulking for waterproofing engineering	Add tung oil to oil ash. Oil ash : Tung oil = 0.7: 1	If hemp caulking is needed, the amount of hemp is 0.13
Hemp-cut oil mortar (麻刀油灰)	Pointing of stacked stones; waterproof pointing of stone works	Add hemp cuttings into oil ash and pound evenly with a wooden stick. Oil ash : Hemp = 100: (3–5)	
Blood-lime mortar (血料灰)	Construction of important bridges, revetments and other hydraulic structures	Dilute blood material and mix into lime mortar. Lime : Blood material = 100: 7	
II. Cellulosic-fiber finishes			
Paper-fiber mortar (纸筋灰)	Surface layer for indoor plastering; surface layer for sculpted flowers and plants	Soak straw paper in water to make pulp, put it into cooked mortar and stir well. Mortar: Pulp = 100: 5–6	Thickness should not exceed 1–2 mm
Reed-catkin mortar (蒲棒灰)	Surface layer for mural plastering	Add reed catkins into cooked mortar and stir well. Mortar: Reed catkins = 100: 3	Thickness should not exceed 1–2 mm
Straw-slurry mortar (滑秸灰)	Wall plastering	Cut straw into 5–6 cm lengths, add water and mix well. Slaked lime mortar: Straw = 100: 4	Can only be used after the straw softens in a few days
Cotton-lime mortar (棉花灰)	Surface layer for mural plastering	Add refined cotton wool into lime plaster and stir well. Mortar: Cotton = 100: 3	Thickness should not exceed 2 mm
Hairy mortar (毛灰)	Eaves plastering	Add animal bristles or human hair (length about 5 cm) into slaked lime mortar and stir well. Mortar: Hair = 100: 3	
III. Mineral-admixed renders			
Brick-face mortar (砖面灰)	Dry-laid, silk-jointed wall surfaces, fine-paved ground spotting	Add lime paste to ground brick. Ground brick : Lime paste = 3:7 to 7:3	May be mixed with glue as appropriate
Sawdust mortar (锯末灰)	Spotting and pointing of whitewashed wall; wall plastering	slaked lime, boiled lime paste or old lime paste with water; sieve and wash sawdust. Sawdust: Quicklime = 1: 1.5 (by volume); mix well and let stand for several days until sawdust softens before use	Sprinkled lime is suitable for outdoor use; Boiled lime mortar is suitable for indoor use
Sand-lime mortar (砂子灰)	Wall plastering, mostly used for the base layer	Sieve sand; dilute lime paste with a small amount of water, then add sand and water to mix well. Sand : Lime = 1: 3	
Cinder ash mortar (焦渣灰)	Wall plastering; plastering cinder floors; applying cinder backing	Mix cinder with sprinkled lime and add water to blend, or add water to quicklime, extract the paste, and mix with cinder. Quicklime : Cinder = 1: 3	Should be left to stand for 2 or 3 days before use to allow quicklime to slake and expand
Coal-ball ash mortar (煤球灰)	Wall plastering	Crush and sieve thoroughly burned furnace ash; dilute lime paste or sprinkled lime with water, mix with furnace ash, and add water to blend. Quicklime paste : Fine furnace ash = 1: 3, mix well with water	
Ternary mortar (三合灰)	Plastering base layer	Add an appropriate amount of cement to white-moon lime paste); hemp fibers may be added as needed	

Lime matrix denotes Ca(OH)₂, produced by traditional slaking; All ratios are by mass except where “by volume” is indicated.

due to its shorter fiber length, which promoted micro-cracking and locally enhances CO₂ diffusion, outweighing the pore-blocking effect.

Lime curing in traditional construction

Lime has been integral to traditional Chinese construction, whether employed as a rammed earth component or masonry mortar, significantly enhanced structural stability, longevity, and resistance to environmental degradation. Although premodern builders lacked modern scientific knowledge of lime carbonation and pozzolanic reactions, their empirical expertise led to remarkably durable constructions.

Historical texts provide substantial evidence of the effective use of lime composites. *Tiangong Kaiwu* contains vivid, albeit somewhat exaggerated, claims such as: “once the material is formed, it will never be damaged when entering the water; being both light and sturdy, it never wears out.”²⁷

Tracing back to the Song Dynasty, in *Zhuzi Jiali* (《朱子家礼》), Zhu’s Family Rituals, 1170), detailed methods for constructing moisture-resistant tomb structures using lime partitions, titled as *hui-ge* (灰隔): “After excavating the grave pit to the prescribed depth, a leveling course of charcoal powder shall first be spread over the base and compacted to a thickness of 2–3 *cun*. A homogeneous mixture of lime, fine river sand and loess is then laid upon it in the volumetric proportion of 3: 1: 1, compacted in lifts 2–3 *cun* thick. A thin wooden plank is inserted to act as a *hui-ge* in the manner of an inner coffin. Lime so treated gains rigidity from sand and adhesiveness from loess; in time it consolidates into a substance as hard as metal or stone, impervious even to ants or grave-robbers.”⁶⁴ This account reflects artisan “lime becomes solid with sand and sticky with earth,” indicating an early practical understanding of composite material behavior.

During the Ming and Qing dynasties, lime was widely used in critical infrastructure. City walls and river embankments were reinforced with mixtures of lime and organic additives such as tung oil or glutinous rice paste. Engineering records from the Qing Dynasty note that in Xuzhou,



Fig. 24 | Pangcun site of the Yongding River ancient embankment, Beijing.

sections without stonework were consolidated with “rice juice lime,” resulting in constructions “as solid as rock.”⁶⁵ Similarly, *Yangfang Shuolue* (《洋防说略》, Outline of Coastal Defense, 1887) describes a mixture of “fifty percent lime, thirty percent mud, and twenty percent sand, combined with glutinous rice juice and pounded to a thickness of eight to two *cun*,” which, once dry, “surpassed iron in hardness and could resist musket balls.”⁶⁶

Archeological evidence strongly corroborates historical accounts of the exceptional durability of traditional lime-based composites. Notable examples include the reservoir structures of the Old Summer Palace⁴⁶ and the renowned site of Tongwan City. Historical records describe the walls of Tongwan City as “white and solid”⁶⁷, noting that “their hardness could sharpen knives and axes”⁶⁸, that they were “tight as a stone”⁶⁹, and that “the foundation, akin to iron and stone, could not be penetrated by attack or chiseling”⁷⁰. These descriptions are validated by the fact that the white walls of Tongwan City have endured in the Mu Us Desert for nearly 1600 years. Modern material analyses confirm that the rammed earth of the Tongwan City walls consists primarily of quartz, clay, and calcium carbonate, consistent with the *san-he-tu*, a ternary mixture of sand, clay and lime.

A similar project of advanced lime technology is evident in the construction of the Ming Dynasty Najing city walls. According to *Fenghuangtai Jishi* (《凤凰台纪事》, Anecdotes of Phoenix Terrace, late 14th century): “When the capital wall was being built, its outer face was consolidated with a slaked-lime and glutinous-millet gruel. The emperor would make unannounced inspections, and the supervising clerks had the work parceled out by the *zhang* and *chi*. If, on striking the wall at random, His Majesty found a core of pure white, the lift was approved; should even a trace of soil be detected, the gang had to rebuild that section. Thus the masons achieved a ‘golden-soup’ solidity within the rampart.”⁷¹ Contemporaneous structures, such as the Ming Central Capital walls in Fengyang, Anhui Province, also employed glutinous rice–lime mortar. As evidenced at the Ming Middle Capital Wall Site (Fig. 29), this material remains remarkably hard and durable even after centuries of exposure.

The experimental results for modern city wall repair projects, as presented in Fig. 30 and Tables 9–12, quantify the mechanical properties and dimensional stability of traditional lime-based masonry mortar and brick-lime powder.

After 7 days of curing, the masonry mortar exhibited average compressive strength of 0.825 MPa and 0.87 MPa across duplicate samples, with corresponding flexural strengths of 0.5 MPa and 0.58 MP. By day 28, the average compressive strength increased significantly to 2.91 MPa and



Fig. 25 | Pounding mortar process in Waterway Conservation Site, Haikou, Hainan.

Fig. 26 | Common tools for brick and tile work in traditional Chinese architecture construction.

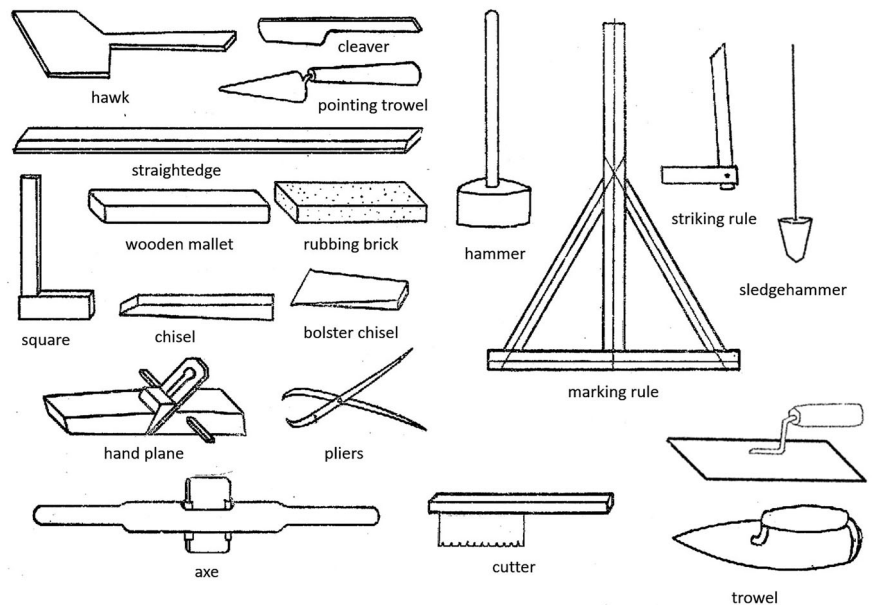


Table 8 | Mix proportions of experimental pounded lime formulations

Group	Number	Length of hemp thread (cm)	Content of hemp silk (%)	Moisture content	Notes
C1	CH010625	1	0.60%	38%	Same number of blows
C2	CH011225	1	1.20%	38%	
C3	CH011815	1	1.80%	42%	
C4	CH021215	2	1.20%	42%	
C5	CH021815	2	1.80%	42%	

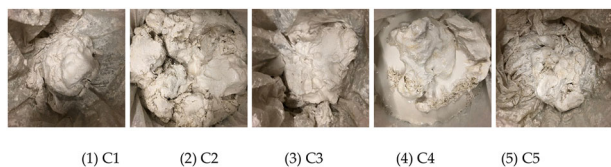


Fig. 27 | Raw materials of lime paste used in experiments.

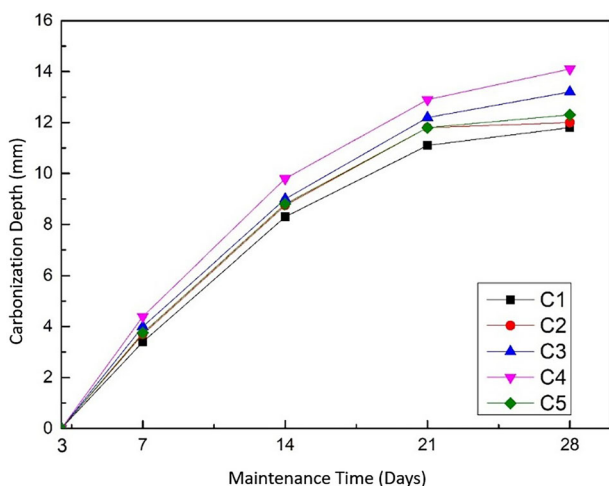


Fig. 28 | Carbonization depths of five experimental lime pastes as a function of curing time.

2.48 MPa, accompanied by flexural strengths of 1.92 MPa and 2.31 MPa. The mortar demonstrated low shrinkage throughout the curing period, with values of 0.12% and 0.09% at 7 days, increasing marginally to 0.18% and 0.12% at 28 days.

The brick-lime repair powder showed superior mechanical performance. At 7 days, it reached average compressive strength reached 1.21 MPa and 1.14 MPa, with flexural strengths of 0.57 MPa and 0.75 MPa. After 28 days, compressive strength increased markedly to 3.97 MPa and 3.71 MPa, while flexural strength rose to 2.19 MPa and 2.24 MPa. This material also exhibited minimal shrinkage, recorded at 0.08% and 0.03% on day 7, and 0.13% and 0.10% on day 28.

These results indicate that both materials develop considerable mechanical strength over time while maintaining high dimensional stability, confirming their suitability for conservation applications requiring material compatibility and minimal deformation.

In summary, the six principal technological processes—raw material selection, calcination, slaking, formulation, construction, and curing — constitute the core framework for understanding the use of lime in traditional Chinese architecture. The overarching objectives of these processes are robustness and durability, underpinned by the scientific interpretation

of lime curing mechanisms. Lime performance is fundamentally influenced by the type of raw lime stone used, while calcination conditions—including fuel type, firing duration, and temperature—determine the viability of the resulting quicklime for construction purposes. Ancient slaking methods, such as weathering or hydration, significantly affect the hardening behavior and ultimate strength of the lime mortar. Furthermore, blending slaked lime with various additives allowed artisans to tailor the material to specific functional requirements.

Through empirical experience and scientific experimentation, these processes collectively contribute to the formation of enduring and resilient structures. Remarkably, the entire lime cycle embodies ecological circularity: from quarrying and calcination to slaking, carbonation, and eventual return to the earth, it reflects the Daoist concept of *fanben guiyuan* (返本归元, returning to the origin), demonstrating a sustainable, closed-loop system inherent to traditional Chinese building culture.

The carbonation of lime constitutes the fundamental chemical mechanism through which traditional lime-based mortars gain strength and durability. This process involves the reaction of calcium hydroxide (Ca(OH)₂) with carbon dioxide (CO₂) from the atmosphere to form calcium carbonate (CaCO₃), effectively reversing the chemical transformation achieved during calcination. Carbonation represents not merely a chemical endpoint but a complex kinetic process governed by environmental and microstructural factors. The reaction initiates at the surface and progresses inward, controlled by the diffusion of CO₂ through the mortar’s pore network. Optimal carbonation occurs at moderate humidity levels (~50–70%), which facilitates the dissolution of CO₂ into pore water and subsequent ionic reaction, while avoiding excessive moisture that would obstruct gaseous diffusion.

The incorporation of organic additives, such as hemp fibers, rice paste, or ash, significantly enhances the carbonation process. These additives form a micro-fibrous network that modifies the mortar’s microstructure, promoting a more interconnected and fine-pored system. This configuration not only improves CO₂ permeability but also mitigates shrinkage and cracking, thereby maintaining continuous pathways for gas diffusion. Furthermore, the gradual decomposition of these organic components contributes to long-term humus formation, linking the material’s lifecycle to natural ecological cycles. The complete carbonation through CO₂ absorption represents a historical prototype of negative carbon building strategy recognized in contemporary research.

From a macro perspective, traditional lime technology exemplifies a sustainable, circular model of material use. The CO₂ released during limestone calcination is partially reabsorbed during the carbonation phase, creating a partial carbon cycle that reduces the overall environmental footprint. Over time, lime mortar exposed to atmospheric conditions reverts chemically to calcium carbonate and, through weathering and biological activity, ultimately returns to a state indistinguishable from natural limestone. This embodies a closed-loop material ecology that aligns with principles of regenerative design and sustainable construction.

Thus, traditional lime craft represents a low-entropy, regenerative cycle: stone is temporarily extracted, transformed using renewable energy (wood-fired kilns), re-carbonates during use, and ultimately returns to the ecological system. The carbonation of lime is more than a hardening mechanism: it is a critical process that integrates material performance with environmental sustainability, offering valuable insights for contemporary efforts in developing low-carbon building materials (Fig. 3).

Results

Living heritage: a symbiotic system of craft, embodiment, and community

Traditional lime craftsmanship represents not a static technological relic, but a form of *living heritage* that continuously regenerates across generations through the dynamic interplay of *body*, *tool*, and *community*. Its vitality derives from three interdependent mechanisms: the transmission of embodied knowledge through mentorship; community-based practice embedded in ritual and spatial contexts; and place-based innovation



Fig. 29 | Lime mortar cracks observed in the walls structure at the Ming Middle Capital Site, Fengyang, Anhui.

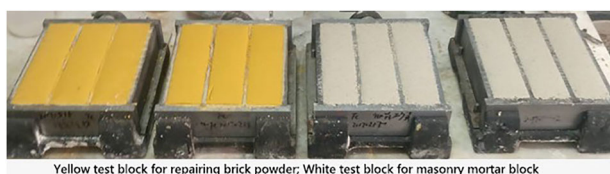


Fig. 30 | Lime masonry test specimens used in strength performance experiments.

Table 9 | Measured flexural and compressive strength of lime masonry mortar

Age (days)	Bending strength (MPa)	Compressive strength (MPa)	Average compressive strength (MPa)
7	0.5	0.85	0.825
		0.8	
	0.58	0.83	0.87
28		0.91	2.91
	1.92	2.85	
		2.97	
	2.31	2.36	2.48
		2.59	

Table 10 | Relative shrinkage ratio of lime masonry mortar over curing time

Age (days)	7	28
Test Block I	0.12%	0.18%
Test Block II	0.09%	0.12%

^aRelative to the contraction on the third day.

adapted to local materials and ecology. Together, these form a symbiotic system integrating technique, society, and symbolism, enabling lime craft to sustain both technical precision and cultural meaning over millennia⁷².

The transmission of traditional lime-working is fundamentally an embodied knowledge system, progressing from oral formulae to physical mastery. Historically, apprentices entered *hui-zuo fang* (灰作房, lime workshops) at ages 12–14, advancing through a seven-year seasonal cycle, from carrying water and pounding lime to cutting hemp and applying plaster. Each stage cultivated specific physical skills and social identity. Knowledge was encoded in both rhymes and gestures: for example, the formula “three parts lime, two parts sand, one part breath” not only specified

Table 11 | Compressive and flexural strength of lime-brick powder composite used for repairs

Age (days)	Bending strength (MPa)	Compressive strength (MPa)	Average compressive strength (MPa)
7	0.57	1.22	1.21
		1.2	
	0.75	1.01	1.14
28		1.27	3.97
	2.19	3.59	
		4.35	
	2.24	4.25	3.71
		3.17	

Table 12 | Relative shrinkage ratio of lime-brick powder repairs at different curing

Age (days)	7	28
Test Block I	0.08%	0.13%
Test Block II	0.03%	0.10%

^aRelative to the contraction on the third day.

mix ratios but also implied tactile cues for judging carbonation. Initiatory practices, such as standing barefoot on steaming wet sacks during the Chaozhou *Lime-Splashing Courage Test*, inscribed both skill and daring into the body. Thus, technique became not detachable information but embodied habitus, seamlessly transferred across generations.

Key technical processes were often ritualized into public events, merging technical time with community time. In Yangcheng, Shanxi, the annual Kiln-Opening Ceremony on the 23rd day of the twelfth lunar month featured offerings of glutinous rice wine and a whole pig to the Kiln God; a novice’s first participation marked formal entry into the craft. In Chaozhou, *he-long-kou* (合龙口, Dragon-Closing) ritual saw the eldest mason pouring the final mortar into a bridge arch, accompanied by collective shouts of “*Dragon closed!*”, elevating a technical act into a communal celebration. Such rituals reinforced technical authority while integrated lime-working into the local cosmological calendar, forming a mnemonic device that linked technique, ritual, and worldview, thereby ensuring the craft’s continual reactivation in daily life⁷³.

Localized systems and characteristics have formed distinct regional dialects of lime craftsmanship across China, each fine-tuned to climate, resources, and symbolic needs. The Shanxi school used high-calcium quicklime blended with local loess and black-millet liquor, achieving plasticity and edge retention suitable for the extreme dry-wet cycles of the Loess Plateau. The Jiangnan school (represented by Suzhou Xiangshan Gang) employed wet-slaked lime putty with river sand and ramie fiber, producing finishes that mirrored regional esthetic ideals. The Lingnan region’s oyster-shell lime incorporated brown-sugar extract, yielding high compressive strength for tidal-zone granaries. In Tibet, Aga earth was mixed with yak-butter whey, whose fatty acids acted as an air-entraining agent, providing freeze-thaw resistance at high altitudes. Each of these regional variations represents a co-evolution of ecology, technique, and symbolism; their color, texture, and finish serve as sensory markers of local identity, transforming lime from mere material into what may be termed landscape skin.

The inheritance of traditional craft was not linear but operated through a resilient network of guilds, lineages, and festivals. Guild apprenticeship, exemplified by cross-provincial industry alliances such as Beijing’s *Luban Community of Lime-Workers* (灰作鲁班社) and

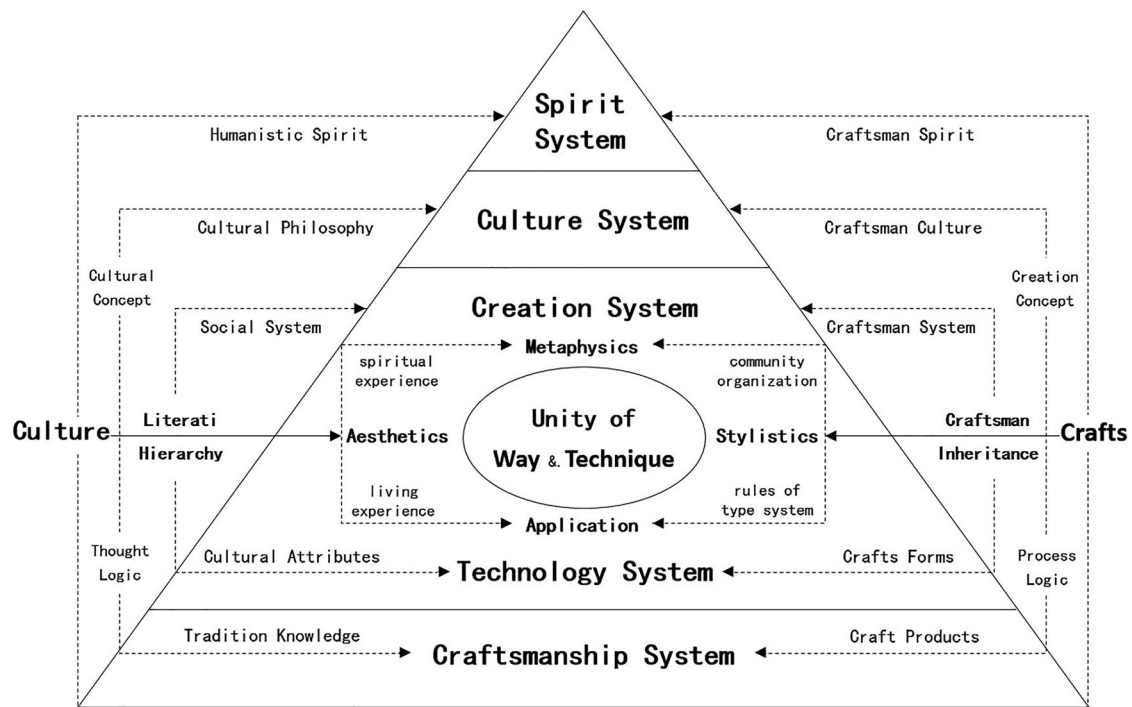


Fig. 31 | Theoretical framework of traditional Chinese craftsman culture.

Southern Fujian’s *Shell-Lime Guild* (壳灰郊), established systems for material supply, labor, and technical exchange. Within familial lineages, recipes functioned as dowry capital; in Southern Jiangsu, mothers passed tung oil lime waterproofing techniques to daughters, ensuring the bride’s economic agency in her new village. Furthermore, temple restoration ceremony converted construction into public praxis, merging the cosmological calendar with pedagogical opportunity. This triple network provided redundant pathways for knowledge transmission, ensuring systemic resilience.

In summary, as a form of living heritage, the value of traditional lime craft lies not in its antiquity but in its aliveness. Through its triple embedding in the body, ritual, and ecology, it continuously renews its technical and cultural relevance, remaining the most vital hidden backbone of China’s traditional architectural system.

Heritage management system: from technical invisibility to institutional recognition

The historical invisibility of traditional lime craftsmanship within formal heritage management systems stems from both its technical characteristics and socio-structural conditions. On one hand, lime work is largely concealed within walls, base layers, and roofs, lacking the immediate visual prominence of wooden structures or painted decorations. On the other, traditional artisans long endured systemic marginalization within a scholarly-official culture that disdained manual labor, resulting in their exclusion from official knowledge systems (Fig. 31). With the ascendancy of modern cement and the closure of wood-fired kilns in the late 20th century, lime craftsmanship faced dual erasure: material replacement and institutional neglect. It was only when heritage science began validating its low-carbon, breathable, and self-healing properties, coupled with a shift in ICH discourse from objects to processes, that lime work gradually emerged from obscurity. Nevertheless, this transition remains hampered by five structural ruptures that demand innovative institutional responses to re-couple technique, ecology, and community.

1. Material and technical disruption: Small-scale wood-fired kilns have been largely shut down under environmental policies, cutting off the supply of traditional wood-fired lime. Industrial quicklime, produced in rotary kilns, exhibits high reactivity and variable MgO content, rendering obsolete

sensory standards such as “seven parts matured, three parts brittle” and invalidating seasonally adjusted mixing formulas. This material mismatch triggers a chain reaction: accelerated carbonation, increased shrinkage cracking, and reduced compatibility with historic substrates, ultimately undermining confidence in lime-based restoration among both craftspeople and clients and creating a dual crisis of technology and trust.

2. Knowledge fragmentation: Prior to the 1980s, lime craftsmanship was transmitted almost exclusively through oral and practical means. Systematic audiovisual documentation did not begin until around 2015, leaving a 40-year archival void. This gap has led not only to the irreversible loss of technical details but also to the erosion of symbolic knowledge related to rituals, taboos, and place-making. When conservation efforts capture only “how to mix” without the “why,” ICH risks becoming a decontextualized recipe, technologically hollowed out.

3. Temporal misalignment: Traditional lime mortar requires 28 days for initial carbonation plus monthly wet-curing to achieve optimal strength and vapor permeability. Modern construction, however, typically operates on a 10-day cycle. This temporal disconnect forces artisans to abandon the traditional three-stage process (quicklime → moist-curing → finishing) in favor of bagged pre-mixed mortars. While this meets speed demands, it sacrifices breathability and self-healing capacity, leading to latent damage that manifests years later as accelerated decay, a form of preservation-induced damage.

4. Diminished artisanal agency: The traditional seven-year apprenticeship system has collapsed due to rural-urban migration and youth outmigration. Although younger generations possess higher formal education, they often lack the dedication to craftsmanship excellence. Some inheritors, enticed by market opportunities, retreat to symbolic roles as “brand ambassadors”, disengaged from hands-on production, resulting in the hollowing out of both spirit and skill. Over-commercialization further promotes fast-track training that replaces manual mastery with mechanical replication, reducing ICH to a photogenic spectacle devoid of endogenous vitality.

5. Institutional misalignment: Although China has established a three-tier protection network (national, provincial, and community micro-museums), evaluation criteria prioritize quantitative metrics such as number of listed items and building volume over processual integrity and

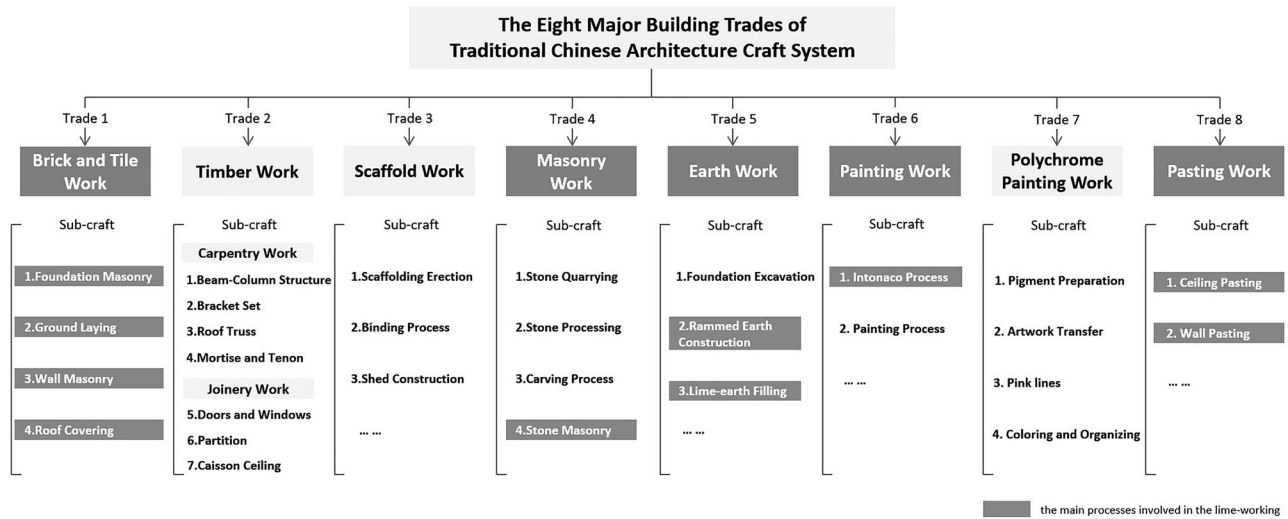


Fig. 32 | Key processes of lime-working within the traditional Chinese architectural craft system.



Fig. 33 | Illustration of lime processing from *Supplement to Lei Gong's Processing Overview* (《补遗雷公炮制便览》)⁷⁴.



Fig. 34 | Pueblos Blancos (white villages), Algar, Andalusia, Spain⁷⁵.

community participation. Consequently, lime work is often narrowly recognized in the form of visible sub-items like lime sculpture, while critical concealed processes, such as lime-earth compactions and mortars, remain excluded. In restoration projects, original materials and techniques clauses are frequently bypassed due to cost and scheduling pressures, creating systemic exceptions that weaken regulatory rigor.

The journey from “hidden binder” to “visible cultural asset” reveals a broader lesson for heritage management: only when conservation systems actively address fractures in materials, knowledge, time, agency, and institutions, through interdisciplinary and policy-driven innovation, can intangible cultural heritage avoid becoming a museum specimen and regain its living vitality in contemporary production and daily life.

ICH framework: holistic reintegration of technical systems and cultural meaning

In China’s *Eight Major Trades* (八大作) of traditional timber construction, lime based materials play an integral role, directly supporting over 30% of core processes and serving as the hidden linking foundations, structures, roofs, and painted decorations (Fig. 32). Historical texts such as the Zhou-era *Kaogongji*, the Song *Yingzao Fashi* (details mortar mixtures and techniques), and the Qing *Gongcheng Zuofa* (quantifies material ratios per unit area), constitute some of the world’s earliest official material standards for building materials. These documents not only record technical parameters but also reflect dynastic control over resource allocation, labor organization, and ritual order, offering a dual chain of evidence, both experimental and textual, for research into ancient materials science, economic history, and political symbolism. In this sense, lime craftsmanship is far more than one of the *eight trades*; it is a critical technical interface connecting institutions, resources, and artisanal practice, with its integrity directly determines architectural longevity.

Within the Chinese *Wuxing* (五行, Five Phases) system, white corresponds to metal and is symbolic associated with warding off evil, generating water, and mediating energies. The Forbidden City’s high-white lime finish embodies the principle of “white metal generating water” to balance imperial *fire phase* (火德); Southern Fujian’s red-brick houses with white lime renderings evoke the homophone “red-and-white events” (weddings and funerals), symbolizing family continuity; in Tibet, the rhythmic singing during Aga earth pounding transforms the white surface into a material axis connecting humans, deities, and the cosmos (Fig. 33). Cross-cultural parallels are also evident: Mediterranean white towns (Fig. 34) used slaked lime for disinfection during plagues outbreaks (16th–19th centuries), giving rise to the *charlas al fresco* custom. The lime-making tradition of Morón de la Frontera, Spain, was inscribed in 2011 on UNESCO’s Register of Good Safeguarding Practices (Fig. 35). Globally, lime’s whiteness carries deep semantic meanings of purification–protection–renewal, enabling its technical function and symbolic significance to co-evolve within local narratives of disease and cosmology.

UNESCO’s *Operational Guidelines* emphasize that architectural authenticity pertains not only to original material but also to the esthetic and



Fig. 35 | Traditional craftsmanship of lime-making in Morón de la Frontera, Seville, Andalusia, Spain. UNESCO ICH element⁷⁶.

wisdom embodied in original craftsmanship⁷⁷. The value of lime work lies precisely in its trinity of *material-process-community*: the same lime may require a Kiln God ceremony in Shanxi, three years of aging in Suzhou for a mirror finish, or a blend of brown sugar and oyster shells in Southern Fujian to resist salt erosion. These regional variations are not technical noise but constitute core heritage value, recording micro-adaptations to local ecosystems and preserving a sensory archive (color, smell, sound, touch) of collective memory. Thus, the authenticity of lime craftsmanship should be understood as dynamic locality, a process continuously regenerated through the interaction of formula, body, and community, rather than a static original recipe.

Although 56 items on China's national ICH list involve lime craftsmanship, most lime-earth, mortar, and plaster techniques remain subsumed within the broader narrative of traditional architectural craftsmanship, accounting for an average of 21% of processes yet lacking independent recognition (Table 13 and Fig. 36). This institutional silencing has concrete consequences: in restoration, lime-based materials can be replaced by cement of equal strength without violating regulations; artisans without representative inheritor status are ineligible for subsidies; and non-technical elements like oral history and ritual taboos remain largely unarchived. This leads to a paradox whereby authenticity is textually acknowledged but practically eroded, such as timber structures coated with cement mortar decay, which in fact also weakens the integrity of ICH conservation goals.

Lime craftsmanship is rightly called the “*underlying operating system*” of ICH because it integrates five dimensions of value: technology, landscape, community, belief, and economy, into a handful of white powder. To lose it is to lose not only an ancient recipe but also the key to interpreting why traditional Chinese architecture has endured for millennia. Only through a holistic reintegration of technical systems and cultural meaning within the

ICH framework can this powder continue to live rather than merely be preserved. In other words, a sustainable future for lime craftsmanship lies not in a fundamentalist return to wood-fired kilns, but in institutional design, scientific validation, and community governance that enable the continuous regeneration of its four minimal units, formula, body, community, and symbolism, within sustainable architecture and ecological civilization.

Discussion

Traditional Chinese architectural lime techniques exemplify a profound synthesis of material performance, artisanal wisdom, and cultural continuity. Sustained for millennia through the strategic use of local materials and regionally adapted methods, these practices are systematized in this study into six principal technical stages: raw material, calcination, slaking, formulation, construction, and curing. Together, they constitute an integrated framework spanning technical, environmental, and cultural dimensions. By integrating historical analysis, archeological evidence, ethnographic inquiry, and materials science, this study redefines lime not merely as a historical building material, but as a dynamic form of ICH that remains critically relevant to contemporary sustainable construction.

Functioning as both a structural binder and a cultural medium, lime transmits architectural techniques, esthetic principles, and communal identity. The authenticity and longevity of traditional structures are intrinsically tied to the use of historically appropriate materials and methods. Even skillfully applied modern substitutes often compromise physical integrity and conceptual authenticity. Consequently, reviving and scientifically validating traditional lime techniques are essential to appropriate heritage conservation.

Nevertheless, the continuity of this craft is threatened by a structural mismatch between artisanal systems and modern industrial paradigms. Industrially produced quicklime proves chemically and mechanically incompatible with historic mortars, disrupting both material performance and cultural continuity. Over the past three decades, inadequate policy protection and unchecked industrial expansion have eroded apprenticeship networks and accelerated the ageing of master craftsmen, resulting in severe knowledge fragmentation. The six-step traditional cycle operates on a temporal scale fundamentally at odds with contemporary demands for speed and cost efficiency. Yet, this very “slowness” constitutes the foundation of its sustainability and local value. Only through institutional recognition, dedicated time, budget allocation, and spatial resources across the heritage-conservation chain can “slow craft” be integrated into “fast systems,” ensuring genuine transmission and living development of traditional lime technology.

To address this crisis, a tripartite approach—spatial, educational, and institutional—is urgently required. First, policy leadership should establish Traditional Lime Eco-Reserves within a 30 km radius of major heritage sites, restoring the full production chain from indigenous limestone quarries and woodlands to traditional kilns, supported by dedicated subsidies and carbon-reduction credits. Second, educational integration ought to implement hybrid apprenticeship and digital twin training platforms, combining master instruction with virtual-kiln simulations, culminating in state-recognized professional licensing. Third, statutory recognition must classify lime burning and mortar craft as an independent national ICH category, accompanied by tailored environmental waivers and mandatory usage ratios in conservation tenders.

Emerging initiatives demonstrate this model's viability. In Dengfeng, Henan and Yongtai, Fujian, Living Kiln projects have attracted 200,000 visitors within three years, generating over CNY 100 million in integrated revenue for local economies, while avoiding 1200 t CO₂ emissions by replacing cement with lime in heritage repairs—equivalent to planting 65,000 trees. When policy, market, and community form a closed loop, traditional lime serves not only as a low-carbon conservation technology but also as a catalyst for cultural revitalization and sustainable rural development.

Future scientific research must integrate four critical strands: first, mapping the petrographic and isotopic fingerprints of regional materials to

Table 13 | Representative Chinese ICH projects involving architectural lime crafts (2006–2021)

Representative project	Project number	Announced time	Category	Declaration region		Type	Inheritors	Involving lime crafts
				Province	County			
1 Huizhou Three Carving Arts	VII-37	2006 First Batch	Traditional Arts	Anhui	Huangshan	New project	Wu Zhenghui, Cao Yongsheng, Kuai Zhenghua, Wang Jinsheng, Feng Youjin, Fang Xinzhong	1.2, 1.3, 4.4
2 Linxia Brick Carving Art	VII-38	2006 First Batch	Traditional Arts	Gansu	Linxia	New project	Shen Zhanwei, Mu Yonglu	1.2, 1.3, 4.4
3 Traditional Architectural Construction Skills of Xiangshan Gang	VIII-27	2006 First Batch	Traditional Crafts	Jiangsu	Suzhou	New project	Xue Lingen, Lu Yaosu, Xue Fuxin	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 6.1, 8.1, 8.2
4 The Construction Skills of Hakka Castle-Like Dwellings	VIII-28	2006 First Batch	Traditional Crafts	Fujian	Longyan	New project	Xu Songsheng	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
5 Traditional Ceramic Kiln and Workshop Construction Skills of Jingdezhen	VIII-29	2006 First Batch	Traditional Crafts	Jiangxi	/	New project	Hu Jiawang, Yu Yunshan	1.1, 1.2, 1.3, 4.4, 5.2, 5.3
6 Construction Techniques of Dong Ethnic Wooden Architecture	VIII-30	2006 First Batch	Traditional Crafts	Guangxi	Liuzhou	New project	/	1.1, 1.4, 4.4, 5.2, 5.3
7 Construction Techniques of Miao Village Stilted Buildings	VIII-31	2006 First Batch	Traditional Crafts	Guangxi	Sanjiang	New project	Yang Qiushi, Yang Siyu	
8 Golden Bricks Making Techniques of Suzhou Imperial Kiln	VIII-32	2006 First Batch	Traditional Crafts	Guizhou	Leishan	New project	/	1.1, 1.4, 4.4, 5.2, 5.3
9 Brick Sculpture	VII-86	2008 Second Batch	Traditional Arts	Shandong	Juancheng	New project	Xie Xinjian, Xie Xueyun	1.2, 1.3, 4.4
10 Clay Sculpture	VII-87	2008 Second Batch	Traditional Arts	Guangdong	Guangzhou	New project	Shao Chengcun	1.3, 1.4
11 Inlaid Porcelain	VII-91	2008 Second Batch	Traditional Arts	Guangdong	Shantou	New project	Xu Shaoxiong	1.3, 1.4
12 Architectural Painting	VII-96	2008 Second Batch	Traditional Arts	Yunnan	Dali	New project	Li Yunyi	8.1, 8.2
13 Linqing Tribute Brick Making Technique	VIII-91	2008 Second Batch	Traditional Crafts	Shaanxi	Yulin	New project	Li Shengbin	
14 Construction Techniques for Official style Ancient Buildings	VIII-174	2008 Second Batch	Traditional Crafts	Shanxi	Rangyuan	New project	Hao Yanning	
15 Traditional Construction Techniques of Wooden Arch Bridges	VIII-175	2008 Second Batch	Traditional Crafts	Shandong	Linqing	New project	Jing Yongxiang	1.2, 1.3, 4.4
16 Stone Bridge Construction Techniques	VIII-176	2008 Second Batch	Traditional Crafts	Beijing	/	New project	Bai Fuchun, Li Jianguo, Wu Shengmao, Li Zenglin, Liu Zengyu, Li Yongge	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 6.1, 8.1, 8.2
17 Traditional Wuzhou style Residential Construction Techniques	VIII-177	2008 Second Batch	Traditional Crafts	Zhejiang	Taishun	New project	Zeng Jiakuai, Dong Zhiji	1.1, 1.2, 4.4, 5.2, 5.3
18	VIII-178	2008 Second Batch	Traditional Crafts	Fujian	Qingyuan	New project	Hu Miao	
					Pingnan		Huang Chuncai	
					Shouning		Zheng Duojin	
				Zhejiang	Shaoxing	New project	Zhang Yuelai	1.1, 4.4, 5.2, 5.3
				Zhejiang	Pujiang	New project	/	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
				Dongyang	Dongyang		Lv Xiongxin	
				Puyi	Puyi		/	
				Nanxi	Nanxi		/	
				Anhui	Huangshan	New project	Hu Gongmin	

Table 13 (continued) | Representative Chinese ICH projects involving architectural lime crafts (2006–2021)

Representative project	Project number	Announced time	Category	Declaration region		Type	Inheritors	Involving lime crafts
				Province	County			
Traditional Huizhou style Residential Construction Techniques		2008 Second Batch	Traditional Crafts					1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
19 Traditional Residential Construction Techniques in the Minnan Region	VIII-179	2008 Second Batch	Traditional Crafts	Fujian	Amnan Huian Quanzhou	New project	Ye Benying Wang Shimeng Liu Dashan, Jiang Qinquan	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
20 Cave Dwelling Construction Techniques	VIII-180	2008 Second Batch	Traditional Crafts	Gansu	Qingyang	New project	Li Maozheng	1.1, 1.2, 1.3, 5.2, 5.3, 8.1, 8.2
21 Mongolian Yurt Construction Techniques	VIII-181	2008 Second Batch	Traditional Crafts	Neimenggu	Luping	New project	Zhang Hecheng	1.2
22 Li Ethnic Boat Shaped House Construction Techniques	VIII-182	2008 Second Batch	Traditional Crafts	Hainan	Chen Barag West Ujimqin	New project	Ban Fengbin Bin Ba Hu Senge	1.1, 1.2, 4.4, 5.2, 5.3
23 Kazakh Felt House Construction Techniques	VIII-183	2008 Second Batch	Traditional Crafts	Xinjiang	Dongfang	New project	Fu Naqing	1.1, 1.2, 4.4, 5.2, 5.3
24 Russian Ethnic Residential Construction Techniques	VIII-184	2008 Second Batch	Traditional Crafts	Xinjiang	Tacheng	New project	Dalilian Habidixi	1.2
25 Salar Ethnic Fence Building Construction Skills	VIII-185	2008 Second Batch	Traditional Crafts	Qinghai	Tacheng	New project	Zhang Huaisheng	1.2
26 Building Techniques of Watchtowers	VIII-186	2008 Second Batch	Traditional Crafts	Sichuan	Xunhua	New project	/	1.1, 1.3, 5.2
27 Brick Carving Art	VII-38	2008 Second Batch	Traditional Arts	Shanxi	Danba	New project	Chimibadan	1.1, 1.2, 1.3, 4.4, 5.2, 5.3
28 Construction Techniques of Dong Ethnic Wooden Architecture	VIII-30	2008 Second Batch	Traditional Crafts	Guizhou	Qingxu	Extension project	/	1.2, 1.3, 4.4
29 Qingxu Decorated Gateway	VII-102	2011 Third Batch	Traditional Arts	Shanxi	Liping	Extension project	/	1.1, 1.4, 4.4, 5.2, 5.3
30 Traditional Construction Techniques of Beijing Courtyard Houses	VIII-208	2011 Third Batch	Traditional Crafts	Beijing	Congjiang	New project	Yang Guangjin	1.1, 1.4, 4.4, 5.2, 5.3
31 Yunnan Residential Construction Techniques	VIII-209	2011 Third Batch	Traditional Crafts	Shanxi	Qingxu	New project	/	1.1, 1.4, 4.4, 5.2, 5.3
32 Architectural Construction Techniques in Shikumen Lane	VIII-210	2011 Third Batch	Traditional Crafts	Shanghai	/	New project	/	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
33 Construction Techniques of Tujia Ethnic Stilted Buildings	VIII-211	2011 Third Batch	Traditional Crafts	Chongqing	Shizhu	New project	Liu Chengbo	1.1, 1.4, 4.4, 5.2, 5.3
34 Architectural Techniques of Uyghur Residential Buildings	VIII-212	2011 Third Batch	Traditional Crafts	Hunan	Yongshun	New project	Wang Wanqi, Peng Shanyao	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
35 Inlaid Porcelain	VII-91	2011 Third Batch	Traditional Arts	Hubei	Xianfeng	New project	Wan Taoyuan	1.3, 1.4
36 Architectural Painting (intonaco and Patting)	VII-96	2011 Third Batch	Traditional Arts	Xinjiang	Hetian	New project	/	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
37	VIII-28	2011 Third Batch	Traditional Arts	Fujian	Chaozhou	Extension project	/	1.3, 1.4
			Traditional Arts	Liaoning	Shenyang	Extension project	/	6.1

Table 13 (continued) | Representative Chinese ICH projects involving architectural lime crafts (2006–2021)

Representative project	Project number	Announced time	Category	Declaration region		Type	Inheritors	Involving lime crafts
				Province	County			
The Construction Skills of Hakka Castle-Like Dwellings			Traditional Crafts	Nanjing		Extension project	Zhang Xianyao	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
38 Cave Dwelling Construction Techniques	VIII-180	2011 Third Batch	Traditional Crafts	Shaanxi	Yanan	Extension project	Wang Shihu	1.1, 1.2, 1.3, 5.2, 5.3, 8.1, 8.2
39 Building Techniques of Watchtowers	VIII-186	2011 Third Batch	Traditional Crafts	Qinghai	Banma	Extension project	Guoluozhequ	1.1, 1.2, 1.3, 4.4, 5.2, 5.3
40 Traditional Chinese Garden Construction Techniques	VIII-238	2014 Fourth Batch	Traditional Crafts	Jiangsu	Yangzhou	New project	Wu Yulin	1.1, 1.2, 4.4, 5.2, 5.3
41 Ancient Stage Construction Techniques	VIII-239	2014 Fourth Batch	Traditional Crafts	Jiangxi	Leping	New project	Chen Leping	1.1, 1.2, 1.3, 4.4, 5.2, 5.3
42 Construction Techniques of Traditional Residential Buildings in Luling	VIII-240	2014 Fourth Batch	Traditional Crafts	Jiangxi	Taihe	New project	/	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
43 Restoration Techniques for Ancient Buildings	VIII-241	2014 Fourth Batch	Traditional Crafts	Gansu	Yongjing	New project	Xu Yuanming	1.1, 1.2, 1.3, 1.4, 5.2, 5.3
44 Brick Carving Art	VII-38	2014 Fourth Batch	Traditional Arts	Ningxia	Guyuan	Extension project	Bu Wenjun, Ma Fengzhang	1.2, 1.3, 4.4
5 The Construction Skills of Hakka Castle-Like Dwellings	VIII-28	2014 Fourth Batch	Traditional Crafts	Jiangxi	Longnan	Extension project	Zhong Yanpeng	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
46 Traditional Residential Construction Techniques in the Minnan Region	VIII-179	2014 Fourth Batch	Traditional Crafts	Fujian	Xiamen	Extension project	Chen Heyong	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 6.1, 8.1, 8.2
47 Porcelain Water Mill Construction Technique	VIII-281	2021 Fifth Batch	Traditional Crafts	Jiangxi	Fuliang	New project	Zhan Hean	1.1, 1.2, 1.3, 4.4, 5.2, 5.3
48 Construction Technique of Heated Brick Bed	VIII-282	2021 Fifth Batch	Traditional Crafts	Liaoning	Benxi	New project	/	1.1, 1.3, 5.2, 5.3
49 Construction Techniques of Chaoshan Ancient Architecture	VIII-283	2021 Fifth Batch	Traditional Crafts	Guangdong	Shantou	New project	Ji Chuanying	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 6.1, 8.1, 8.2
50 Yi Ethnic Traditional Residential Construction Techniques	VIII-284	2021 Fifth Batch	Traditional Crafts	Sichuan	Liangshan	New project	Axi Lapi	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3
51 Traditional Tent Weaving Techniques	VIII-285	2021 Fifth Batch	Traditional Crafts	Xizang	Naqu	New project	/	1.1, 5.2, 5.3
52 Traditional Residential Construction Techniques in Guanzhong	VIII-286	2021 Fifth Batch	Traditional Crafts	Shaanxi	Xian	New project	Wang Shunli	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
53 Traditional Residential Construction Techniques in Guyuan	VIII-287	2021 Fifth Batch	Traditional Crafts	Ningxia	Guyuan	New project	Ma Zhenren	1.1, 1.2, 1.3, 1.4, 4.4, 5.2, 5.3, 8.1, 8.2
54 Architectural Painting	VII-96	2021 Fifth Batch	Traditional Arts	Beijing	/	Extension project	/	8.1, 8.2
55 Construction Techniques of Dong Ethnic Wooden Architecture	VIII-30	2021 Fifth Batch	Traditional Crafts	Hunan	Tongdao	Extension project	/	1.1, 1.4, 4.4, 5.2, 5.3
56 Mongolian Yurt Construction Techniques	VIII-181	2021 Fifth Batch	Traditional Crafts	Qinghai	Henan	Extension project	/	1.2

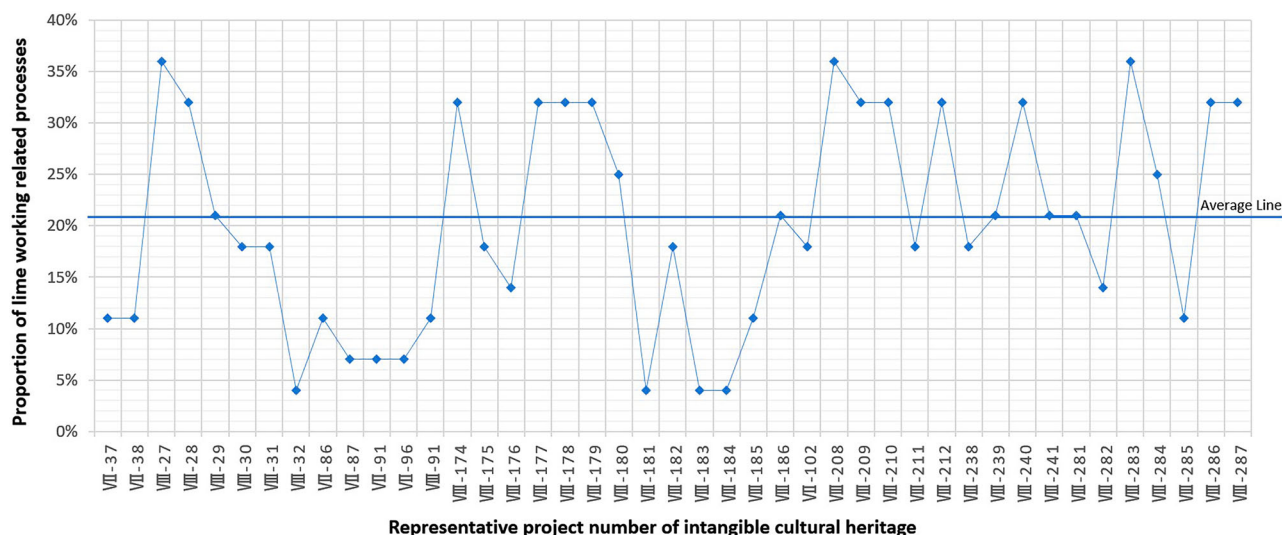


Fig. 36 | Proportion of Chinese national ICH projects in traditional architecture involving lime-based techniques.

create a national raw-material atlas; second, leveraging these data in experimental reconstructions of historical processing techniques to quantify how parameters control performance; third, conducting cradle-to-grave life-cycle assessments to evaluate environmental impacts and generate tradable carbon-reduction factors; and finally, developing advanced lime composites with enhanced durability, self-healing capacity, and bio-receptivity, while maintaining full reversibility.

In summary, traditional lime craftsmanship embodies a sophisticated integration of ecological, technological, and cultural systems. Its preservation constitutes not merely the safeguarding of historical techniques but a vital investment in a sustainable and culturally meaningful future. Through collaborative engagement across research, policy, and community practice, traditional lime can endure as both a functional material and a living cultural process, connecting ancestral wisdom with future resilience in the built heritage.

Data availability

All data generated or analyzed during this study are included in this published article. The data presented in this study are available on request from the corresponding authors.

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Competing interests

The authors declare no competing interests.

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