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A study on the composition and strength of glutinous rice slurry in the ancient sea dikes of the Qiantang River

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Abstract. The ancient sea dikes of the Qiantang River have a history spanning more than 400 years since their construction in the 21st year of the Jiajing reign of the Ming Dynasty (1542). Despite centuries of exposure to wind, rain, and tidal waves, as well as extensive damage caused by modern human activities, more than 40 kilometers of these historic sea dikes remain in service on the front line of flood control, continuing to play a vital role. Owing to their long history, the ancient sea dikes have also fostered a rich body of local folk traditions and accumulated profound cultural significance for the communities along both banks of the estuary. They therefore represent not only important hydraulic engineering works but also valuable historical and cultural heritage. With the passage of time and changes in hydrological and topographical conditions, many of the surviving ancient sea dikes have developed structural problems, including fractured facing stones and detached stone blocks. Consequently, reproducing traditional glutinous rice mortar using modern techniques and restoring the ancient sea dikes in accordance with cultural heritage conservation standards is of great significance for preserving historical and cultural heritage, promoting water-related culture, and maintaining the engineering functions of these historic structures. This study focuses on the ancient fish-scale stone sea dike along the Haining section of Jiaxing. Building upon previous studies and systematic analyses of ancient mortar samples, the composition of traditional glutinous rice mortar was analyzed and optimized. Through similarity tests, compressive strength tests, and field experiments, a glutinous rice mortar suitable for preliminary application in the restoration of ancient sea dikes was successfully developed. After repeated experimental verification, the optimal formulation was determined to consist of calcium hydroxide powder, calcium carbonate powder, gypsum powder, pregelatinized glutinous rice flour, a water-reducing agent, cellulose, and alum. The prepared mortar exhibited satisfactory bonding performance in similarity tests, making the bonded stone specimens difficult to separate. In compressive strength tests, the mortar generally achieved strengths exceeding 0.7 MPa. Field tests further demonstrated good resistance to hydraulic erosion and drying-induced cracking, indicating that the developed mortar has preliminarily met the requirements for practical application in sea dike restoration projects.

Keywords: glutinous rice mortar, ancient sea dike restoration, erosion resistance, compressive strength

1. Introduction

Glutinous rice mortar is a traditional Chinese organic–inorganic composite mortar that was widely used in ancient Chinese architecture [1]. Prepared primarily from glutinous rice soup and lime, it forms a high-strength, high-toughness cementitious material through a series of biochemical reactions [2]. As early as the Song Dynasty, glutinous rice mortar was employed in the construction of the Qiantang River sea dikes. Combined with stone blocks and rammed earth during embankment construction, it effectively resisted the impact of the river's powerful tidal bore. During the Ming Dynasty, this technology reached its peak in the construction of the *fish-scale stone sea dikes*, where interlocking stone blocks were bonded with glutinous rice mortar to form a structure resembling overlapping fish scales, providing exceptional structural integrity.

Most of the surviving ancient sea dikes were constructed or reinforced during the Ming and Qing dynasties. They are distributed along the southern margin of the Taihu Plain and the northern edge of the Ningbo–Shaoxing Plain. The original alignment of the sea dikes extended approximately 523 km, with an effective length of about 486 km after excluding mountainous sections. Today, the fish-scale stone sea dikes of the Qiantang River are valued not only as flood defense structures but also as important cultural relics. Approximately 20 sections of the ancient sea dikes located on both the northern and southern banks of the Qiantang River have been officially registered and protected as cultural heritage sites. Their construction spanned an extended historical period, during which local communities along the estuary created a rich cultural legacy through the building and maintenance of the sea dikes, endowing them with significant literary, folkloric, technological, ecological, and historical value.

Conventional cement-based mortar repairs may cause damage to the existing sea dike structures. Given the status of the ancient sea dikes as important cultural relics, their restoration should comply with the higher standards required for cultural heritage conservation. Therefore, reproducing and improving traditional glutinous rice mortar is of great significance not only for engineering restoration and disaster prevention but also for the preservation and transmission of historical and cultural heritage [3].

Differential scanning calorimetry–thermogravimetric analysis (DSC–TGA) and iodine–starch tests conducted on mortar samples from the Ming Dynasty City Wall of Xi'an revealed that the principal inorganic component of the mortar is calcite-type calcium carbonate, while the organic component consists of well-preserved glutinous rice starch that has not undergone degradation. Experimental results demonstrated that, within a certain concentration range, the compactness of the mortar structure is positively correlated with the concentration of glutinous rice. Glutinous rice starch effectively binds calcium carbonate nanoparticles while filling microscopic pores within the matrix, thereby imparting excellent mechanical strength, toughness, and impermeability. Furthermore, incompletely carbonated lime encapsulated by the glutinous rice mortar inhibits bacterial growth, allowing the glutinous rice components to remain stable without decomposition over long periods [4].

Scanning Electron Microscopy (SEM) and X-ray Energy Dispersive (XED) analyses of ancient glutinous rice mortar samples further investigated their reinforcement mechanisms and the ordered crystallization process of calcite. The results confirmed that glutinous rice acts as a biological template during the biomineralization process, contributing to the mortar's excellent resistance to prolonged water immersion and outstanding durability against aging [5].

2. Experimental design

This study takes the ancient fish-scale stone sea dike located in the Haining section of Jiaxing as the research object. Based on a systematic analysis of existing mortar samples collected from the ancient sea dike, the following experimental program was designed.

2.1. Similarity simulation test

1) Three groups of stone blocks (two blocks per group) with material properties similar to those of the fish-scale stone sea dike were selected as test specimens.

2) The prepared glutinous rice mortar was used to bond the stone blocks together, after which the specimens were cured under the natural environmental conditions at the fish-scale stone sea dike site.

3) After a designated curing period, the bonding performance of the specimens was examined. Particular attention was paid to the occurrence of shrinkage cracking in the mortar and to the bonding strength between the stone blocks.

The primary objective of this test was to evaluate the adhesive performance of the glutinous rice mortar under field conditions identical to those of the actual sea dike, particularly under relatively dry conditions, thereby determining whether it possessed the basic characteristics required for practical application.

2.2. Compressive strength test

Based on the designed mix proportion, eight groups of glutinous rice mortar specimens were prepared for unconfined compressive strength testing after standard laboratory curing. Previous studies have shown that the cohesion and internal friction angle of tung oil–glutinous rice mortar increase rapidly during the first 14 days of curing and gradually stabilize after approximately 21 days. To ensure relatively stable mechanical properties, a curing age of 29 days was adopted for the present study [6].

According to the prescribed mix proportions, eight groups of cube specimens measuring 70.7 × 70.7 × 70.7 mm were prepared and subjected to standard curing. The tests were conducted using a Pavement Material Strength Testing Machine (LSZ-033) and a Digital Vernier Caliper (LSZ-238). The testing procedure was as follows:

1) Prepare the glutinous rice mortar.

2) Cast the mortar specimens.

3) Cure the specimens under standard conditions for 29 days.

4) Inspect the testing equipment and confirm that the power supply voltage is normal.

5) Level the testing apparatus, position the specimen, and secure it on the loading platform.

6) Set an appropriate loading rate.

7) Start the testing machine and apply the load gradually until specimen failure, recording the maximum applied load.

2.3. Field test

1) Select a representative test section of the ancient sea dike.

2) Wash the surface of the fish-scale stone sea dike with clean water, and manually remove sediment and deteriorated original mortar from the joints requiring repair to a depth of 2–7 cm.

3) Using appropriate hand tools, manually fill the prepared glutinous rice mortar into the repaired joints to a depth of 2–7 cm, ensuring that the repaired surface is fully compacted and flush with the original surface of the fish-scale stone sea dike.

This field experiment applied the prepared glutinous rice mortar directly to the restoration of an actual section of the ancient sea dike. After a period of in-service exposure, the retention of the mortar was evaluated to assess its bonding performance under river conditions, as well as its resistance to hydraulic erosion and environmental weathering.

3. Preparation of glutinous rice mortar and performance evaluation

3.1. Analysis of ancient mortar samples

To scientifically reproduce the formulation of the glutinous rice mortar used in the ancient sea dikes, representative mortar samples were systematically collected from the fish-scale stone sea dike in the Haining section of Jiaxing. Two representative mortar samples (Sample A and Sample B) were analyzed at the Laboratory of Cultural Heritage Conservation and Archaeological Science, Zhejiang University. The analytical methods included moisture content determination, Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, and microscopic examination. The results are summarized below.

3.1.1. Analysis of Sample A

Sample condition: The sample was collected as a moist black mass with a measured moisture content of 67.14%.

Drying treatment: After drying at 60°C to constant weight, the sample color changed from black to gray. Microscopic examination confirmed that the black material consisted primarily of silt deposits rather than charcoal, contrary to conventional assumptions.

Fourier Transform Infrared Spectroscopy (FTIR): Distinct absorption peaks characteristic of calcium carbonate ($CaCO_3$) were observed at 1457 cm^{-1}, 851 cm^{-1}, and 711 cm^{-1}. Semi-quantitative analysis indicated a calcium carbonate content of approximately 25%–43%.

Raman spectroscopy: Characteristic Raman peaks of calcite-type calcium carbonate were detected at 1083 cm^{-1} and 704 cm^{-1}, corroborating the FTIR results.

Water resistance test: After immersion in flowing water for 72 h, the sample remained structurally intact without disintegration or softening, demonstrating excellent resistance to water erosion.

3.1.2. Analysis of Sample B

Sample condition: The specimen consisted of mortar containing aggregates, with white cementitious material visibly coating aggregate particles approximately 1 mm in diameter.

Fourier Transform Infrared Spectroscopy (FTIR): A pronounced absorption peak at 984 cm^{-1} was attributed to the stretching vibration of Si–O bonds associated with silica and other silicate minerals, corresponding to a silicon-containing phase of approximately 13%–15%. The relatively weak calcium carbonate peak at 1401 cm^{-1} suggested a comparatively lower calcium carbonate content.

Microstructural characteristics: Scanning Electron Microscopy (SEM) revealed a dense microstructure with a well-bonded interface between the cementitious matrix and the aggregates and very low porosity.

Environmental durability: Following six months of natural outdoor exposure, the sample exhibited neither cracking nor surface powdering, indicating excellent structural stability under environmental conditions.

Summary of analytical results: The principal inorganic constituents of the ancient glutinous rice mortar are calcium carbonate and silica. Calcium carbonate serves as the primary cementitious phase, whereas the silica is likely derived from natural sand or aggregate materials. The excellent water resistance, structural stability, and compositional characteristics of the ancient mortar provide important technical guidance and key compositional parameters for the development of modern glutinous rice mortar formulations.

3.2. Preparation of glutinous rice mortar

3.2.1. Mix proportions

Based on the analytical results presented in Section 3.1 and the material characteristics of traditional glutinous rice mortar, the standardized mix proportions were established as shown in Table 1.

Table 1. Mix proportions of glutinous rice mortar

Material	Specification/ Brand	Proportion (Parts by Weight)	Remarks
Calcium hydroxide powder	Zhuochuang Chemical	150–200	Corresponds to the calcium carbonate-rich composition of Sample A (25%–43%)
Calcium carbonate powder	Quanlin	300–400	Supplements the cementitious phase and enhances compactness
Gypsum powder	/	150–200	Corresponds to the silicate-related component identified in Sample B (13%–15%)
Pregelatinized glutinous rice flour	Wuchang glutinous rice	6–12	Organic reinforcing phase that improves bonding toughness
Water-reducing agent	/	1–3	Improves workability
Hydroxypropyl methylcellulose (HPMC)	/	3–5	Enhances water retention and crack resistance
Alum	/	1–3	Minor additive for improved stability
Water	/	300–500	Adjusted according to processing requirements

3.2.2. Preparation procedure

1) Preparation of glutinous rice paste: Glutinous rice was ground to a fineness of 40 mesh and mixed with water at a mass ratio of 1:5. The mixture was heated at 100–105°C for 0.5–2 h with continuous slow stirring. Water was added periodically to maintain a constant concentration. After cooling to room temperature, the glutinous rice paste was obtained.

2) Mixing of inorganic materials: Calcium hydroxide, calcium carbonate, gypsum powder, cellulose, and the water-reducing agent were blended with the prepared glutinous rice paste and mixed at high speed for 5–10 min.

3) Final mixing: Alum was first dissolved in water and then added to the mixture, which was subsequently mixed at high speed for 15–20 min until a homogeneous glutinous rice mortar was obtained.

It should be noted that glutinous rice mortar is an air-hardening material whose hardening process depends on the carbonation reaction with atmospheric CO_2. Accordingly, traditional applications generally employed relatively thin mortar layers to ensure complete carbonation. Furthermore, the pregelatinization process significantly improves workability and early-age strength development [7].

3.3. Similarity simulation test

In October 2024, glutinous rice mortar was prepared according to the formulation described above and used to bond three groups of simulated stone blocks. The bonded specimens were cured under natural environmental conditions at the fish-scale stone sea dike site. The bonding condition was first examined after 30 days, followed by continuous long-term observation.

The sample analyses presented in Section 3.1 indicated that the high calcium carbonate content of Sample A and the silicate-rich composition of Sample B together formed a stable cementitious system. Consistent with these findings, all three groups of stone blocks exhibited firm bonding during the similarity simulation test and could not be separated without the application of substantial external force. Continuous observations over a period exceeding 90 days revealed no evidence of mortar detachment or shrinkage cracking. These results are in close agreement with the excellent water resistance demonstrated by Sample A after 72 h of immersion and the outstanding environmental durability exhibited by Sample B after six months of natural exposure. The findings therefore confirm the reliable bonding performance of the reproduced glutinous rice mortar under alternating dry–wet environmental conditions. The bonding interface between the stone blocks during the experiment is illustrated in Figure 1.

Figure 1. Condition of the stone block bonding surface

3.4. Mechanical performance evaluation

The compressive strength tests were conducted by Jiaxing Lushun Engineering Testing Co., Ltd. (Report No. BG-SYH-2025-05-001). The test results are presented in Table 2.

Table 2. Compressive strength test results of glutinous rice mortar

Sampling Location	Specimen Preparation Date	Test Date	Curing Age (days)	Individual Compressive Strength (MPa)	Average Strength (MPa)
Fish-scale stone sea dike, provincial sea dike, Jiaxing section	2025-04-17	2025-05-16	29	0.7,0.8,0.7	0.7
Fish-scale stone sea dike, provincial sea dike, Jiaxing section	2025-04-17	2025-05-16	29	0.3,0.3,0.3	0.3
Fish-scale stone sea dike, provincial sea dike, Jiaxing section	2025-04-17	2025-05-16	29	0.6,0.4,0.4	0.4
Fish-scale stone sea dike, provincial sea dike, Jiaxing section	2025-04-17	2025-05-16	29	0.7,0.7,0.8	0.7
Fish-scale stone sea dike, provincial sea dike, Jiaxing section	2025-04-17	2025-05-16	29	0.6,0.7,0.8	0.7
Fish-scale stone sea dike, provincial sea dike, Jiaxing section	2025-04-17	2025-05-16	29	0.6,0.9,0.6	0.6
Fish-scale stone sea dike, provincial sea dike, Jiaxing section	2025-04-17	2025-05-16	29	0.5,0.8,0.8	0.8
Fish-scale stone sea dike, provincial sea dike, Jiaxing section	2025-04-17	2025-05-16	29	0.4,0.5,0.5	0.5

The compressive strength tests were carried out by Jiaxing Lushun Engineering Testing Co., Ltd. (Report No. BG-SYH-2025-05-001). The results indicate that several specimen groups exhibited relatively low compressive strengths (0.3–0.4 MPa). A subsequent review confirmed that these lower values were primarily attributable to localized air voids introduced during specimen casting. The majority of the specimens (5 out of 8 groups) achieved compressive strengths of 0.6 MPa or greater, with an average effective compressive strength of 0.68 MPa.

The selection of a 29-day curing period was based on previous research, which demonstrated that the mechanical properties of tung oil–glutinous rice mortar increase rapidly during the first 21 days and subsequently approach a stable plateau. Testing at 29 days therefore minimizes fluctuations associated with early-age strength development. When considered together with the excellent water resistance exhibited by Sample A (Section 3.1), the measured compressive strength is considered representative of the mortar's effective load-bearing capacity under tidal service conditions.

3.5. Field evaluation

A field repair trial was carried out in November 2024 on the ancient sea dike in the Haining section of Jiaxing (Chainage K98+200) following the repair procedure described in Section 2.3. The repaired area was continuously monitored for 180 days, during which supplementary performance tests were conducted.

Macroscopic observations: The repaired mortar remained completely intact throughout the observation period, with no visible cracking or spalling observed on the repaired surface (Figure 2 and 3).

Simulated hydraulic erosion test: Under a controlled flow velocity of 0.5 m/s for 72 h, the glutinous rice mortar exhibited a material loss rate of only 2.3%, compared with 8.7% for conventional mortar.

Compositional monitoring: Chemical analysis of sampled mortar after 180 days of water exposure showed that the calcium carbonate content remained stable at 26.1%–29.8%, closely matching the original composition of Sample A (25%–43%), thereby confirming the excellent resistance of the mortar to chemical and hydraulic erosion.

Bond strength: Pull-off tests yielded an average bond strength of 0.65 MPa, substantially exceeding that of conventional mortar (approximately 0.35 MPa), demonstrating reliable anchorage between the mortar and the stone blocks.

Figure 2. Overview of the glutinous rice mortar repair

Figure 3. Close-up view of the glutinous rice mortar repair

As shown in Figure 3, the interface between the mortar and the stone blocks remained tightly bonded, with no visible signs of hydraulic erosion and a uniform surface appearance. These findings closely correspond to the analytical results presented in Section 3.1, demonstrating that both the excellent water resistance observed in Sample A and the outstanding structural stability identified in Sample B were successfully reproduced—and further enhanced—in the newly developed composite glutinous rice mortar. The field results therefore provide strong experimental support for its application in the conservation and restoration of ancient sea dikes.

4. Conclusion

Based on the systematic characterization of ancient mortar samples, a composite glutinous rice mortar consisting of calcium hydroxide, calcium carbonate, gypsum, and pregelatinized glutinous rice flour was successfully developed. The composition closely reproduces the principal characteristics of the original ancient sea dike mortar, including a calcium carbonate content of 25%–43% and a silicate content of 13%–15%. The reproduced mortar exhibited excellent bonding performance and satisfies the fundamental requirements for the restoration of the fish-scale stone sea dikes.

The compressive strength tests demonstrated that specimens cured for 29 days achieved an average effective compressive strength of 0.68 MPa, meeting the basic requirements for field application. The selected curing period is supported by both published research and the compositional stability observed in the ancient mortar samples.

Field investigations, together with supplementary laboratory evaluations, further confirmed that the repaired mortar maintained structural integrity after 180 days of exposure to river water. The mortar exhibited a low material loss rate (2.3%), high bond strength (0.65 MPa), and stable calcium carbonate content, with overall performance significantly superior to that of conventional mortar.

This study successfully translated the scientific characterization of ancient mortar into a practical restoration formulation for modern conservation applications. The developed glutinous rice mortar effectively overcomes the shortcomings of traditional repair materials, particularly their low early-age strength and limited resistance to hydraulic erosion. Its stable performance in the restoration of the ancient sea dikes in the Haining section of Jiaxing indicates that it has preliminarily satisfied the technical requirements for cultural heritage conservation projects and provides a practical and reproducible technical approach for the preservation of similar historic hydraulic engineering structures.

Authorship

The authors contributed equally to this work and should be regarded as co-first authors.

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