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Study on the Material Properties of Chuihui (a Traditional Mortar) Used in the Leshan Giant Buddha

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Abstract **- As a World Cultural Heritage site, the Leshan Giant Buddha has long been affected by environmental factors, leading to deterioration issues such as cracking, hollow drumming, and damage in its restoration Chuihui materials. This study developed five distinct restoration materials tailored to the environmental conditions and repair requirements of different sections of the Leshan Giant Buddha. It systematically investigated their performance evolution under dry curing, pure water curing, and simulated permeating solution curing conditions. By measuring physical and mechanical properties and analyzing changes over curing periods, the study examined the degradation characteristics and adaptability of different materials in various environments. Results indicate: Sulfoaluminate cement Chuihui demonstrated the most significant enhancement under dry curing; In aqueous environments, while traditional Chuihui continued to deteriorate, the other materials initially declined then improved. Underwater cement Chuihui and Metakaolin Chuihui exhibited good water resistance. The comprehensive performance ranking was: sulfoaluminate cement Chuihui > Metakaolin Chuihui > underwater cement Chuihui > Silicate cement Chuihui > traditional Chuihui. This study provides theoretical basis and data support for selecting restoration materials and implementing preventive conservation for the Leshan Giant Buddha and similar stone cultural relics.**

Keywords - Leshan Giant Buddha; Chuihui materials; Heritage conservation; curing environments;

I. INTRODUCTION

The Leshan Giant Buddha, situated at the confluence of three rivers in Leshan City, Sichuan Province, China, stands 71 metres tall. As the largest extant stone-carved seated Maitreya Buddha statue, it was inscribed on the UNESCO World Heritage List as a dual natural and cultural site in 1996[1], as illustrated in Figure 1. However, prolonged environmental exposure has caused significant deterioration of the rock mass in which the Buddha is embedded, as illustrated in Figure 2. Over the past century, experts have undertaken seven restoration projects using Chuihui materials[2].In the 1990s, Jiayu Ma [3] from the Sichuan Provincial Institute of Cultural Relics and Archaeology, building upon traditional Chuihui research, developed a Mixed Chuihui using cement, lime, carbon ash, and hemp fibre.Qiao Zhen [4] further enhanced the mechanical properties of the modified Chuihui by incorporating metokaolin into the Mixed Chuihui.

Near the fissures on the upper levels, the deterioration of the Leshan Giant Buddha's cave complex has become increasingly severe. This is due to the combined effects of soluble salts, the aquatic environment, and biological factors, compounded by recent intensified environmental pollution, water seepage erosion, and the washing and dissolution caused by acid rain. Regional cracking and damage are evident in the Buddha's hair bun, facial features, chest and abdomen, and hands, necessitating meticulous restoration using Chuihui materials [5].Sun Bo [6] discovered that seepage at the interface between the rock substrate and the restoration layer causes cracking and delamination, presenting obstacles to

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cultural heritage conservation; shear stress at this interface is the primary cause of cracking in the restoration layer.He Peng [7] investigated the failure mechanism of the Leshan Giant Buddha's hair bun, concluding that the primary causes of failure in the restoration material at this location were acid rain, water, CO_2, and the restoration material itself.

Fig 1 Schematic diagram of the Leshan Giant Buddha in Sichuan

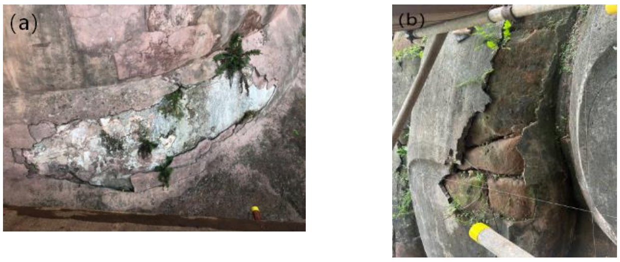

Fig 2 Deterioration status of Chuihui materials a. breast and abdominal reconstruction material failure,b. failure of hand repair materials

With advances in cultural heritage conservation technology, restoration materials for the Leshan Giant Buddha must exhibit physical and mechanical properties closely matching the reinforced rock. They must possess excellent adhesion, low viscosity, good pourability, and room-temperature curability, while meeting durability and water resistance requirements.In light of this, this study investigates the performance variations of different types of Chuihui materials by preparing Leshan Giant Buddha traditional Chuihui, Mixed Chuihui, and modified Chuihui.

II. EXPERIMENTAL

A. Material Proportions

Chuihui is an ancient building material belonging to the lime category, primarily composed of cement, lime, carbon ash, and hemp fibre, which are homogenised through pounding to form a restoration material[8]. Under prolonged external influences, Chuihui undergoes varying degrees of performance degradation, necessitating modification to enhance its properties and extend its service life. Through literature review, field research, and on-site investigations, and based on the degradation characteristics and decay patterns of the restoration materials, the mix ratios for five types of Chuihui materials have been determined, as detailed in Table I.

TABLE I. MIX PROPORTIONS FOR DIFFERENT TYPES OF CHUIHUI

Type	Primary Components	Proportion
Traditional Chuihui	Lime, carbon ash, hemp fibre	1:3:0.2 Water as required
Mixed Chuihui 1	Lime, cement (silicate cement - ordinary cement), carbon ash, standard sand, hemp fibre	1:0.5:1.8:1.2:0.1 Hemp fibre as required (Cement content 11%) Water-to-binder ratio 0.3
Mixed Chuihui 2	Lime, cement (low-alkali sulphoaluminate cement R), carbonated fly ash, standard sand, hemp fibre	1:0.5:1.8:1.2:0.1 Hemp fibre as required (Cement content 11%) Water-cement ratio 0.3
Mixed Chuihui 3	Lime, underwater cement (silicate cement + anti-dispersant), carbon ash, standard sand, hemp fibre	1:0.5:1.8:1.2:0.1 Hemp fibre as required (Cement content 11%) Water-to-solid ratio 0.3
Modified Chuihui	Lime, cement (low-alkali sulfoaluminate cement), carbonated fly ash, standard sand, metakaolin, hemp fibre	2.1:1.1:4:2.6:2.5:2.5 Hemp fibre as required (Cement + metakaolin content 29%) Water-to-solid ratio 0.33

B. Test Materials

The cementitious materials employed in the experiments comprised PO42.5 grade cement manufactured by Wuhan Yadong Cement Plant, inorganic mineral polymers procured from Shenzhen Aerospace Innovation Research Institute, and metakaolin produced by Inner Mongolia Tianzhijiao Kaolin Co., Ltd. Natural river sand was selected for testing purposes, with its chemical composition and detailed in Table II-IV.

TABLE II. CHEMICAL COMPOSITION OF ORDINARY PORTLAND CEMENT

Name	Chemical Composition (%)							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3
PO42.5	21.33	6.72	3.33	57.32	2.61	0.77	0.16	4.20

TABLE III. CHEMICAL COMPOSITION OF SULFOALUMINATE CEMENT

Name	Chemical Composition (%)							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3
PO42.5	21.33	6.72	3.33	57.32	2.61	0.77	0.16	4.20

TABLE IV. CHEMICAL COMPOSITION OF METAKAOLIN

Name	Chemical Composition (%)					
	Al_2O_3	SiO_2	CaO	K_2O	Fe_2O_3	TiO_2
MK	45.42	51.57	0.377	0.174	0.502	1.34

C. Experimental Design Approach

1) Environmental Characteristics of Chuihui

Through reviewing relevant literature, conducting on-site investigations, and interviewing the original designers, the construction techniques for the Chuihui were clarified. This research quantified each preparation stage, strictly controlling raw material quantities and water usage while optimising mixing speeds. Furthermore, mechanising the traditional Chuihui process not only enhanced efficiency but also facilitated material quality control.Furthermore, during the

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restoration of the Leshan Giant Buddha, construction personnel applied the Chuihui in layers from the interior outward, with a thickness ranging from approximately 10mm to 30mm. Surveys of the Buddha revealed significant variations in the environmental conditions of different sections due to its immense scale, primarily manifesting in two scenarios:Chuihui materials exposed on the surface of the cave structure have been subjected to prolonged dry conditions, but the chest and abdominal regions of the Leshan Giant Buddha have endured continuous erosion from seepage water. Certain internal layers (underlay) of the Chuihui materials have been persistently submerged in seepage solutions, isolated from air, as illustrated in Figure 3.

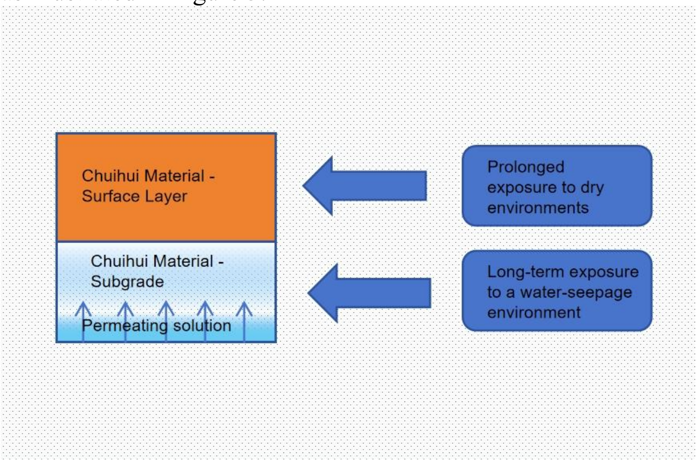

Fig 3 Schematic diagram of Chuihui

2) Construction and curing conditions of the Chuihui

When undertaking restoration work on the Leshan Giant Buddha using Chuihui materials, designers typically select dry periods for construction. Through extensive field research and site investigations, the following scenarios have been identified:

- After applying the Chuihui materials, construction crews generally allow them to cure naturally for five days in dry climatic conditions. Subsequently, the plaster faces erosion from water damage such as seepage and rainfall.
- Review of literature and monitoring of Leshan's regional climate indicate ambient temperatures and humidity levels of approximately 25°C and 65% respectively during this period.
- Prior research indicates that significant changes in the performance characteristics of the plastering materials primarily occur within the first month.

3) Determination and Analysis of Ion Concentration in Seepage Solutions

Seepage water collected from the chest and abdominal regions of the Leshan Giant Buddha was analysed for ionic concentration, with results detailed in Table V. Based on the identified ions and their concentrations, the soluble salt types present in the solution were characterised, alongside assessment of its acidity or alkalinity. Based on this, the permeating solution was prepared as follows: 0.6 mmol/L $CaCl_2$, 1.8 mmol/L $NaNO_3$, 1.1 mmol/L $KHCO_3$, 2.7 mmol/L $MgSO_4$, and 16.3 mmol/L $CaSO_4$.

TABLE V. ION ANALYSIS OF INFILTRATION AND PRECIPITATION SOLUTIONS

Ion	Seepage (mmol/L)	Atmospheric Precipitation (mmol/L)
Ca^{2+}	19.92	0.034
K^{+}	0.88	0
Mg^{2+}	2.72	0
Na^{+}	1.24	0.028
Cl^{-}	1.19	0.033
NO_3^{-}	1.80	0.018
HCO_3^{-}	1.07	0.031
SO_4^{2-}	19.00	0.132

D. Material Preparation and Experimental Process

Taking into account the regional environment of the Chuihui materials, microenvironmental characteristics of the restoration area, water conditions, soluble salts, and other factors, combined with on-site construction conditions and the manufacturing process of the Chuihui materials, a design scheme incorporating different types of Chuihui materials was developed. The specific procedure is as follows:

- Prepare five types of Chuihui materials according to the construction process.
- All Chuihui samples were dried and cured for five days under controlled conditions of 25°C and 65% relative humidity. These environmental parameters (temperature and humidity) were maintained throughout the testing process.
- Expose the five Chuihui materials to three distinct environments: dry curing, immersion in permeable solution, and pure water curing (control group).
- Weathering indices were measured at curing ages of 0, 1, 3, 7, 14, and 28 days, primarily comprising four parameters: wave velocity, compressive strength, flexural strength, and shear strength;To account for variations in weathering indicators caused by differing rock moisture contents during testing, specimens immersed in permeable water or pure water solutions were placed in a forced-air drying oven for 4 hours at 35°C humidity, ensuring near-uniform moisture content across all hammered Chuihui samples under different conditions.

III. RESULTS

This study primarily investigates the performance variations of five Chuihui materials under three curing conditions (dry, pure water, and permeating water curing), focusing on the effects of environmental conditions and curing duration on material properties. Test results are presented sequentially for traditional Chuihui, silicate cement Chuihui, metakaolin cement Chuihui, sulphoaluminate cement Chuihui, and underwater cement Chuihui. The decay patterns and variation ranges of weathering indices for the same material under different conditions are presented sequentially (longitudinal comparison). Subsequently, the variations of different materials under identical conditions are analysed to evaluate the relative performance strengths of various types of Chuihui.

A. Variations in the Same Mortar Material Under Different Curing Condition

1) Traditional Chuihui material

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According to Figure 4, the following can be obtained under dry curing conditions, the wave velocity, compressive strength, flexural strength, cohesiveness, and internal friction angle of traditional mortar exhibit an initial rapid followed by a gradual increase.Under permeating water and pure water conditions, all indicators exhibit a decline from rapid to gradual rates, with no significant distinction between the two. Taking compressive strength as an example, permeating water and pure water curing result in decreases of 0.14 MPa and 0.13 MPa respectively. This primarily stems from the continuous dissolution of lime in water, significantly weakening the cohesiveness between different materials. The progressive reduction in weathering indicators corroborates this observation.After 14 days of curing, pure water curing yielded slightly higher values than permeating water curing, with the overall sequence being dry curing > pure water curing > permeating water curing. This may stem from the loose structure of traditional lime mortar materials, where soluble salts in permeating solutions accumulate within rock pores. During testing, crystallisation formed during the drying process, leading to degradation.

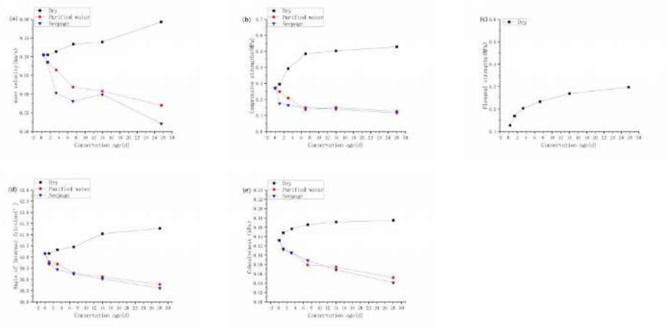
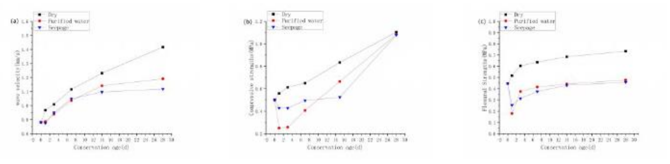


Fig 4 Variation curves of traditional Chuihui material properties under different conditions a. wave velocity variation curve, b. compressive strength variation curve, c. flexural strength variation curve, d. internal friction angle variation curve, e. cohesiveness variation curve.

2) Silicate Cement Chuihui material

According to Figure 5, the following can be obtained under dry curing conditions, the wave velocity, compressive strength, and flexural strength of the samples exhibit an upward trend, though the rates of increase differ markedly. Specifically, the wave velocity increased by 0.543 km/s. Under permeating water and pure water conditions, the overall trend shows a decrease followed by an increase, with no significant distinction between the two. Mirroring the patterns observed in other weathering indicators, shear strength exhibits a rapid initial increase followed by a slower rise in dry-cured specimens. Conversely, specimens cured in pure water and permeating water conditions first decrease and then increase. The shear-related indicators for pure water and permeating water specimens show no significant distinction, indicating that "water" is the primary factor driving material degradation. By 28 days, the internal friction angle and cohesiveness reached 41.6° and 0.25 kPa respectively. Overall performance ranked as follows: dry-curing > pure water-curing > permeating water-curing.



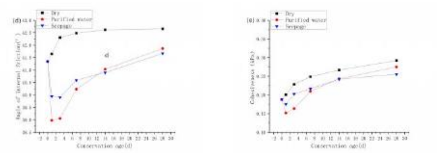


Fig 5 Variation curves of silicate cement Chuihui material properties under different conditions a. wave velocity variation curve, b. compressive strength variation curve, c. flexural strength variation curve, d. internal friction angle variation curve, e. cohesiveness variation curve.

3) Underwater Cement Chuihui material

According to Figure 6, the following can be obtained under dry curing conditions, wave velocity, compressive strength, and flexural strength also exhibited an initial rapid followed by a gradual increase. Under permeating water and pure water conditions, the overall trend showed a slight initial decrease followed by an increase, though the decrease was minimal. Through testing and literature review, it was found that underwater cement contains anti-dispersants, making it less prone to degradation in identical aquatic environments. Shear resistance parameters exhibited an initial rapid increase followed by a gradual slowdown in dry-cured specimens, whereas specimens cured in pure water and permeating water conditions first decreased before increasing. The shear resistance parameters of pure water and permeating water cured specimens showed no significant distinction, indicating that weathering induced by the "water" effect is the primary factor controlling specimen deterioration.

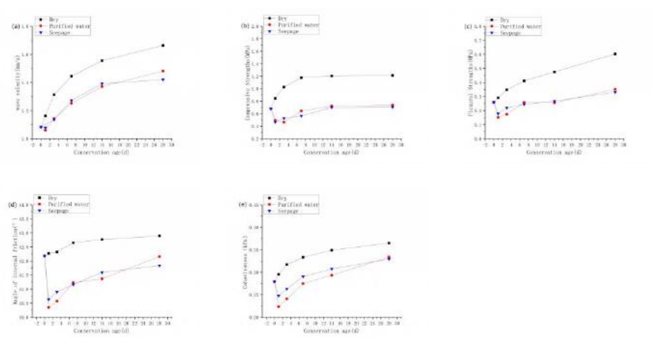


Fig 6 Variation curves of underwater cement Chuihui material properties under different conditions a. wave velocity variation curve, b. compressive strength variation curve, c. flexural strength variation curve, d. internal friction angle variation curve, e. cohesiveness variation curve.

4) Metakaolin Chuihui material

According to Figure 7, the following can be obtained under dry curing conditions, both wave velocity and compressive and flexural strengths exhibit a trend of initially rapid increase before eventually stabilising. All three weathering indices exhibited a pronounced inflection point at 14 days. The compressive strength values at 0d, 1d, 3d, 7d, 14d, and 28d were 0.76 MPa, 1.18 MPa, 1.37 MPa, 1.81 MPa, 1.93 MPa, and 2.01 MPa respectively. This indicates that adding metokaolin reduces the time required for lime-based materials to achieve stable performance, thereby facilitating construction to some extent. Under permeating water and pure water conditions, the overall trend showed a decrease followed by an increase. Comparing weathering index values across the three curing conditions, dry-cured samples exhibited significantly higher values than water-cured samples, particularly evident in strength parameters. For instance, at 28 days, the flexural strength of dry-cured specimens reached 1.23 MPa, exceeding water-cured specimens by 0.75 MPa. Regarding shear properties, the internal friction angle and cohesion of dry-cured

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specimens exhibited a non-linear growth pattern, accelerating initially before slowing. The internal friction angles at 0, 1, 3, 7, 14, and 28 days were 43°, 43.2°, 43.3°, 43.6°, 43.8°, and 44°, respectively. with overall variation not exceeding 1°. Cohesion, however, exhibited some variation between 7 and 28 days, potentially related to sample size, moisture content, and surface porosity. The trends and values of shear-related indicators for samples cured with pure water and seepage water were largely consistent, exhibiting a decrease followed by an increase. By 28 days, the internal friction angles and cohesion values for both pure water and seepage water-cured samples were approximately 43° and 0.31 kPa, respectively, similar to their initial values.

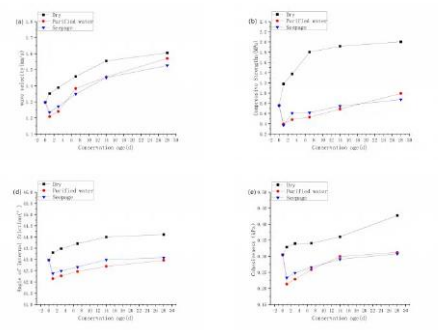

Fig 7 Variation curves of metakaolin Chuihui material properties under different conditions a. wave velocity variation curve, b. compressive strength variation curve, c. flexural strength variation curve, d. internal friction angle variation curve, e. cohesiveness variation curve.

5) Sulfoaluminate Cement Chuihui material

According to Figure 8, the following can be obtained under dry curing conditions, weathering indicators such as wave velocity, compressive strength, and flexural strength exhibit an almost linear upward trend with relatively rapid rates of change. At 0d, 1d, 3d, 7d, 14d, and 28d, wave velocities were 1.392 km/s, 1.451 km/s, 1.499 km/s, 1.603 km/s, 1.716 km/s, and 1.815 km/s respectively. with wave velocity increasing by merely 0.5 km/s. The internal density of the samples markedly enhanced, reducing pore and fissure dimensions, indicating thorough inter-material reactions. Compressive strength values reached 1.67 MPa, 1.89 MPa, 2.14 MPa, 2.59 MPa, 2.97 MPa, and 3.73 MPa, representing an increase of 2.06 MPa. Flexural strength also varied from 0.81 MPa to 1.35 MPa, indirectly indicating a correlation between the macroscopic indicators of the samples. Under water seepage and pure water conditions, the overall trend showed a decrease followed by an increase. The increase in strength parameters was modest, with compressive strength and flexural strength increasing by approximately 0.65 MPa and 0.21 MPa respectively. The internal friction angle of dry-cured specimens did not exceed 0.5°, while cohesiveness increased from 0.35 kPa to 0.52 kPa, representing an overall improvement of 0.17 kPa. The shear-related indicators for both pure water and permeating water-cured specimens exhibited largely consistent trends and values, showing a decrease followed by an increase. By day 28, the internal friction angle and cohesiveness for both pure water and permeating water-cured specimens were approximately 44° and 0.33 kPa respectively.

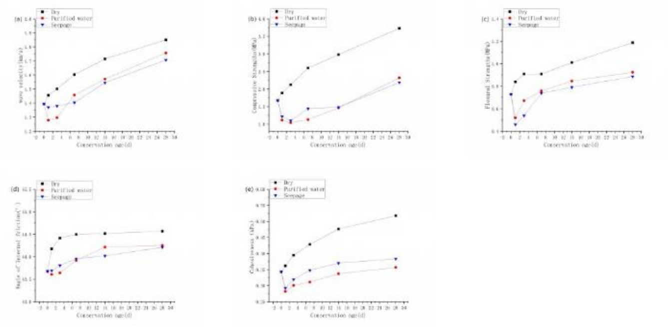

Fig 8 Variation curves of sulfoaluminate cement Chuihui material properties under different conditions a. wave velocity variation curve, b. compressive strength variation curve, c. flexural strength variation curve, d. internal friction angle variation curve, e. cohesiveness variation curve.

B. *Variations in Different Chuihui Materials Under Identical Curing Conditions*

1) Physical property indices of different types of Chuihui materials under dry curing conditions

Figure 9 indicates that under dry curing conditions, the weathering indices of various types of Chuihui materials all exhibit a non-linear upward trend, though differences exist in the magnitude of increase and rate of change.When considering physical properties such as wave velocity, compressive strength, and flexural strength, the overall sequence is: Sulphoaluminate cement Chuihui> Metakaolin Chuihui> Underwater cement Chuihui> Silicate cement Chuihui> Traditional Chuihui. Cementitious materials enhance the mechanical properties of Chuihui, with sulphoaluminate cement demonstrating the most pronounced effect. Variations were observed in weathering index test results, such as inconsistent compressive and flexural strength values for underwater cement. This may be closely linked to the homogeneity and microstructure of the Chuihui material.The internal friction angle of dry-cured specimens varied within approximately 1°,cohesiveness ranged between 0.2KPa and 1.5KPa.

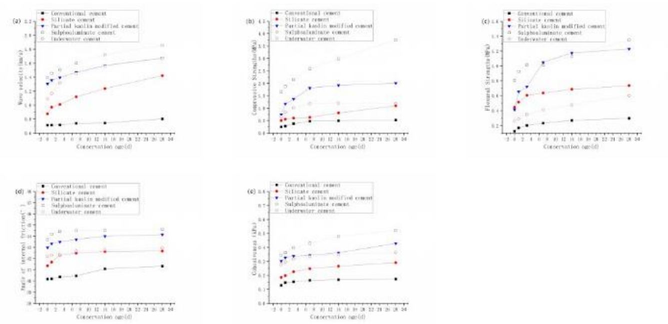

Fig 9 Variation curves of indicators for different types of Chuihui materials under dry curing conditions a. wave velocity variation curve, b. compressive strength variation curve, c. flexural strength variation curve, d. internal friction angle variation curve, e. cohesiveness variation curve.

2) Physical property indices of different types of Chuihui materials under water-permeable curing conditions

Analysis above indicates that sample performance variations under pure water and permeating water conditions are nearly identical. Considering permeating water conditions represent the actual weathering scenario for Chuihui materials, this section focuses solely on performance changes under permeating water. Furthermore, the internal friction angle variation under permeating water is minimal, approximately within 1°, thus the analysis concentrates on cohesiveness variation patterns.

Figure 10 indicates that comprehensive comparison of Chuihui material indices: Sulfoaluminate cement Chuihui > Metakaolin Chuihui > Underwater cement Chuihui > Silicate cement Chuihui > Traditional Chuihui. Under permeation curing, traditional Chuihui exhibits a declining trend, while other mortar types show an initial decline followed by an increase in all indices. This outcome aligns with the lowest performance metrics of traditional Chuihui, indirectly highlighting cementitious materials' crucial role in restoration processes. Compared to other mortar types, sulfoaluminate cement-modified mortar exhibits the most pronounced initial susceptibility to aquatic environments, particularly demonstrating significant strength degradation. The microenvironment at the restoration site of the Leshan Giant Buddha significantly impacts the performance of Chuihui materials. Water and the resulting weathering effects substantially diminish the material's properties.

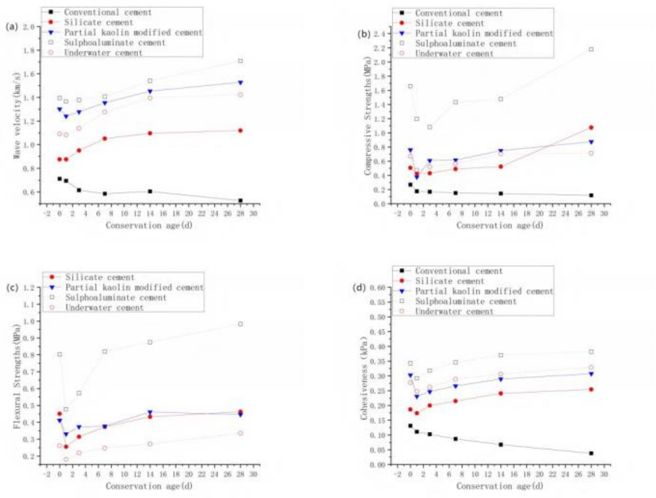

Fig 10 Variation curves of indicators for different types of Chuihui materials water-permeable curing conditions a. wave velocity variation curve, b. compressive strength variation curve, c. flexural strength variation curve, d. cohesiveness variation curve.

IV. CONCLUSION

This study conducted laboratory tests based on literature review and field investigations, comprehensively considering factors such as the degradation characteristics of the restoration materials for the Leshan Giant Buddha, regional environmental features, microenvironments in different parts of the cave complex, and ion concentrations in the water environment.Five types of Chuihui materials were first prepared and subjected to three curing conditions (dry curing, pure water-control group, permeation water) for 0d, 1d, 3d, 7d, 14d, and 28d. The variation patterns of physical properties – including wave velocity, compressive strength, and flexural strength – were measured and analysed across Chuihui types, yielding the following principal conclusions:

- Under dry curing conditions, the physical properties of the Chuihui materials exhibited a non-linear increase, initially rapid then slowing. Overall, the order of performance was: Sulphoaluminate cement Chuihui > Metakaolin Chuihui > Underwater cement Chuihui > Silicate cement Chuihui > Traditional Chuihui Chuihui.
- Under pure water and permeating water curing conditions, the physical properties of the materials first decreased then increased, with no significant difference between the two conditions.
- At identical ages, the index values of specimens cured under pure water and permeating water conditions were lower than those of dry-cured specimens. Water and the resulting weathering processes are key factors causing deterioration in Chuihui materials, with Mixed Chuihui 2 (Sulphoaluminate cement) being most significantly affected.
- The material composition of the Chuihui, regional environment, microenvironments at different locations, and curing age are all primary factors influencing changes in sample performance.
- For Chuihui materials, intrinsic correlations exist between indicators such as wave velocity, compressive strength, and flexural strength. However, variations arise during testing due to sample homogeneity, moisture content, and degradation state. Comprehensive consideration of multiple weathering indicators, cross-validated against one another, enables more precise assessment of performance changes in these materials.

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