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STICKY RICE SLURRY-MODIFIED LIME-METAKAOLIN STABILIZATION OF SILTY CLAY: MECHANICAL PERFORMANCE AND MICROSTRUCTURAL CHARACTERIZATION

Tao Jiang[1*], ChunLong Liu[2,3], ZhiQiang Zhang[3]
[1]*School of Civil Engineering and Architecture, Hubei Polytechnic University, Huangshi 435003, Hubei, China.*
[2]*Pingyang County Transportation Bureau, Wenzhou 325400, Zhejiang, China.*
[3]*Institute of Geotechnical Engineering, Xi'an University of Technology, Xi'an 710048, Shaanxi, China.*
[*]*Corresponding Author: Tao Jiang*

Abstract: Lime-stabilized silty clays are widely used in subgrade construction and earthen heritage conservation, but their relatively slow strength development, susceptibility to wet-dry deterioration and limited long-term durability still constrain their broader engineering applications. In this study, a ternary binder consisting of sticky rice (SR) slurry, metakaolin (MK) and hydrated lime was formulated to stabilize a low-plasticity silty clay, with the aim of exploiting both the pozzolanic reactivity of calcined kaolin and the biomolecular templating effect of amylopectin. A systematic series of unconfined compressive strength (UCS) tests was conducted on lime-soil (LS), metakaolin-lime-soil (ML) and sticky rice-metakaolin-lime-soil (SM) specimens with varying lime contents, metakaolin dosages, sticky rice concentrations and water-to-solid ratios, cured for 7, 28 and 90 days. The microstructural and mineralogical evolution of the stabilized matrix was characterized using scanning electron microscopy (SEM) and X-ray diffraction (XRD), and the internal water retention behavior was tracked throughout the curing period. The experimental results indicate that the optimum binder composition corresponds to 13% lime, 10% metakaolin and 3% sticky rice at a water-to-solid ratio of approximately 0.34, beyond which strength either plateaus or declines because of dilution or excess organic phase. Compared with conventional LS and ML systems, the SM specimens develop a denser and more homogeneous gel-rich microstructure, exhibit a more pronounced consumption of portlandite and a stronger amorphous hump associated with C-S-H and C-A-H, and retain internal moisture more effectively during curing. The synergetic interaction between the biopolymer network of sticky rice and the pozzolanic products of the lime-metakaolin system is identified as the principal mechanism underlying the strength enhancement, providing a sustainable and historically inspired stabilization route for silty clay.
Keywords: Sticky rice slurry; Metakaolin; Lime; Silty clay; Unconfined compressive strength; Microstructure

1 INTRODUCTION

Silty clays of low to medium plasticity are widely distributed across the alluvial plains and loess regions of China, and their inferior shear strength, pronounced compressibility and marked sensitivity to moisture fluctuations frequently impair the serviceability of road embankments, foundation works and earthen architectural relics [1,2]. Chemical stabilization has long been adopted as a practical means of upgrading such problematic soils, with calcium-based binders, including quicklime, hydrated lime and ordinary Portland cement, dominating engineering practice [3,4]. Although the use of lime is economically attractive and can effectively reduce plasticity through cation exchange and flocculation, its strength contribution stems mainly from slow pozzolanic reactions between calcium hydroxide and the soluble aluminosilicate fraction of the soil, leading to limited early-age strength and a stabilized matrix that remains vulnerable under prolonged exposure to water or repeated wetting and drying [5].

To compensate for these intrinsic shortcomings, supplementary cementitious materials such as fly ash, ground granulated blast-furnace slag and, more recently, metakaolin have been incorporated into lime-stabilized systems [6,7]. Metakaolin, obtained through the dehydroxylation of kaolinite at 600-800 °C, possesses a highly disordered aluminosilicate framework rich in reactive Al_2O_3 and SiO_2; when combined with calcium hydroxide in an aqueous medium, it promotes the rapid formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) phases, together with stratlingite-type products, that confer denser packing and improved cohesion to the stabilized soil [8]. Yet, despite their effectiveness, lime-metakaolin systems still suffer from microcracking induced by drying shrinkage and from the brittle nature of inorganic gels, limiting the ductility and durability of the stabilized matrix [9].

In a parallel historical context, traditional Chinese masonry mortars dating back to the Southern and Northern Dynasties incorporated boiled sticky rice slurry into lime binders, and archaeological mortars from the Ming and Qing dynasties have proved remarkably durable [10-13]. Modern chemical investigations have established that the principal active component of sticky rice slurry, amylopectin, acts as a biopolymer template that regulates the nucleation and growth of calcium carbonate, refines crystal size, and binds the inorganic phase into a dense organic-inorganic composite [14]. While such a sticky rice-lime mortar has been extensively studied for the conservation of historical masonry, its extension to soil stabilization, particularly in a ternary system also containing a highly reactive pozzolan such as

metakaolin, has so far received only limited attention, and the coupled mechanisms governing the strength evolution and microstructural densification of such a quaternary mixture (soil-lime-metakaolin-sticky rice) remain poorly understood.

The present work therefore aims to systematically characterize the mechanical response, microstructural development and mineralogical evolution of a silty clay stabilized with a sticky rice-metakaolin-ime composite binder. Through a parametric UCS investigation, complemented by SEM, XRD and water-retention measurements, the optimum mix proportions are identified and the underlying strengthening mechanism is interpreted, with the broader objective of providing a sustainable, historically rooted yet scientifically optimized alternative for silty clay stabilization in geotechnical and heritage engineering.

2 MATERIALS AND METHODS

2.1 Raw Materials

The silty clay used in this investigation was sampled from a representative construction site, oven-dried, ground and passed through a 2 mm sieve before use. Its basic physical indices, summarized in Table 1, comprise a specific gravity of 2.66, a natural moisture content of 1.07%, a plastic limit of 21.03%, a liquid limit of 32.42% and a plasticity index of 11.39, classifying the material as a low-plasticity silty clay according to the unified soil classification system. The particle size distribution curves of the soil and metakaolin are presented in Fig. 1, from which it can be seen that metakaolin is appreciably finer than the natural soil and therefore capable of acting both as a pozzolanic reactant and as a particulate filler within the inter-grain voids of the soil skeleton.

Commercial calcined metakaolin with a whiteness of more than 90 was selected as the pozzolanic admixture, and its chemical composition, determined by X-ray fluorescence spectrometry and listed in Table 2, is dominated by SiO_2 (50.54%) and Al_2O_3 (32.21%), with the sum of the two reactive oxides exceeding 82% by mass and minor amounts of CaO, TiO_2, Fe_2O_3 and MgO that are not expected to interfere significantly with the pozzolanic chemistry. Industrial hydrated lime of analytical grade, with a $Ca(OH)_2$ content above 95%, served as the calcium source. The sticky rice slurry was freshly prepared in the laboratory by boiling food-grade glutinous rice in deionized water at 100 °C for approximately two hours under continuous stirring until a homogeneous, viscous paste was obtained; the concentration of the slurry is hereinafter defined as the mass ratio of dry rice to the total slurry.

Representative SEM micrographs of the four raw materials are shown in Fig. 2. The natural soil exhibits irregular, plate-like particles with rough surfaces and an evident agglomerated texture, the hydrated lime appears as loose, porous aggregates of submicron crystals, the metakaolin consists of stacked lamellar plates typical of dehydroxylated kaolinite, and the gelatinized sticky rice slurry forms a continuous, film-like polymeric network suggestive of well-developed amylopectin chains in the aqueous phase.

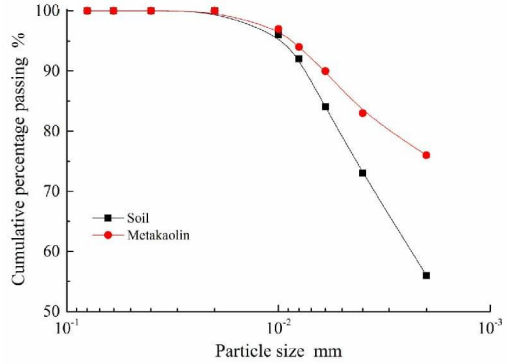

Figure 1 Particle Size Distribution of Soil and Metakaolin

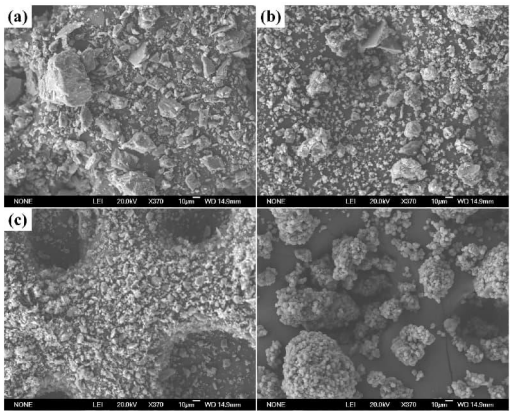

Figure 2 SEM Images of (a) Soil; (b) Lime; (c) Metakaolin; (d) Sticky rice

Table 1 Physical Parameters of Soil

	G_s	w (%)	w_p (%)	w_L (%)	I_p
Soil	2.66	1.07	21.03	32.42	11.39

Table 2 Chemical Composition of Metakaolin

Composition	SiO_2	Al_2O_3	CaO	TiO_2	Fe_2O_3	MgO
Content/%	50.54	32.21	0.65	0.92	0.43	0.31

2.2 Mix Design

To decouple the contributions of each constituent, three groups of mixtures were designed and their compositions are reported in Tables 3-5. In the lime–soil series (Table 3), the lime content of mixture LS1 was varied at 7%, 10%, 13% and 16% by dry mass of soil at a fixed water-to-solid ratio of 0.28, while in mixture LS2 the water-to-solid ratio was varied from 0.24 to 0.30 at a fixed lime content of 13%. In the metakaolin-lime-soil series (Table 4), the metakaolin dosage was varied from 8% to 13% in ML1 at fixed 13% lime, the lime content was varied between 10% and 20% in ML2 at fixed 10% metakaolin, and the water-to-solid ratio was varied between 0.26 and 0.32 in ML3 at fixed 10% metakaolin and 13% lime. Finally, in the sticky rice-metakaolin-lime-soil series (Table 5), the sticky rice slurry concentration in SM1 was varied from 1% to 5% with 10% metakaolin and 13% lime, while in SM2 the water-to-solid ratio was varied from 0.32 to 0.36 at a fixed sticky rice concentration of 3% and the same MK and lime dosages.

Table 3 Lime-Soil Mix Compositions

Mix	Lime (%)				Ratio of water/solid				
LS1	7	10	13	16	0.28				
LS2	13				0.24	0.26	0.28	0.30	

Table 4 Lime-Metakaolin-Soil Mix Compositions

Mix	**Metakaolin (%)**			**Lime (%)**				**Ratio of water/solid**		
ML1	8	10	13	13				0.30		
ML2	10			10	13	16	20	0.30		
ML3	10			13				0.26	0.28	0.32

Table 5 Lime-Metakaolin-Sticky rice-Soil Mix Compositions

Mix	**Concentration of Sticky rice (%)**					**Metakaolin (%)**	**Lime (%)**	**Ratio of water/solid**		
SM1	1	2	3	4	5	10	13	0.30		
SM2	3					10	13	0.32	0.34	0.36

2.3 Specimen Preparation and Testing Procedures

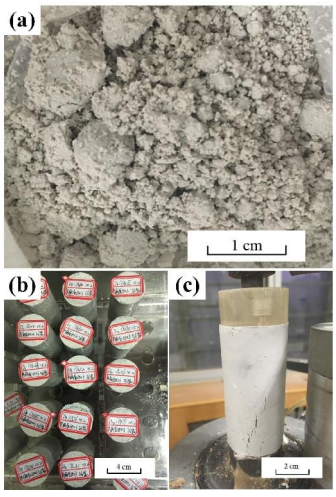

Figure 3 (a) Representative Soil-additive Mixture; (b) Cured Samples; (c) Sample being under Compression

Cylindrical specimens with a diameter of 50 mm and a height of 100 mm were fabricated by static compaction in three equal layers in a steel mould, demoulded after 24 h, and cured in a standard chamber maintained at 20 ± 2 °C and a relative humidity of no less than 95% for 7, 28 and 90 days. Representative specimens and the UCS testing apparatus are shown in Fig. 3. UCS tests were performed on a universal testing machine at a constant displacement rate of 1 mm·min^{-1}, with at least three replicate specimens tested for each mix and curing age, and the mean value reported as the characteristic strength.

Following mechanical testing, fragments extracted from the failure surfaces were oven-dried at 40 °C, sputter-coated with gold and examined by field-emission SEM to characterize the microstructural evolution. Companion specimens were ground and analyzed by XRD using Cu-Kα radiation at a scanning rate of 4°·min^{-1} over the 2θ range of 5°–60° to identify the crystalline phases and to monitor the consumption of portlandite. In parallel, the internal moisture content of representative specimens was tracked by periodic gravimetric measurement throughout the 90-day curing period.

3 RESULTS AND DISCUSSION

3.1 Mechanical Behavior of Lime-Stabilized Silty Clay

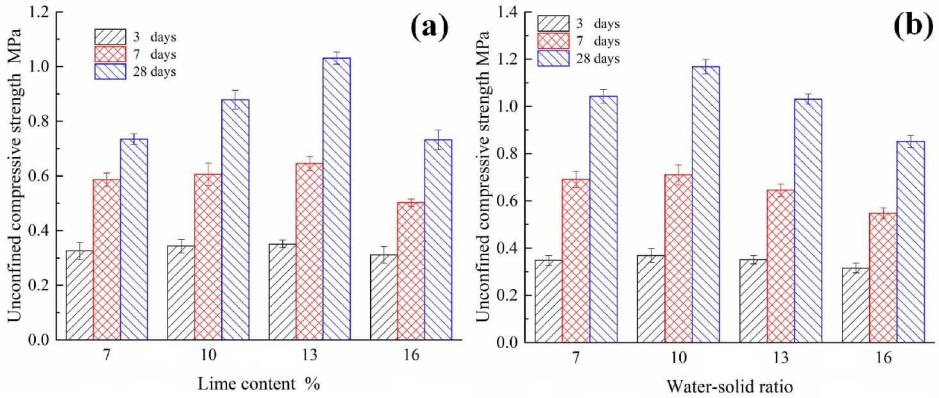

Figure 4 (a) UCS of LS1 at Varying Lime Contents; (b) UCS of LS2 at Varying Water-solid Ratios

The evolution of UCS in the LS series with lime content and water-to-solid ratio is shown in Fig. 4. At a fixed water-to-solid ratio of 0.28, the 7-, 28- and 90-day UCS values of LS1 all rise progressively as the lime content increases from 7% to 13%, and then exhibit a clear decline at 16% (Fig. 4a). Such a non-monotonic dependence is consistent with the dual role of lime in the stabilized matrix: at low dosages, the available Ca^{2+} is preferentially consumed by cation exchange and pozzolanic reaction with the soluble aluminosilicates of the clay fraction, leading to flocculation and progressive cementation, whereas at dosages beyond the so-called lime fixation point a substantial proportion of the calcium hydroxide remains unreacted and acts as a soft, porous filler that dilutes the cementitious skeleton and even imposes additional shrinkage cracking, thus reducing the macroscopic strength. The water-to-solid ratio exerts a similarly non-monotonic effect (Fig. 4b), with the peak UCS occurring at approximately 0.28; at lower values the paste is too stiff to fully wet and disperse the lime, while at higher values the surplus mixing water increases the inter-particle distance and the residual porosity, both of which are detrimental to strength development.

3.2 Mechanical Behavior of Metakaolin–Lime-Stabilized Silty Clay

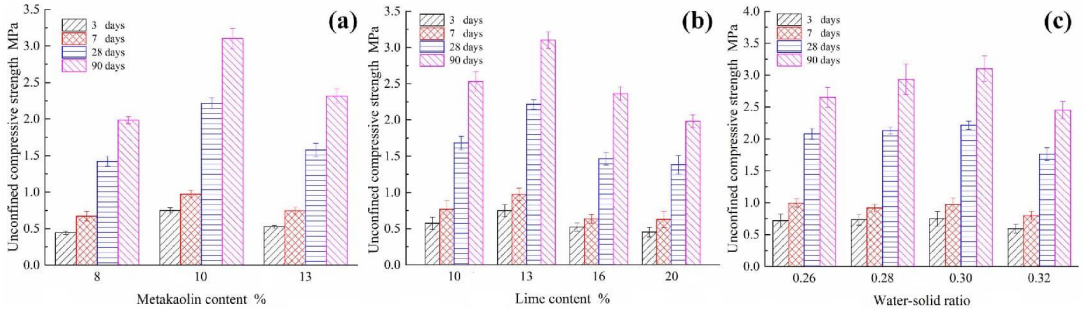

Figure 5 (a) UCS of ML1 at Varying Metakaolin Contents; (b) UCS of ML2 at Varying Lime Contents;; (b) UCS of ML3 at Varying Water-solid Ratios

The introduction of metakaolin substantially elevates the strength envelope of the lime-stabilized soil, as illustrated in Fig. 5. The 90-day UCS of ML1 increases sharply when the metakaolin dosage rises from 8% to 10%, but stabilizes or slightly decreases beyond 10% (Fig. 5a), implying that an optimum stoichiometric ratio exists between the reactive aluminosilicate supplied by metakaolin and the calcium hydroxide available from lime. Beyond this ratio, the system becomes calcium-deficient and the surplus metakaolin remains essentially inert, acting as a fine filler that no longer

contributes to gel formation. This interpretation is corroborated by the lime-variation experiment in ML2 (Fig. 5b), in which the UCS reaches its maximum at 13% lime and declines markedly for both lower and higher lime contents, indicating that the optimum lime-to-metakaolin mass ratio lies in the vicinity of 1.3. The water-to-solid ratio response of ML3 (Fig. 5c) parallels that of the LS series but with the optimum shifted slightly upward to about 0.28-0.30, presumably because the high specific surface area of metakaolin demands additional water both for adequate dispersion and for sustaining the pozzolanic reactions during prolonged curing.

3.3 Mechanical Behavior of Sticky Rice–Metakaolin–Lime-Stabilized Silty Clay

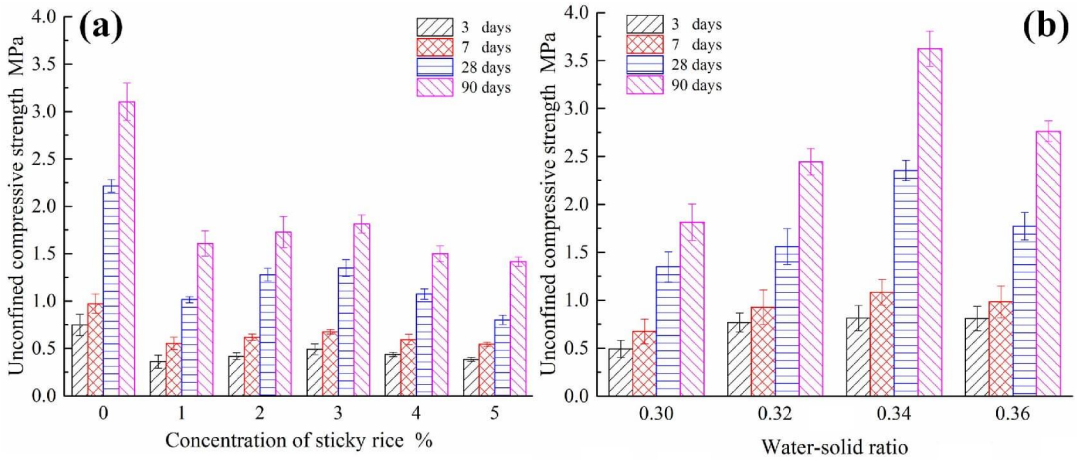

Figure 6 (a) UCS of SM1 at Varying Concentration of Sticky Rice; (b) UCS of SM2 at Varying Water-solid Ratios

The incorporation of sticky rice slurry into the metakaolin-lime system produces a further appreciable enhancement of UCS, particularly at the longer curing age, as shown in Fig. 6. In SM1, the 90-day UCS rises with sticky rice concentration up to 3% and then decreases for higher concentrations (Fig. 6a), revealing a clear optimum dosage. At low concentrations, the amylopectin chains adsorb selectively onto the surfaces of soil particles and nascent hydration products, bridging adjacent grains and templating the precipitation of fine, well-dispersed C-S-H, C-A-H and carbonate crystals; this organic-inorganic interpenetration densifies the matrix and confers an additional load-transfer mechanism. When the sticky rice concentration becomes excessive, however, the surplus organic phase forms a thick polymeric film that physically isolates the lime and metakaolin particles, hindering the ionic transport required for pozzolanic reaction, and the unreacted polymer constitutes a soft inclusion that weakens the overall skeleton. The water-to-solid ratio dependence of SM2 (Fig. 6b) shows an optimum value of approximately 0.34, which is noticeably higher than that of the LS and ML systems. This upward shift can be rationalized by the markedly higher viscosity of the sticky rice slurry, which requires a larger volume of mixing water to achieve adequate workability and uniform dispersion of the polymeric phase throughout the soil-binder system.

3.4 Microstructural Evolution

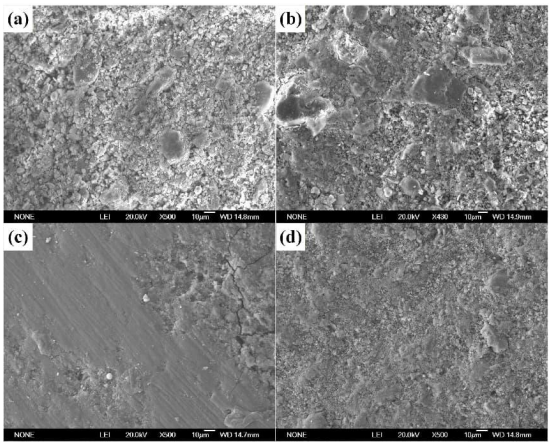

Figure 7 SEM Images of (a) LS; (b) ML; (c) SM with 0.3 at Water/Solid Ratio; (d) SM2 at 0.34 Water/Solid Ratio after 90 Days Curing

The SEM micrographs of LS, ML and SM specimens after 90 days of curing, presented in Fig. 7, provide direct visual evidence of the microstructural origin of the macroscopic strength trends. The LS sample (Fig. 7a) exhibits a relatively open structure in which the soil aggregates are loosely connected and discrete pores and microcracks remain clearly visible, with only sparse fibrous hydration products bridging adjacent particles. The ML sample (Fig. 7b) shows a

substantially denser texture, in which abundant flocculent gels coat the soil grains and partially fill the inter-aggregate voids, an arrangement characteristic of an active pozzolanic system in which C-S-H and C-A-H phases continuously precipitate during the 90-day curing period. The SM specimens (Fig. 7c, d) display the densest and most homogeneous morphologies of the three series; the hydration products are no longer randomly distributed but form a continuous, gel-rich matrix that envelops the soil particles and seals most of the residual porosity. In particular, the SM2 specimen prepared at a water-to-solid ratio of 0.34 (Fig. 7d) shows an almost featureless, monolithic appearance at the same magnification, consistent with its highest macroscopic UCS. These observations strongly suggest that the amylopectin-mediated templating effect not only refines the size and morphology of the individual gel particles but also promotes their coalescence into a continuous, three-dimensionally interconnected network.

3.5 Mineralogical Evolution

The XRD patterns of the natural soil and of the stabilized specimens after 90 days of curing, compiled in Fig. 8, illustrate the progressive transformation of the mineral assemblage as the binder system is enriched. The diffractogram of the untreated soil (Fig. 8a) is dominated by quartz, with additional reflections of albite, nontronite and muscovite, indicative of a silica-rich and moderately aluminous matrix. Upon stabilization with lime alone (Fig. 8b), the intensity of the nontronite reflections decreases slightly, sharp portlandite peaks emerge, and only weak signatures of newly formed hydrate phases are detectable, in line with the limited extent of the pozzolanic reaction in this system. In the ML sample (Fig. 8c), the portlandite peaks are markedly attenuated relative to those of LS, and broad humps consistent with semi-crystalline C-S-H and C-A-H become evident in the low-angle region, accompanied by minor crystalline aluminate phases, signaling that a substantial fraction of the calcium hydroxide has been consumed through reaction with the reactive aluminosilicate fraction of metakaolin. In the SM sample (Fig. 8d), the portlandite reflections are nearly extinguished, the amorphous hump becomes broader and stronger, and weak calcite peaks emerge, the latter being attributable to controlled carbonation of residual lime in the presence of the polysaccharide, which is known from heritage mortar studies to favor the precipitation of fine, evenly dispersed calcite crystals rather than coarse calcite blooms. Taken together, the XRD evidence corroborates the interpretation that sticky rice not only does not impede the pozzolanic reactions but in fact promotes the consumption of lime and the development of cementitious phases.

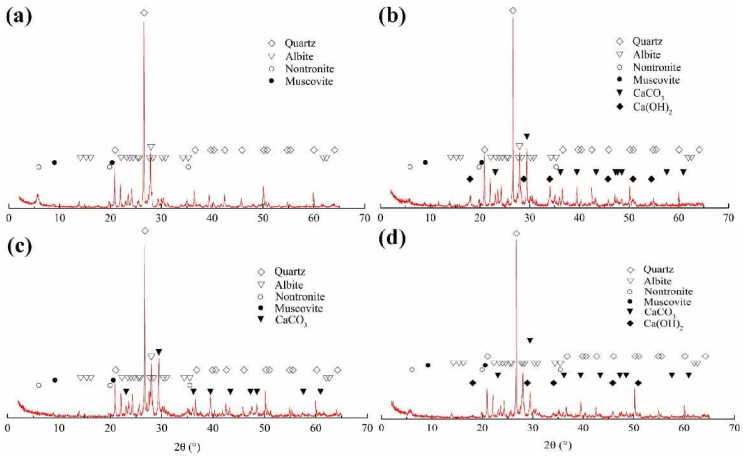

Figure 8 XRD Patterns of Samples after 90-day Curing: (a) Soil; (b) LS; (c) ML; (d) SM

3.6 Internal Moisture Retention

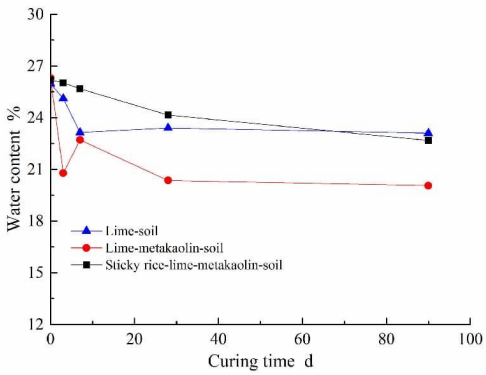

Figure 9 Water Content Variation with Curing Time for LS, ML and SM Samples

The water content evolution of LS, ML and SM specimens during the 90-day curing period is shown in Fig. 9. All three systems exhibit a monotonic decrease in internal moisture, reflecting the combined effect of chemical consumption by

hydration and pozzolanic reactions and slow physical evaporation through the specimen boundaries. The decline is most rapid in the LS system, somewhat slower in the ML system, and slowest of all in the SM system. The pronounced moisture-retaining behavior of the SM specimens can be attributed to the strongly hydrophilic and film-forming character of the amylopectin, which not only binds water through hydrogen bonding to its hydroxyl-rich backbone but also forms a quasi-continuous polymeric coating that reduces the effective permeability of the matrix. This sustained internal moisture supply is favorable for the long-term progression of the pozzolanic reactions and therefore directly underpins the superior 90-day strength of the SM series.

3.7 Synergetic Strengthening Mechanism

A comparative summary of the UCS of the three binder systems is presented in Fig. 10. At all curing ages the strength ranks in the order SM > ML > LS, and the relative advantage of the SM system becomes increasingly pronounced as curing proceeds, indicating that the contribution of sticky rice is not merely a short-term physical effect but rather a sustained chemo-mechanical interaction with the inorganic phases. The strengthening mechanism of the ternary sticky rice-metakaolin-lime binder can therefore be rationalized as the superposition of several mutually reinforcing processes that operate simultaneously within the soil matrix. The reactive aluminosilicate of metakaolin reacts with the calcium hydroxide supplied by lime under alkaline conditions to generate C-S-H and C-A-H gels that constitute the primary cementitious skeleton; the amylopectin chains of sticky rice adsorb onto soil particles, hydrate surfaces and nascent crystals, acting as a biopolymer template that refines crystal size and bridges otherwise isolated inorganic clusters into a continuous hybrid network; the same polymeric film regulates the carbonation of any residual lime, favoring the precipitation of finely divided calcite that fills sub-microscopic voids rather than coarse crystals that would otherwise weaken the matrix; and the moisture-retaining capacity of the polysaccharide phase prolongs the time window during which the pozzolanic reactions can proceed, thereby translating into measurable long-term strength gains. The combination of these processes accounts for the markedly denser microstructure, the more complete consumption of portlandite and the higher long-term UCS observed in the SM specimens relative to the LS and ML benchmarks.

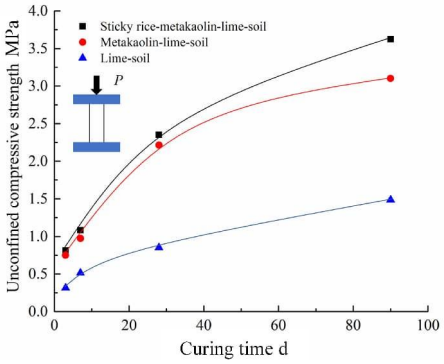

Figure 10 Variation of UCS with Curing Time for Different Soil Mixtures

4 CONCLUSIONS

This study has experimentally examined the mechanical performance and microstructural development of a low-plasticity silty clay stabilized by lime, by a binary metakaolin-lime system and by a ternary sticky rice-metakaolin-lime composite binder, and the results collectively support several conclusions of both fundamental and practical relevance. From a mix-design perspective, an optimum binder formulation has been identified comprising 13% hydrated lime, 10% metakaolin and 3% sticky rice slurry at a water-to-solid ratio close to 0.34, the variations of strength on either side of this optimum being readily explained by stoichiometric considerations governing the lime–metakaolin reaction and by the competing dispersing and isolating effects of the polysaccharide phase. From a microstructural perspective, the introduction of metakaolin transforms an otherwise lime-dominated, weakly cemented matrix into a pozzolanically active system rich in semi-crystalline C-S-H and C-A-H, and the further addition of sticky rice promotes the coalescence of these gels into a continuous, gel-rich and visibly denser network whose formation is paralleled by the near-complete consumption of portlandite revealed in the XRD patterns. From a kinetic perspective, the marked moisture-retention capacity conferred by the amylopectin chains sustains the pozzolanic reactions over a longer period and is therefore directly responsible for the disproportionate gain in 90-day UCS observed in the SM series. Beyond its immediate engineering implications, the demonstrated efficacy of a sticky rice-modified lime-metakaolin binder bridges a millennium-old empirical tradition with contemporary geotechnical practice and offers a sustainable, low-carbon and historically rooted alternative for the stabilization of silty clay in road, foundation and earthen heritage applications. Future work will focus on the durability of the proposed binder under wet-dry and freeze-thaw cycling, on its long-term creep behavior and on a quantitative thermodynamic description of the amylopectin-calcium aluminosilicate interaction.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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