

# GEOPOLYMER STABILIZATION OF KHON KAEN LOESS USING RICE HUSK ASH AND METAKAOLIN FOR PAVEMENT APPLICATIONS

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**ABSTRACT:** Loess, a highly compressible and moisture-sensitive silty soil found in Khon Kaen, Thailand, is generally unsuitable for pavement construction without stabilization. This research investigates the geotechnical performance of loess stabilized using a traditional 5% Ordinary Portland Cement (OPC) benchmark, versus geopolymer binders. The geopolymer system utilized 5% total binder (by dry mass of soil) of Rice Husk Ash (RHA) and metakaolin (MK), activated by 8M NaOH and Na<sub>2</sub>SiO<sub>3</sub> (1:2 ratio). Standard tests, including compaction, UCS, CBR, and wet-dry durability, were conducted. Results showed RHA/MK additions slightly impacted compaction properties. The optimal mix, 1% RHA + 4% MK (1R4M), achieved a maximum Unconfined Compressive Strength (UCS) of 9,234.05 kPa, a 2.4-fold strength increase over the 5% cement (3833.39 kPa) reference. Durability assessment, conducted using wet-dry cycles with drying at 105°C, confirmed high strength retention (>90%). This superior performance is attributed to the optimal Si/Al ratio achieved in the 1R4M mix, which promoted the formation of a dense Sodium Aluminate Silicate Hydrate (N-A-S-H) geopolymer gel. The resulting CBR values support RHA/MK stabilization as an effective and sustainable alternative solution for pavement subgrade applications.

*Keywords: Stabilization, Loess soil, Rice husk ash, Kaolin clay, Pavement structures.*

## 1. INTRODUCTION

Loess, a wind-deposited silty soil commonly found in regions like Khon Kaen, Thailand, presents significant challenges for construction due to its high compressibility, collapsibility upon wetting, and moisture sensitivity [1]. As a subgrade material, unstabilized loess often leads to pavement deformation, reduced service life, and costly maintenance, making the stabilization of this foundational layer essential for robust road construction [2].

Soil stabilization is the process of improving the engineering properties of soil to increase bearing capacity and stability [3]. Historically, this has been achieved using Conventional chemical binders, such as Ordinary Portland Cement (OPC) or lime. While effective, OPC production is a major environmental concern, contributing approximately 7% to 8% of global industrial CO<sub>2</sub> emissions [4].

In response to the substantial environmental impact of cement, geopolymer technology has emerged as a promising, sustainable alternative [5]. Geopolymer systems utilize aluminosilicate-rich waste materials as cementitious binders, offering a path for both soil improvement and the beneficial reuse of industrial and agricultural by-products.

Materials such as rice husk ash (RHA) and kaolin clay (which is calcined to create metakaolin, MK) have been increasingly utilized as sustainable alternatives to cement. RHA, a significant agricultural waste byproduct rich in silica, enhances pozzolanic activity and aids in forming strong cementitious compounds [6]. Metakaolin (calcined kaolin) serves as a highly

reactive source of both alumina and silica, contributing significantly to improved soil cohesion and structure [7].

Despite their individual proven benefits in soil stabilization and concrete applications, limited published research exists on the combined effect of rice husk ash (RHA) and metakaolin (MK) as a geopolymer system for stabilizing highly problematic loess soils, particularly under the mechanical performance and durability criteria necessary for pavement applications in the Khon Kaen region [8]. The effective application requires optimizing mix ratios to achieve maximum strength and durability while promoting the reuse of regional by-products for sustainable engineering.

Recent reviews on the valorization of industrial by-products, such as coal gangue and agricultural ashes, emphasize the critical role of activation methods in maximizing the pozzolanic potential of waste materials [9]. While Rice Husk Ash (RHA) and Metakaolin (MK) have been studied individually, their combined effect on the stabilization of collapsing loess soils remains underexplored. RHA, rich in amorphous silica, enhances the pozzolanic reaction but often lacks sufficient alumina for rapid geopolymerization. Conversely, MK provides high alumina content but can be cost-prohibitive in large quantities. Combining these precursors allows for the optimization of the Silicon-to-Aluminum (Si/Al) ratio, which is critical for the formation of strength-giving Sodium-Aluminosilicate-Hydrate (N-A-S-H) gels. Furthermore, limited research has addressed the durability of such geopolymer-stabilized loess under the aggressive

wet-dry cycles typical of the tropical Khon Kaen region. The selection of alkaline activators is equally critical for dissolving these precursors. Prior research indicates that an 8 Molar (8M) Sodium Hydroxide (NaOH) concentration combined with Sodium Silicate ( $\text{Na}_2\text{SiO}_3$ ) in a 1:2 ratio provides an optimal balance of alkalinity and soluble silicates. This ratio facilitates the dissolution of aluminosilicate precursors without causing excessive efflorescence or rapid setting issues often associated with higher molarities, a phenomenon also observed in other waste-stabilized soil systems [10].

This study investigates the specific gravity, Atterberg limits, compaction behavior, sieve and hydrometer, unconfined compressive strength (UCS), California Bearing Ratio (CBR), and durability under wet-dry cycling of Khon Kaen loess stabilized with various combinations of RHA and metakaolin in a geopolymer matrix. The objective is to determine the effectiveness of these alternative binder materials in significantly improving the geotechnical performance of loess, thereby providing a more economical and eco-friendly solution than traditional cement stabilization method.

## 2. RESEARCH SIGNIFICANCE

This study demonstrates the viability of using rice husk ash (RHA) and metakaolin (MK) as sustainable stabilizers for improving the engineering properties of loess. The findings shows that these materials significantly enhanced the strength, durability, and moisture resistance of the soil, offering a cost-effective and environmentally responsible alternative to cement. This research supports the reuse of agricultural waste in geotechnical applications, promoting sustainable construction practices, and provides practical insights for improving pavement performance in loess-prone regions.

## 3. MATERIALS AND METHODS

### 3.1 Materials

The loess soil used in this study was collected in a land near College of Local Administration (COLA), Khon Kaen University, Thailand. The top soil was stripped and the underlying loess was manually excavated.

Kaolin clay was calcined to form metakaolin (MK) by putting a representative sample (approx. 300g each) in a crucible, placed inside a muffle furnace and heated at different temperatures (650, 700, 750, 800, and 850°C) and heating time (30, 60, 90, and 120 minutes) at a heating rate of 10°C/mins as presented in figure 1. After heating, the crucibles containing the metakaolin were allowed to cool at room temperature before measuring the mass loss. Based on the thermal dehydroxylation analysis, calcination

at 800°C for 90 minutes was selected for all stabilization mixes, as it achieved a degree of dehydroxylation of approximately 1.0, indicating complete transformation to amorphous metakaolin. The alkaline activator was prepared by dissolving NaOH flakes in distilled water and allowed to cool to room temperature for 24 hours to form an 8 Molar (8M) solution, which was then mixed with commercial-grade  $\text{Na}_2\text{SiO}_3$  in a 1:2 ratio by weight. Unlike a fixed liquid-to-binder ratio, the quantity of alkaline activator added to each mix was calculated to achieve the specific moisture content corresponding to 95% of the maximum dry unit weight ( $\gamma_{dmax}$ ) on the wet-side of the compaction curve. This condition was chosen to represent standard field compaction quality control and to ensure sufficient moisture availability for the geopolymerization reaction. This ensured that all UCS, CBR, and durability specimens were prepared at a consistent density state.

The rice husk ash used was bought from the KPS Goods shop, Kampaeng Saen, Nakhon Pathom, Thailand. It was further blended and sieved through sieve No. 200 to obtain a finer, more uniform reactive ash.



Fig. 1 Thermal activation of kaolin clay: (a) Muffle furnace used for calcination. (b) Cooled crucibles containing the resulting metakaolin after heating.

Before using the Khon Kaen loess, it was oven-dried and sieved through a 4.75 mm mesh. However, the unstabilized loess was manually mixed with hand while the stabilized loess at 5% cement and various percentages of rice husk ash (RHA) and metakaolin (MK) as presented in table 1, were mechanically mixed due to its chemical content (figure 2). A total of eight mix combinations were tested as presented in table 1. The compaction test was conducted using a standard 4-inch proctor mold (101.6 mm x 116.5 mm) compacted in five layers. Unconfined Compressive Strength (UCS) and durability samples were prepared in a mold of 50 mm x 100mm dimensions while the California Bearing Ratio (CBR) samples were prepared in a mold of 152 mm x 178 mm. All the stabilized samples were sealed in a plastic wrap and cured for 7 days before further testing continued (figure 2). Curing was conducted at an ambient laboratory temperature of  $27 \pm 3^\circ\text{C}$ , with relative humidity maintained near saturation (>95%) by sealing the

specimens in plastic wrap to prevent moisture loss. A 7-day curing period was selected to evaluate the early-strength development potential, serving as a rapid indicator of stabilization feasibility without the extended 28-day curing period typical of conventional cement applications. The CBR samples after the 7 days curing was soaked for 4 days (96 hours) to simulate moisture sensitivity before testing. These processes of samples preparation are shown in figure 2.



Fig. 2 Sample preparation: (a) Manual mixing (unstabilized); (b) Mechanical mixing (stabilized); (c) 7-day sealed curing (CBR); (d) 7-day sealed curing (UCS); (e) 4-day soaking /swelling measurement

Table 1. Mix ratios

Sample ID.	Soil (%)	Binder material for geopolymer		Cement (%)
		RHA (%)	Kaolin Clay /MK (%)	
Unstabilized loess	100	0	0	
Soil cement	95			5
Soil geopolymer	95	5	0	
	95	4	1	
	95	3	2	
	95	2	3	
	95	1	4	
	95	0	5	

Note: All binder percentages (Cement, RHA, MK) are calculated based on the dry weight of the loess soil. The alkaline activator solution was added as the total liquid content, adjusted for each mix to meet the target moisture content determined from the compaction tests.

### 3.2 TEST METHODS

Specific gravity test was done using ASTM D854, 2014. The Atterberg limit test was performed using ASTM D4318, 2017. Particle size distribution (sieve and hydrometer) test was performed in accordance with ASTM D421 and D422. Compaction characteristics were evaluated using Modified Proctor test (ASTM D1557). UCS test were performed after 7days of curing following ASTM D1633. Durability was assessed under wet-dry cycles (ASTM D559),

with UCS testing conducted after 1st, 3rd, 6th, 9th, and 12th cycles. Mass loss and physical damages were monitored. CBR test followed ASTM D1883 and AASHTO T193, with penetration values recorded at 2.5 and 5.0 mm for soaked and unsoaked conditions.

## 4. RESULTS AND DISCUSSIONS

### 4.1 Basic Properties of Khon Kaen Loess

The Khon Kaen loess basic properties are shown in table 2. The final classification of the Khon Kaen loess soil (USCS) as presented in table 2 was based on the results of the particle size distribution and the Atterberg limit test. The optimum moisture content and the maximum dry unit weight were determined in accordance with modified proctor test (ASTM D1557).

Table 2. Basic properties of Khon Kaen loess

Properties	
Plastic Limit (PL) %	NP
Liquid Limit (LL) %	–
Plasticity index (PI) %	–
Specific gravity	2.66
Maximum dry unit weight ( $\gamma_{dmax}$ ) kN/m <sup>3</sup>	21.15
% of Sand	55.22
% of Silt	27.23
% of Clay	17.55
USCS classification	SM

The Khon Kaen loess particle size distribution test was performed with the use of sieve and hydrometer analysis for the coarse fraction and the fine fraction. The sieve test showed that Khon Kaen loess consist of 55% of sand, 27% of silt and 18% of clay. Based on USCS, the soil was classified as silty sand (SM). This aligns with previous studies identifying Khon Kaen loess as fine-grained and weakly plastic soil [11-12].

### 4.2 Compaction Test

The compaction results, presented in table 3 and Fig. 3, indicate that the unstabilized loess achieved a maximum dry unit weight ( $\gamma_{dmax}$ ) of 21.15kN/m<sup>3</sup> and an Optimum Moisture Content (OMC) of 6.84%. The addition of RHA and MK resulted in minor fluctuations in unit weight, ranging from 20.53kN/m<sup>3</sup> (5% RHA) to 21.23kN/m<sup>3</sup> (5% MK). The observed reduction in dry unit weight for RHA-rich mixes is attributed to the replacement of heavier soil solids ( $G_s = 2.66$ ) with porous RHA particles, confirming that these variations are governed by physical mixture properties rather than random statistical error [13]. Conversely, the 5% MK mix showed a slight increase in unit weight, likely due to the filler effect of the fine

metakaolin particles packing into the loess voids [9]. Overall, the changes in compaction parameters were marginal, suggesting that the additives do not significantly alter the required compaction energy in field applications.

Table 3. The  $\gamma_{dmax}$  and OMC values for each compacted mix ratio of Khon Kaen loess

Samples	Sym-bol	$\gamma_{dmax}$ (kN/m <sup>3</sup> )	OMC (%)
Unstabilized Loess	Un	21.15	6.84
5% cement	5C	20.94	6.65
5% RHA	5R0M	20.53	5.93
4% RHA+1% MK	4R1M	20.91	6.55
3% RHA+2% MK	3R2M	21.06	6.60
2% RHA+3% MK	2R3M	20.95	6.48
1% RHA+4% MK	1R4M	20.88	6.19
5% MK	0R5M	21.23	6.13

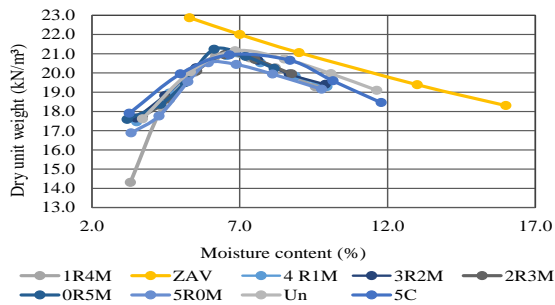


Fig. 3 Compaction behavior of unstabilized and stabilized loess soil

**4.3 Unconfined Compressive Strength (UCS)**

The unconfined compressive strength test samples were compacted in a mold of 50 mm x 100 mm at 95% of the maximum dry unit weight ( $\gamma_{dmax}$ ) at the wet-side of the compaction curve, extruded from the mold and cured for 7 days before testing. Then, a strain rate of 1mm/minutes was applied on the samples until failure occurred as shown in figure 4 for the 5% cement and the geopolymer stabilized loess. In each mixture, 5 samples were tested to ensure statistical reliability. Table 4 confirms that initial dry unit weights were strictly controlled (approx. 19.4kN/m<sup>3</sup>) to isolate binder efficiency as the primary strength variable. Additionally, the moisture reduction observed during curing (e.g., 5.05% down to 3.70% for 1R4M) indicates the consumption of pore water for geopolymerization. The results, summarized in Table 5, reveal a significant enhancement in strength for the geopolymer-stabilized mixes. As shown in Fig. 5, the unstabilized loess exhibited a baseline UCS of only 84.25 kPa with a ductile stress-strain behavior. The 5% cement control achieved 3,833.39 kPa, displaying

a brittle failure mode typical of cementitious bonding (Fig. 4).

The optimal mix, 1% RHA + 4% MK (1R4M), achieved the highest compressive strength of 9,234.05 kPa, which is approximately 2.4 times higher than the 5% cement stabilized soil. Unlike the cement control, which failed abruptly, the 1R4M mix exhibited a distinct stress-strain behavior (Fig. 6), maintaining high structural integrity even at peak load.

The exceptionally high strength of the 1R4M mix compared to the MK-only mix (0R5M, 5,733.48 kPa) highlights the synergistic effect of combining precursors (Fig. 7). While MK provides the necessary alumina, the addition of 1% RHA contributes highly reactive amorphous silica. This combination optimizes the Silicon-to-Aluminum (Si/Al) ratio, which is a governing factor in geopolymerization. The balanced Si/Al ratio facilitates the extensive formation of a rigid Sodium-Aluminosilicate-Hydrate (N-A-S-H) gel matrix, a mechanism well-documented in recent studies on waste-based geopolymers [9-10]. However, the dry unit weight of 0R5M mix is low which might be the cause of the low UCS (table 4 and 5).

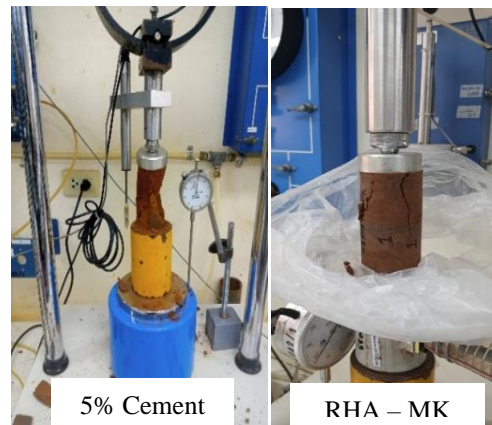


Fig. 4 Failure mode of the 5% cement and the RHA – Mk stabilized loess

Table 4. UCS summary table for the initial, final and dry unit weight of unstabilized and stabilized loess

Mix ratios	Initial m.c (%)	Final m.c (%)	Ini. $\gamma_{dry}$ (kN/m <sup>3</sup> )
Un	10	9.66	19.42
5C	11.36	8.23	19.52
5R0M	5.77	5.41	19.03
4R1M	5.71	4.85	18.74
3R2M	5.45	4.13	19.03
2R3M	5.15	4.16	19.42
1R4M	5.05	3.70	19.33
0R5M	4.72	3.17	18.93

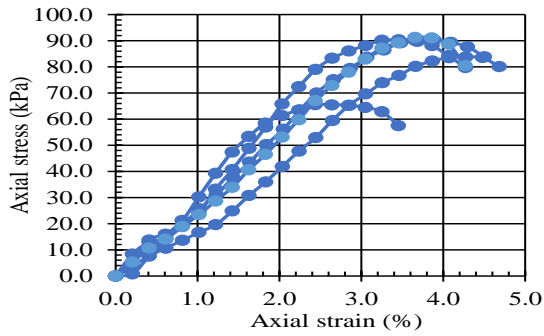


Fig. 5 Stress-strain behavior of unstabilized loess (showing failure curve of multiple replicate)

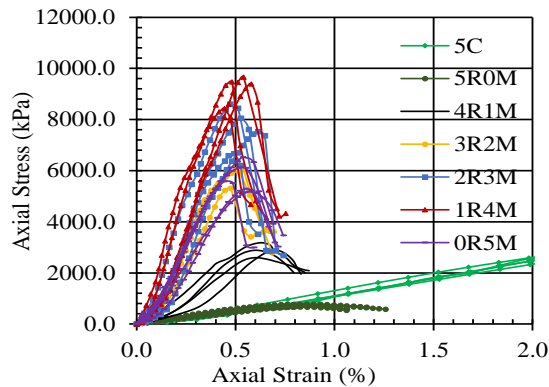


Fig. 6 UCS behavior of stabilized loess

Table 5. Summary of UCS, E., and EA, for stabilized and Unstabilized Loess Mixtures

Mix ratios	Avg. $q_u$ (kPa)	Avg. $E_{50}$ (MPa)	Avg. $E_A$ (kJ/m <sup>3</sup> )
Un	84.25	2.64	183.02
5C	3,833.39	123.36	6,108.10
5R0M	724.62	114.29	359.02
4R1M	2,884.70	415.10	957.76
3R2M	5,763.40	1,078.73	1,675.86
2R3M	7,715.36	1,499.03	2,232.44
1R4M	9,234.05	1,932.95	3,877.55
0R5M	5,733.48	1,036.30	1,730.27

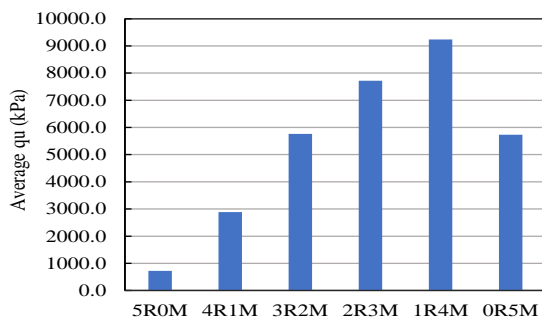


Fig. 7 The effect of RHA-MK mixes on UCS of Khon Kaen loess

#### 4.4 California Bearing Ratio (CBR)

The CBR tests were conducted in accordance with ASTM D1883. Specimens were prepared in a standard 152mm x 178mm mold and compacted in 5 layers with 56 blows per layer to ensure uniform density. After compaction, samples were sealed and cured for 7 days, followed by a standard 96-hour soaking period to simulate worst-case field moisture conditions. Testing was performed using a plunger diameter of 50mm at a strain rate of 1.25mm/mins.

As shown in Table 6 and Fig. 8, the unstabilized loess exhibited a low soaked CBR of 11.69%, classifying it as a fair-to-poor subgrade. The 5% cement control improved this to 642.89%, with a slight swelling of 0.018%. However, the geopolymer mixes demonstrated superior load-bearing capacity. The 1R4M mix achieved the highest values: 1,165.62% (unsoaked) and 997.24% (soaked).

The moisture sensitivity of these mixes is quantified in table 6 and Fig. 9. While the 1R4M mix experienced a reduction in strength upon soaking (approximately 14% loss), the final soaked value remained far superior to the control samples. This indicates that although the geopolymer matrix is slightly sensitive to saturation, it maintains its structural integrity significantly better than the unstabilized and cement stabilized loess.

It is noted that these CBR values are exceptionally high compared to traditional soil stabilization. To ensure accuracy, the calculations were verified against standard load values of 13.44 kN (6,844 kPa) at 2.5 mm penetration and 20.16 kN (10,267 kPa) at 5.0 mm penetration. The magnitude of these results indicates that the 1R4M mix behaves less like a flexible soil layer and more like a semi-rigid pavement base, attributable to the formation of a stiff geopolymer matrix [9].

In terms of volume stability, the optimized geopolymer mixes (1R4M, 3R2M) exhibited 0% swelling (Table 6), significantly outperforming the unstabilized soil (0.0585%). Table 7 and 8 also details the physical changes during the soaking period. It is observed that the optimized 1R4M mix maintained a constant dry unit weight of 12.75 kN/m<sup>3</sup> under both unsoaked and soaked conditions, demonstrating exceptional structural stability. Although the moisture content increased from an initial 3.74% to a final 11.23% upon saturation, this water ingress did not induce volume change, as evidenced by the 0% swelling value. This indicates that the N-A-S-H gel network effectively binds the soil particles, maintaining the density state even when the pores are saturated [10]. Interestingly, while the 0R5M (5% MK) mix achieved a higher dry unit weight during compaction (as noted in section 4.2), it yielded a lower CBR (555.23%) compared to the 1R4M mix (997.24%). This confirms that chemical optimization (Si/Al ratio) is more critical than physical density alone; the 1R4M

mix provides the necessary soluble silica from RHA to react with the alumina from MK, creating a stronger inter-particle bond than MK alone [6-10].

Table 6. The adopted CBR, percentage loss or gain values, and the swelling potentials.

Mix Design	Adopted CBR un-soaked (%)	Adopted CBR soaked (%)	Loss or Gain (%)	Swelling (%)
Un	12.17	11.69	-3.40	0.0585
5C	533.31	642.89	20.55	0.018
5R0M	224.04	198.00	-11.62	0.0138
4R1M	526.00	642.89	22.22	0
3R2M	1,108.53	993.56	-10.37	0
2R3M	1,117.68	713.97	-36.12	0
1R4M	1,165.62	997.24	-14.45	0
0R5M	553.541	555.23	0.30	0

Table 7. Variations in moisture content and dry unit weight of the unsoaked CBR values

Mix ratios	Initial m.c un-soaked (%)	Initial $\gamma_{dry}$ un-soaked (kN/m <sup>3</sup> )
Un	9.62	19.52
5C	9.25	19.91
5R0M	5.40	19.33
4R1M	5.24	19.52
3R2M	4.95	19.42
2R3M	4.90	19.23
1R4M	4.87	19.23
0R5M	4.76	18.93

Table 8. Variations in moisture content and dry unit weight of the soaked CBR values

Mix ratios	Initial m.c soaked (%)	Final m.c soaked (%)	Initial $\gamma_{dry}$ soaked (kN/m <sup>3</sup> )
Un	9.57	9.94	19.42
5C	10.30	8.70	19.82
5R0M	5.33	9.06	19.52
4R1M	5.19	9.74	19.52
3R2M	5.04	9.91	19.33
2R3M	4.98	11.34	19.33
1R4M	4.98	11.23	19.03
0R5M	4.65	12.44	18.93

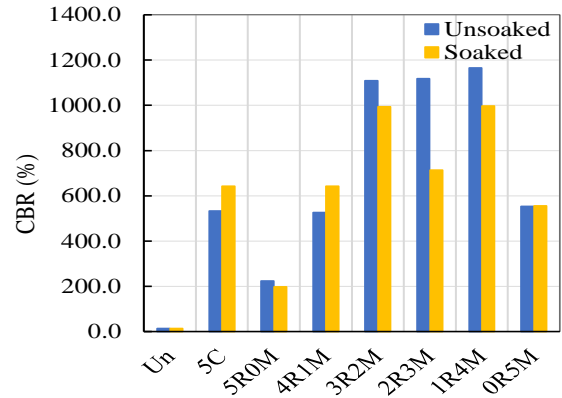


Fig. 8 Comparison for the unsoaked and soaked CBR values for all the mix

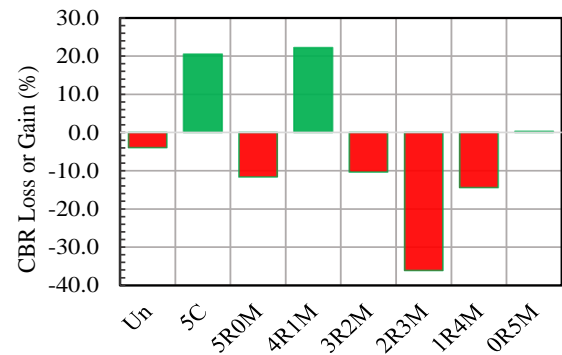


Fig. 9 Percentage change in adopted CBR values after soaking showing loss or gain

#### 4.5 Wet-Dry Durability

The durability of stabilized loess was evaluated using UCS retention and mass loss across 12 wet-dry cycles in accordance with ASTM D559. The samples (2 replicates per cycle) were compacted at 95% of the maximum dry unit weight (wet-side) using a 50mm x 100mm mold. After compaction, samples were sealed in plastic wrap and cured for 7 days to simulate early-stage curing prior to durability testing. Upon completion of curing, the samples underwent wet-dry cycles consisting of soaking for 24 hours, oven drying at 105°C for 24 hours, and cooling at room temperature for at least 2 hours. At the end of each cycle, compressive strength was determined at a strain rate of 1 mm/min. The results (Table 9, 10 and Fig. 11) reveal distinct behaviors. The 5% cement mix showed continuous strength gain, retaining 2.5 times its original UCS up to Cycle 6, followed by exceeding the machine capacity (>9,741 kPa) in later cycles (9 and 12), indicating continued hydration [14]. In contrast, the 1R4M geopolymers mix exhibited exceptional early strength, exceeding the machine capacity (>10,128 kPa) from Cycles 1 to 6. However, measurable failure loads were recorded at Cycles 9 (84.85% retention) and 12 (91.39% retention). This slight reduction at

later cycles is attributed to thermal fatigue from the aggressive 105°C drying, yet the recovery at Cycle 12 suggests continued geopolymer densification filling micro-voids [9]. Mass loss analysis (Table 10 and Fig. 10) confirms the superior durability of the geopolymer. The RHA-MK mix mass loss ranged from 3.60% to 4.49%, significantly lower than the cement mix (5.99% - 4.85%). These results classify the 1R4M mix as “Excellent” (Table 11), supported by minimal surface damage and strong structural integrity [15].

Table 9. Individual UCS results, Retained UCS, and mass loss for 5% cement per cycle

Cycles	Sample 1 UCS (kPa)	Sample 2 UCS (kPa)	Avg. UCS (kPa)	Retained UCS (%)	Mass Loss (%)
0	–	–	3,833.39	100.00	–
1st	8,146.13	9,634.54	8,890.33	231.92	5.99
3rd	7,982.58	7,896.86	7,939.72	207.12	5.60
6th	9,380.95	9,679.19	9,530.07	248.61	4.79
9th	>9,741.83	9,719.39	–	–	4.81
12th	>9,689.96	9,493.81	–	–	4.85

Table 10. Individual UCS results, Retained Strength, and mass loss for 1R4M per cycle

Cycles	Sample 1 UCS (kPa)	Sample 2 UCS (kPa)	Avg. UCS (kPa)	Retained UCS (%)	Mass Loss (%)
0	–	–	9234.05	100.00	–
1st	>10,128.08	10,147.53	–	–	3.60
3rd	>10,193.84	9,992.10	–	–	4.26
6th	>9,858.91	9,851.29	–	–	4.47
9th	7,896.20	7,774.86	7,835.53	84.85	4.38
12th	8,321.28	8,557.38	8,439.33	91.39	4.49

Table 11. Comparative performance of stabilized loess mixes based on UCS, mass loss, and durability.

Mix type	Initial UCS (kPa)	Peak Retained UCS (%)	Mass Loss Range (%)	Durability Indicator
5C	3,833.39	248.61 (Cycle 6)	5.99 → 4.85	Very Good (Strength)
1R4M	9234.05	>100% (cycles 1-6), 91.39% (Cycle 12)	3.60 → 4.49	Excellent (Strength and Mass Retention)

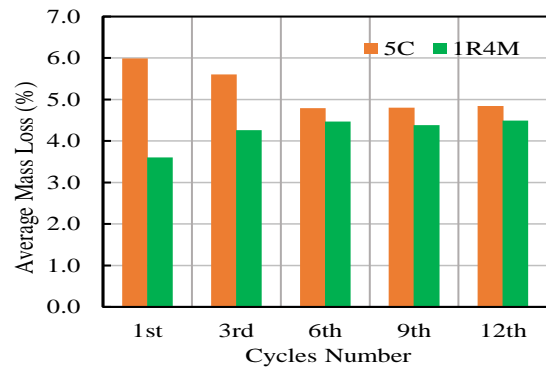


Fig. 10 Variation of average mass loss with wet-dry cycle numbers for stabilized loess mixtures

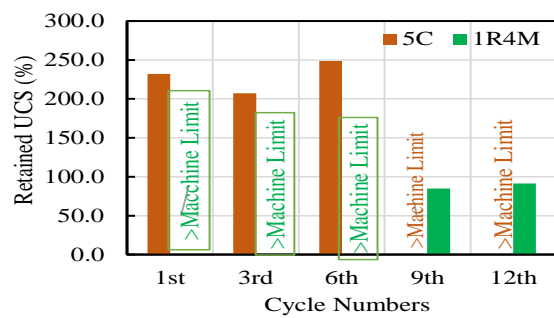


Fig. 11 Retained compressive strength of stabilized loess across wet-dry cycles

### 5. CONCLUSION

This study investigated the geopolymer stabilization of Khon Kaen loess using Rice Husk Ash (RHA) and Metakaolin (MK) as sustainable alternatives to ordinary Portland cement. Based on the laboratory experimental results, the following conclusions are drawn:

- The inclusion of RHA and MK had a marginal effect on compaction characteristics. The slight variations in dry unit weight were physically governed by the low specific gravity of RHA and the filler effect of MK, suggesting that standard field compaction energy would remain effective without significant adjustment.
- The optimal geopolymer mix (1% RHA + 4% MK) achieved a peak UCS of 9,234.05 kPa after only 7 days of curing, surpassing the 5% cement control by approximately 2.4 times. This rapid strength gain demonstrates the material's suitability for time-sensitive construction scenarios where early traffic opening is required.
- Geopolymer-stabilized specimens demonstrated superior durability under aggressive wet-dry cycling (105°C drying). The 1R4M mix retained 91.39% of its strength after 12 cycles, whereas cement specimens suffered from micro-cracking and machine-limit failures in later cycles.

- The CBR values for the optimized mix exceeded 100% under both soaked and unsoaked conditions. These exceptionally high values indicate that the stabilized material behaves as a semi-rigid pavement base, offering superior load distribution compared to flexible subgrades.

**Limitations and Future Work:** While these findings verify the mechanical viability of RHA-MK geopolymers, this study was limited to macroscopic mechanical testing. Detailed microstructural analyses (e.g., XRD, XRF, FTIR, SEM) are recommended for future studies to scientifically verify the specific phases of N-A-S-H gel formation suggested by the strength results. Furthermore, to transition this technology to practice, research must focus on large-scale field trials, Life-Cycle Assessment (LCA), and economic cost analysis to quantify the environmental benefits and cost-effectiveness relative to traditional cement stabilization.

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