Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1542

Evaluation of mechanical properties of stabilized soils with quick lime under extreme moisture conditions

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ABSTRACT: Pavements must withstand traffic loading and variable climate conditions. Recent years have shown extreme events, including, floodings, leaving road structures submerged for extended periods interrupting traffic and causing significant economic losses. It would be desirable to build pavements with materials to withstand the change in water content without failure. This study evaluates the mechanical behavior of lime-stabilized soils subjected to extreme water exposure. Laboratory tests were conducted to determine unconfined compressive strength and resilient modulus of soil specimens on soil-lime treated soils. After a seven-day curing period, specimens were submerged in water for seven days and compared to specimens cured for fourteen days. The findings quantify reductions in strength under saturated conditions and provide insight into the durability of lime-stabilized soils for pavements application in flood-prone regions.

KEYWORDS: unconfined compressive strength, resilient modulus, extreme conditions, saturation.

1 INTRODUCTION

1.1 *Flooded roads*

Roadway structures increasingly experience flooding, with water remaining on the pavement for prolonged periods. These conditions, combined with low-frequency loads from slow-moving traffic, can degrade the properties of pavement materials and compromise serviceability. Documented events include the September 8th, 2021, flooding near km 56 on the Mexico–Queretaro highway, where overflow from a nearby dam inundated the pavement (Figure 1).

Figure 1. Flooding in road Mexico-Queretaro km 56 (lasillarota, 2021).

Another flooding near km 162 on the La Gloria–Nuevo Laredo highway due to the Salado River overflow happened in 2017 (Figure 2). The pavement failed due to the amount of water flowing.

Figure 2. Flooded road. La Gloria-Nuevo Laredo (milenio, 2017).

Such events highlight the need for materials that maintain mechanical performance under full submersion.

Due to the prolonged presence of water on the pavement surface, combined with low-frequency loads generated by the slow movement of vehicles, the properties of the materials that make up the pavement structure can deteriorate. Ideally, under these conditions, the materials should maintain their strength and stability against stresses and extreme climatic factors so that, once the flooding subsides, the pavement structure remains suitable for the safe and efficient flow of traffic.

1.2 *Behavior of lime stabilized soils under soaked conditions*

In 2015, Aldaood et al. investigated the long-term behavior of lime-stabilized gypseous soil under soaking conditions. Cylindrical specimens were prepared at the optimum water content and maximum dry density determined by the Proctor standard test for natural soil. The mixes included soil, gypsum (0%, 5%, 15%, and 25%), and 3% lime, and were cured for 28 days before being soaked for 7, 14, 28, 90, or 180 days. Results indicated that pH, electrical conductivity, and unconfined compression strength decreased as soaking duration increased. The most significant reduction in strength occurred within the first 7 days, after which the rate of change diminished. Strength degradation, expressed as the k-value (k = soaked strength / strength of 28-day cured specimen), was approximately 65% for specimens containing 5%, 15%, and 25% gypsum after 90 days of soaking, while specimens soaked for 180 days failed by erosion of the upper part. The study concluded that strength loss was primarily due to water absorption, volume expansion, and gypsum dissolution.

Bozbey et al. (2021) investigated the effect of capillary soaking on soil–lime mixtures. Cylindrical specimens were prepared with lime contents of 4%, 6%, and 9%. Two series were compacted: the first using pulverized soil (passing the No. 4 sieve) and the second using coarse soil (60% passing the No. 4 sieve and 40% retained between 20 mm and 4.75 mm). After compaction, specimens were cured for 7, 28, and 56 days and then allowed to absorb water by capillarity. Results showed that strength and secant modulus were more adversely affected in coarse-grained soils. The study introduced a soaking index factor (SIF), defined as the ratio of soaked strength to cured strength at the same age. Specimens with 6% and 9% lime exhibited the highest SIF values, indicating that higher lime contents improved resistance to strength loss under soaking conditions.

Little (1999), as cited by Bozbey et al. (2021), reported that once a significant pozzolanic reaction has occurred in a soil–

lime mixture, the impact of soaking is minimal—typically less than 10%. In contrast, when soaking takes place before substantial pozzolanic reactions develop, strength losses can reach approximately 40%.

This study presents laboratory findings on soil specimens stabilized with calcium oxide (quicklime), focusing on unconfined compressive strength (UCS) and resilient modulus (Mr). Results of specimens cured for seven days and subsequently submerged for seven days were compared to specimens cured for fourteen days to assess property degradation at equivalent ages. The objective is to provide data-driven insights into the durability of lime-stabilized soils under extreme moisture conditions, supporting more resilient pavement design in flood-prone environments.

2 MATERIALS

2.1 *Soils*

Three soils were evaluated in this study: two were sampled along the Tren Maya project, and the third was collected near Lago de Chapala in Guadalajara (Figure 3).


(a) (b)

Figure 3. (a) Soil sampled near Lago Chapala, Guadalajara, Mexico; (b) soil 1 of Tren Maya project.

Upon arrival at the Mexican Transport Institute, the soils were sieved through a one-inch mesh, and oversized aggregates were discarded. Soil 1 from the Tren Maya project contained rounded river gravel, whereas Soil 2 (Tren Maya) and the Guadalajara soil passed the No. 4 sieve. After removing oversized particles, all soils were air-dried under ambient conditions for several days and then stored in sealed plastic bags.

2.2 *Lime*

Quicklime, consisting of pulverized 80–95% calcium oxide according to manufacturer specifications, with a bulk density ranging from 700 to 1300 kg/m³.

3 PROCEDURES

3.1 *Index and compaction properties*

The index properties of the natural soils were determined following ASTM C702-18, ASTM D1140-17, ASTM C136-06, ASTM D4318-17, and ASTM D854-14 standards. Lime demand was evaluated using ASTM D6276-19.

For all three soils, the required lime content was 4%, which was adopted in the preparation of the mixtures.

3.2 *Compaction curves*

Compaction characteristics were determined in accordance with ASTM D698-12. The mellowing period for mixtures used in compaction curve development was set between 18 and 24 hours.

3.3 *Compaction characteristics to prepare specimens*

Specimens for mechanical property evaluation were compacted at optimum conditions corresponding to Proctor standard energy. For the Guadalajara soil, the compaction curve after a 24-hour mellowing period did not exhibit a distinct maximum; instead, the dry unit weight decreased across all water contents. Consequently, the optimum water content and maximum dry unit weight determined from the curve with a 0-hour mellowing period were adopted as reference values, while the mixture used for specimen preparation was still mellowed for 24 hours.

3.4 *Compaction of specimens and preconditioning*

Sample preparation:

- The soil–lime–water mixture was prepared as shown in Figure 4a, b, and c. After mixing the soil was placed in a polyethylene bag and allowed to mellow for 18 to 24 hours.


(a) (b) (c)

Figure 4. Mixture preparation.

- After the mellowing period, specimens were manually compacted. For soils passing the No. 4 sieve (Soil 2 from the Tren Maya project and the Guadalajara soil), molds with a diameter of 7.1 cm and a height of 14.4 cm were used. These specimens were compacted in eight layers using a 1 kg rammer with a 30.5 cm drop height (Figure 5b), applying the required number of blows per layer to achieve the target dry unit weight. For Soil 1 from the Tren Maya project, which contained gravel, larger molds (15 cm diameter and 30 cm height) were employed. These specimens were compacted in six layers using a 4.5 kg rammer with a 45.7 cm drop height (Figure 5a), applying the necessary impacts per layer to reach the specified dry unit weight.


(a) (b)

Figure 5. Compaction of specimens. (a) Samples of 15 cm in diameter and (b) Samples of 7.1 cm in diameter.

- After compacting the final layer, the specimen surface was leveled, the specimen was carefully removed from the mold, and its dimensions and weight were recorded.
- Before conducting unconfined compressive strength or resilient modulus tests, specimens were cured for seven or fourteen days. During this period, each specimen was wrapped in cling film and placed in tightly sealed polyethylene bags to prevent moisture loss (Figure 6).

Figure 6. Specimens placed in plastic bags and cured for 7 days.

- The specimens with seven days curing were submerged in water for 7 days (Figure 7).

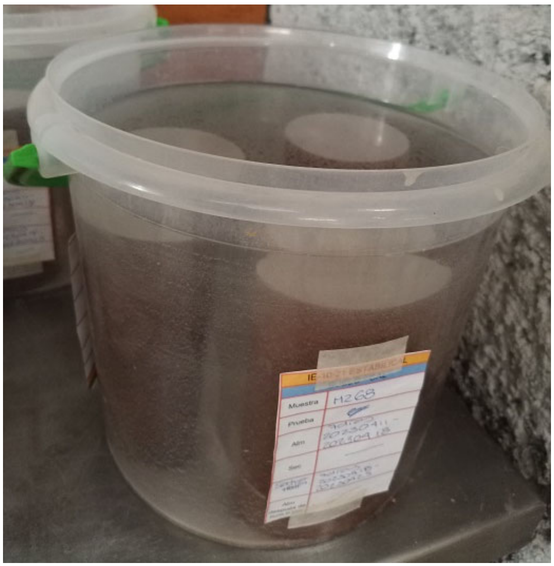


Figure 7. Submergence of specimens for 7 days.

3.5 *Testing*

Unconfined compressive strength (UCS) was determined in accordance with ASTM D2166-06, using a strain rate of 1.2% per minute. After completing the compression test, each specimen was disintegrated to measure its final water content. Resilient modulus (Mr) testing followed the NCHRP 1-28A protocol, specifically the section applicable to subgrade soils.

4 DISCUSSION OF RESULTS

4.1 *Index properties*

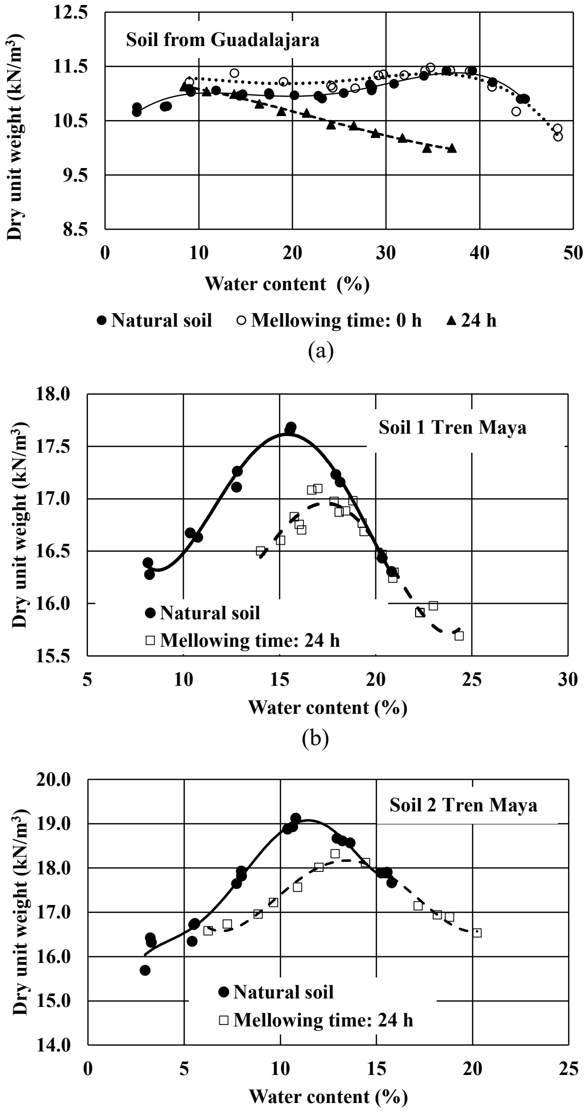
Table 1 summarizes the index properties of the soils and includes their classification according to the Unified Soil Classification System (USCS).

Table 1. Summary of index properties.

Property	Soil from Guadalajara	Soil 1, Tren Maya	Soil 2, Tren Maya
LL (%)	64	41	22
PL (%)	30	21	14
PI (%)	34	20	8
Gs	2.4	2.63	2.63
Passing 200 sieve (%)	63.7	39.2	30.7
pH	9.9	7.06	9.40
Class. USCS	MH	SC	SC

4.2 *Compaction characteristics*

Figure 8a, b and c show the Proctor standard compaction curves for natural soil and soil-lime mixtures. For Guadalajara soil, the plot shows also the compaction curve of the soil-lime mixture with cero hours of mellowing period, this curve shows a maximum. Note that for 24 hours of mellowing period of the mix, the dry unit weight reduces as the water content increases. The optimums were the reference condition to compact test specimens (the optimum of the soil-lime mixture).



(a)

(b)

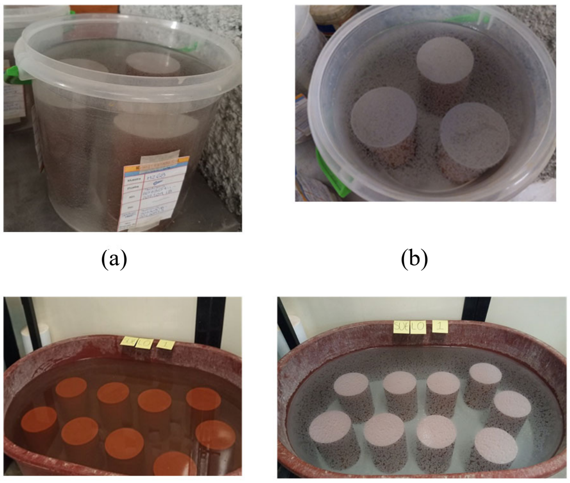
(c)

Figure 8. Compaction curves (Proctor standard).

4.3 *Unconfined compression*

To assess strength degradation at equivalent specimen ages, the unconfined compressive strength of specimens cured for 14 days was compared with that of specimens cured for 7 days and subsequently saturated for 7 days. Under the latter condition, soils 1 and 2 from the Tren Maya project exhibited a noticeable accumulation of a white substance on the water surface and specimen surfaces (Figure 9b and d), whereas this phenomenon was less pronounced for the Guadalajara soil.

Subsequently, microphotographs of this white substance were taken for other soils using a cell phone. The images revealed that the material consisted of very small crystals (Figure 10).



(a) (b)

(c) (d)

Figure 9. (a and b) Tren Maya Soil 2; (c and d) Tren Maya Soil 1.

(a) (b)

Figure 10. (a) Photograph of the crystals on the surface of the water; (b) Photograph of crystals removed from the surface of water and allowed to dry.

Figure 11, Figure 12 and Figure 13 illustrate the stress-strain curves for both conditions and the three soils.

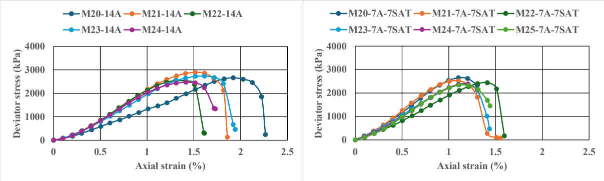


Figure 11. Stress-strain curves Guadalajara soil.

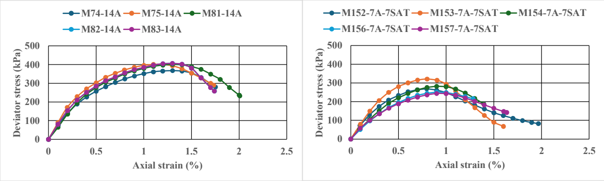


Figure 12. Stress-strain curves Tren Maya soil 1.

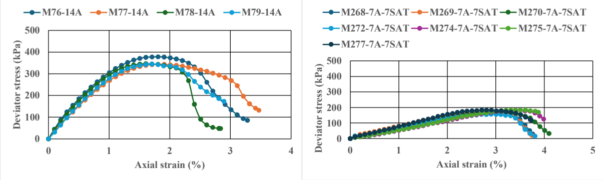


Figure 13. Stress-strain curves for soil 2 Tren Maya.

Table 2 summarizes the initial and final characteristics of specimens tested for unconfined compressive strength, including changes in water content for both cured and saturated conditions. Minimal variation in water content was expected for specimens wrapped in plastic film, and in general, they lost approximately 1.0%. For specimens saturated for seven days, water absorption was approximately 4.34% for the Guadalajara soil, 1.13% for Tren Maya soil 1, and 0.61% for Tren Maya soil 2.

Table 2. Summary of initial and final characteristics of specimens tested in unconfined compression.

Specimen ID	wo (%)	gdo (kN/m3)	wf (%)	gdf (kN/m3)	Dw(%)
Soil from Guadalajara					
20-14A	34.16	12.14	33.11	12.02	1.05
21-14A	34.16	12.06	31.46	11.98	2.70
22-14A	34.16	12.10	33.62	11.95	0.54
23-14A	34.16	12.05	33.18	11.94	0.98
24-14A	34.16	12.05	34.12	11.92	0.04
20-7A-7SAT	35.23	11.79	39.26	11.78	4.03
21-7A-7SAT	35.23	11.76	39.51	11.69	4.28
22-7A-7SAT	35.23	11.79	39.56	11.73	4.33
23-7A-7SAT	35.23	11.79	39.43	11.70	4.20
24-7A-7SAT	35.23	11.77	39.81	11.72	4.58
25-7A-7SAT	35.23	11.83	39.86	11.67	4.63
Soil 1 Tren Maya					
74-14A	17.81	16.98	16.60	17.22	1.21
75-14A	17.89	16.74	16.68	16.96	1.21
82-14A	18.10	16.60	17.07	16.67	1.03
83-14A	17.70	16.76	17.4	16.79	0.27
152-7A-7SAT	17.46	16.77	19.21	16.71	1.71
153-7A-7SAT	17.71	16.77	18.58	16.82	0.87
154-7A-7SAT	17.77	16.88	18.64	16.87	0.87
156-7A-7SAT	17.90	16.86	18.73	16.90	0.83
157-7A-7SAT	17.53	16.93	18.90	16.85	1.37
Soil 2 Tren Maya					
76-14A	13.21	18.03	12.09	18.21	1.11
77-14A	13.21	18.16	12.06	18.31	1.15
78-14A	13.21	18.04	12.81	18.10	0.40
79-14A	13.21	18.04	11.99	18.27	1.22
268-7A-7SAT	13.40	18.38	13.87	18.32	0.47
269-7A-7SAT	13.40	18.32	13.92	18.34	0.52
270-7A-7SAT	13.40	18.31	13.87	18.24	0.47
272-7A-7SAT	13.48	18.27	14.17	18.24	0.69
274-7A-7SAT	13.48	18.30	14.09	18.31	0.61
276-7A-7SAT	13.30	18.32	13.91	18.36	0.61
277-7A-7SAT	13.30	18.30	14.22	18.35	0.92

Table 3 presents the average unconfined compressive strength (qu) values for both conditions—curing and saturation. The results indicate that strength degradation varies significantly among the three soils. The Guadalajara soil exhibited only an 8% reduction in strength, despite absorbing the highest amount of water. In contrast, Soil 1 and Soil 2 from the Tren Maya project experienced reductions of approximately 31% and 51%, respectively. This trend suggests a correlation between strength loss, plasticity index (PI), and sand content: lower PI and higher sand fractions appear to increase susceptibility to degradation. However, it remains unclear whether the observed strength reduction is also influenced by the leaching and migration of crystalline components during saturation.

Table 3. Summary of unconfined compression strength.

Soil	14A		7A-7SAT		Ratio = (qu7A-7SAT/qu14A)*100
	qu (kPa)	s (kPa)	qu (kPa)	s (kPa)	
Guadalajara	2660	166	2447	119	92
Tren Maya 1	396	17	273	31	69
Tren Maya 2	353	17	175	10	49

Note: q_u = Unconfined compression strength; 14A =14 days of curing in storage, 7A-7SAT = 7 days curing and 7 days saturation; s = Standard deviation.

4.4 *Resilient modulus results*

For the Guadalajara soil, the resilient modulus of saturated specimens was compared to that of specimens cured for seven days, as results for 14-day curing were not available at the time of writing. The comparison revealed that saturation did not reduce resilient modulus; on the contrary, values increased by approximately 9% to 20% (Figure 14).

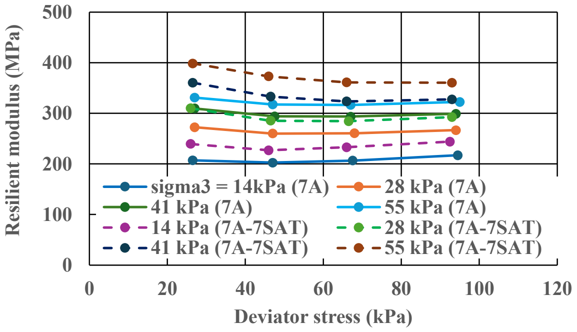


Figure 14. Comparison of resilient modulus for Guadalajara soil.

Figure 15 illustrates the comparison for Tren Maya soil 1. In this case, water absorption caused the resilient modulus values to decrease by approximately 2% to 45%. The reduction in stiffness was more pronounced at lower confining pressures.

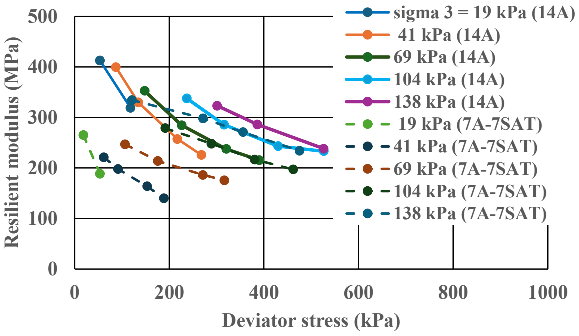


Figure 15. Comparison of resilient modulus for soil 1 Tren Maya.

Although the specimens of Tren Maya soil 1 contained gravel (Figure 16), the resilient modulus curves exhibited a pattern similar to that observed in fine-grained soils. This suggests that the gravel particles were embedded within the fine matrix and contributed little to strength through frictional interaction.

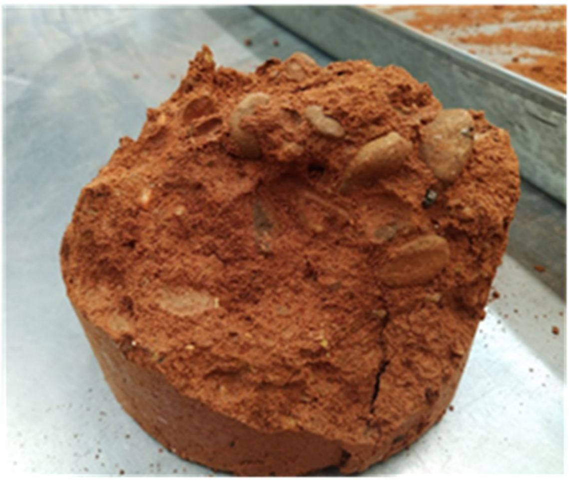


Figure 16. Aspect of a piece of soil after a test of resilient modulus.

For Tren Maya Soil 2, the resilient modulus values of saturated specimens were found to be lower than those of specimens stored for only 14 days. In this case, the retained resilient modulus ranged from 66% to 89%, corresponding to a degradation range of 34% to 11% (Figure 17).

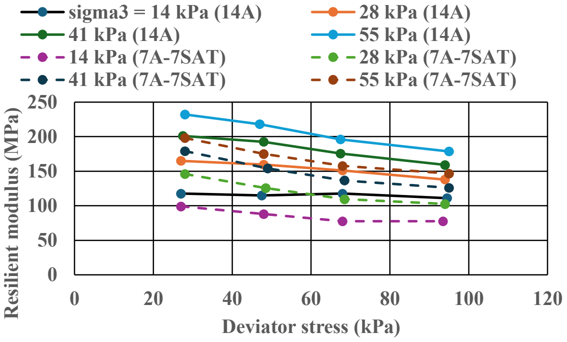


Figure 17. Comparison of resilient modulus for soil 2 Tren Maya.

Table 4 summarizes the characteristics of the specimens. The data indicates that the soils from Guadalajara, Tren Maya Soil 1, and Tren Maya Soil 2 absorbed 5.4%, 1.6%, and 0.54%, respectively. The higher water absorption observed in the Guadalajara soil is likely due to the presence of pumitic sand, as illustrated in Figure 18.

Table 4. Summary of initial and final characteristics of specimens tested in resilient modulus.

Specimen ID	wo (%)	gdo (kN/m3)	wf (%)	gdf (kN/m3)	Dw(%)
Soil from Guadalajara					
43-7A	34.84	11.87	33.06	11.91	1.78
44-7A	34.84	12.00	33.15	11.86	0.69
27-7A-7SAT	34.87	11.64	40.06	11.61	5.19
31-7A-7SAT	34.87	11.66	40.51	11.58	5.69
Soil 1 Tren Maya					
166-14A	17.54	16.85	17.17	16.80	0.37
167-14A	17.54	16.91	17.09	16.94	0.45
189-7A-7SAT	17.57	16.81	19.36	16.85	1.79
190-7A-7SAT	17.11	16.79	19.26	16.75	2.15
191-7A-7SAT	17.83	16.81	18.67	16.91	0.84
Soil 2 Tren Maya					
190-14A	12.95	18.21	12.41	18.28	0.54
191-14A	12.95	18.17	12.41	18.23	0.54
273-7A-7SAT	13.48	18.29	13.95	18.34	0.47
276-7A-7SAT	13.30	18.32	13.91	18.36	0.61

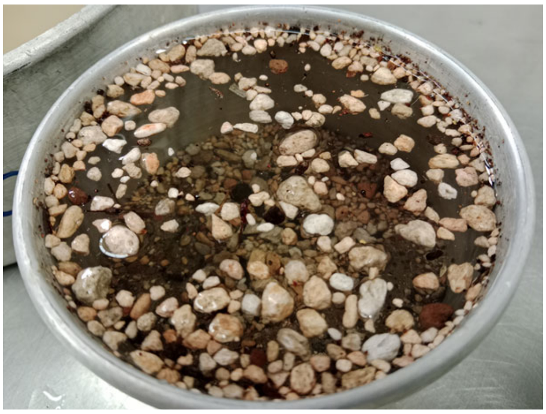


Figure 18. Sand retained on sieve No. 200 for Guadalajara soil.

5 CONCLUSIONS

Improving soil properties with lime is a widely adopted practice due to its proven effectiveness in both laboratory and field applications. In this study, the unconfined compressive strength and resilient modulus of three soils subjected to extreme moisture conditions (7 days of submergence) were evaluated. It is generally expected that the mechanical properties of materials deteriorate when water is absorbed. In this case, the UCS of the three soils decreased, but to varying degrees: the soil from Guadalajara, Tren Maya Soil 1, and Tren Maya Soil 2 lost approximately 8%, 31%, and 50% of their strength, respectively. The limited strength reduction in the Guadalajara soil (8%) appears to be associated with the presence of pumitic sand. Regarding the resilient modulus, degradation was observed in all three soils, with a more pronounced effect in the Tren Maya soils.

Based on the results presented in this paper, it is not possible to draw generalized conclusions. A larger dataset is required to determine whether the observed degradation in mechanical properties is related to plasticity index (PI) values, sand type, percent passing the No. 200 sieve, and potential leaching of crystals during saturation.

Finally, the kind of results presented in this paper can be used to develop or update standards and specifications in Mexico.

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