

Mechanical properties of a RAP stabilized with lime, cement, and foamed asphalt

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ABSTRACT: This paper presents an experimental evaluation of the mechanical performance of reclaimed asphalt pavement (RAP) aggregate stabilized with hydrated lime, Portland cement, and foamed asphalt. Mixtures were prepared with 5% lime, 4% cement, and 2.2% foamed asphalt combined with 1% lime as filler. Laboratory tests included unconfined compressive strength (UCS), resilient modulus (Mr), and permanent deformation under varying curing and moisture conditions. Cement-stabilized RAP exhibited the highest UCS and Mr values, followed by lime, while foamed asphalt mixtures showed the lowest strength, likely due to the aggregate's minimal fines content (0.2%). Permanent deformation was significantly reduced by cement stabilization, whereas foamed asphalt mixtures showed the largest deformation. These findings provide critical data for optimizing RAP stabilization strategies and support the development of updated specifications for sustainable pavement design.

KEYWORDS: RAP aggregate, foamed asphalt, resilient modulus, permanent deformation, unconfined compressive strength.

1 INTRODUCTION

Reclaimed asphalt pavement (RAP) aggregate is widely utilized in the construction of subbase, base, and asphalt pavement layers for flexible pavements in the United States and Europe (EAPA, 2022). In contrast, its adoption in Mexico remains limited, as contractors tend to favor conventional aggregates with well-documented performance. One of the primary barriers to RAP implementation is the scarcity of field and laboratory research at the national level, despite the existence of extensive international literature on the subject. To address this gap, the Mexican Transport Institute has initiated research programs aimed at characterizing the engineering behavior of RAP under controlled laboratory conditions. The study presented herein evaluates the mechanical properties of 100% RAP aggregate stabilized with hydrated lime, Portland cement, and foamed asphalt.

2 MATERIALS

2.1 RAP aggregate

The progressive aging of asphalt concrete pavements in Mexico has necessitated extensive rehabilitation and reconstruction efforts. During these processes, the asphalt layer is typically milled and removed, and the reclaimed material is often treated as waste or temporarily stockpiled along highway shoulders, as illustrated in Figure 1.



Figure 1. Stockpiled RAP aggregate at a storage yard (Pérez et al., 2022).

In recent years, regulatory authorities have increasingly sought to mandate the use of recycled materials in construction. For instance, Mexico City introduced the environmental standard

NACDMX-007-RNAT-2019, which defines the classification and management of construction and demolition byproducts. This standard specifies allowable percentages of recycled materials for use in structural applications such as bases, subbases, and embankments and so on.

Existing literature indicates that the resilient modulus of RAP aggregates is comparable to that of conventional base aggregates (Garg and Thompson, 1996; Bennert et al., 2000), while permanent deformation tends to be greater than that observed in RAP mixtures with traditional aggregates (Bennert et al., 2000). Comprehensive summaries of RAP properties and RAP stabilized with additives have been documented by Perez et al. (2022) and Perez and Martinez (2024).

3 AGGREGATE AND ADDITIVES

3.1 Aggregate preparation

The aggregate employed in this study was obtained by milling an asphalt pavement along a highway in Guanajuato, Mexico. The reclaimed material initially contained particles exceeding one inch in size; therefore, it was screened to remove oversized fractions. Prior to testing, the aggregate was air-dried and subdivided into samples of approximately 15 kilograms (Figure 2).



Figure 2. Aggregate preparation (Perez et al., 2022).

3.2 Lime

The stabilizing agent used was hydrated lime with a calcium oxide content of approximately 80%. A dosage of 5% by dry weight of aggregate was incorporated, following the specification provided by local supplier.

3.3 Cement

The cement used was CPC Portland Type II, incorporated at a dosage of 4% by dry weight of aggregate. This proportion aligns with typical practice in Mexico, where cement contents between 4% and 5% are commonly specified for base stabilization.

3.4 Asphalt

The asphalt binder employed for foamed asphalt stabilization was classified as PG64-22, in accordance with performance grading of Mexican specifications.

4 TEST PROCEDURES

4.1 Index and compaction properties

Index and compaction properties were obtained according to ASTM D1140-17, ASTM C136-14, ASTM D4318-10, ASTM D854-14 y and ASTM D1557-12.

4.2 Cement and lime mixtures specimens preparation.

Specimen compaction was performed at the optimum moisture content (w_{opt}) and maximum dry unit weight (γ_{dmax}) determined from the Modified Proctor test. To account for sample variability, tolerances of $\pm 0.5\%$ in moisture content and $\pm 1\%$ in dry unit weight were permitted. After establishing the compaction curves, mixtures of RAP with lime or cement were prepared by thoroughly blending the aggregate with the stabilizing agent and water to achieve w_{opt} . The material was then compacted in cylindrical molds measuring 15 cm in diameter and 30 cm in height. Specimens were formed in six layers, applying 163 blows per layer for lime-stabilized mixtures and 120 blows for cement-stabilized mixtures, using a 4.5 kg rammer with a drop height of 45.7 cm (Figure 3). The number of blows was selected to achieve the target dry unit weight within the specified tolerance. Following compaction, specimens were extruded from the mold, weighed, and their dimensions recorded (Figure 4).



Figure 3. Specimen compaction.

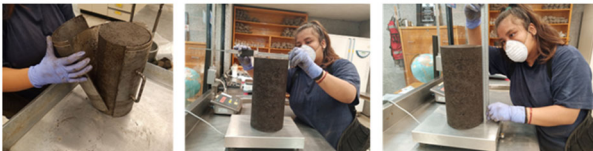


Figure 4. Recording weight, diameter and height of specimen.

4.3 Specimens preconditioning

Observation was conducted through unconfined compressive strength, resilient modulus, and permanent deformation tests on specimens subjected to two preconditioning regimes:

- Direct testing after compaction (designated as 0A) and after curing periods of 7, 14, or 28 days (designated as 7A, 14A, and 28A) (Figure 5a).
- Curing–wetting–storage sequence, in which specimens were cured for 7, 14, or 28 days, followed by 14 days of capillary wetting and an additional 14 days of storage to allow uniform moisture redistribution (designated as 7A-14H-14A, 14A-14H-14A, and 28A-14H-14A). Wetting was applied to both specimen surfaces, with each surface exposed for seven days.

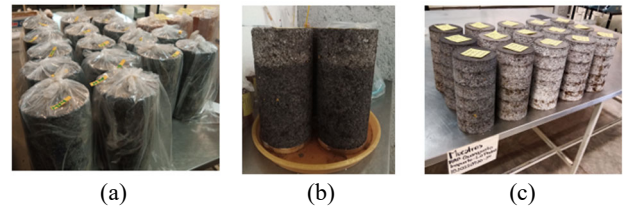


Figure 5. (a) Curing, (b) Capillary wetting (c) Drying.

4.4 Foamed asphalt mixture design

To prepare the foamed asphalt mixture, it was necessary to determine the optimum asphalt content to be combined with the aggregate and filler (1% hydrated lime). The procedure was as follows:

- Evaluation of the aggregate characteristics
- Determine maximum dry unit weight and optimum moisture content using the Modified Proctor test.
- Weigh representative samples of 12.5 kg of aggregate.
- Add 1% hydrated lime by dry weight of aggregate (Figure 6a and b).
- Mix aggregate and filler for one minute (one cycle) (Figure 6c).
- Add 75% of the water required to reach optimum moisture and mix for another cycle (Figure 7a and b).
- Inject the designated percentage of foamed asphalt and mix for one cycle (Figure 8a).
- Add the remaining 25% of water and mix thoroughly (Figure 8b).
- Remove the mixture from the equipment (Figure 8c).

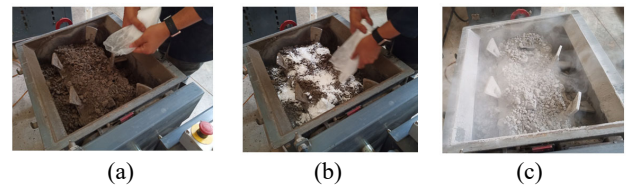


Figure 6. (a) Placing RAP in mixer, (b) Adding the percentage of lime and, (c) Mixing lime and aggregate.



Figure 7. (a) Adding 75% of water, (b) Mixing aggregate-lime-water.

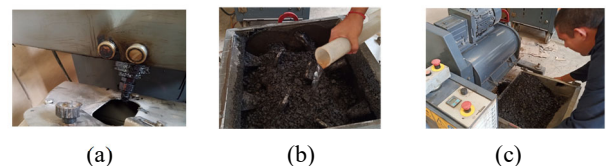


Figure 8. (a) Adding the foamed asphalt, (b) Adding 25% of water and (c) Final mix.

Specimens measuring 15 cm in diameter and 9.5 cm in thickness were compacted using the following procedure:

- The required mass of material for each specimen was calculated based on target density.
- A gyratory compactor was employed, operating under the following parameters: vertical pressure of 600 kPa, gyration angle of 1.16° , 500 gyrations, and a 30 gyrations per minute.

- Six specimens were prepared for each foamed asphalt content evaluated: 1.8%, 2.0%, 2.2%, and 2.4%.



Figure 9. Compaction of specimens in gyratory compactor.

The 24 specimens underwent a curing process consisting of 24 hours of drying at 40 °C (Figure 10a), followed by storage in sealed plastic bags in an oven at 40 °C for an additional 48 hours.

Specimens designated for dry testing were cooled to 25 °C for several hours, weighed, measured, and subsequently tested for indirect tensile strength at a controlled strain rate of 50.88 mm/min (Figure 10c).

For saturated testing, specimens were cooled for 4 hours, weighed, measured, and then submerged in water at 25 °C for 24 hours (Figure 10b) prior to indirect tensile testing.

After testing, all specimens were disintegrated to determine final moisture content. Indirect tensile strength results were used to calculate the tensile strength ratio (TSR) according to Equation (1).

$$TSR(\%) = \frac{RTI_{wetted}}{RTI_{dry}} \quad (1)$$

Where: RTI_{wetted} = Tensile strength in saturated condition (kPa), RTI_{dry} = Tensile strength in dry condition (kPa).

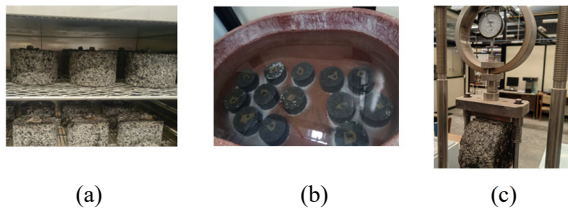


Figure 10. (a) Drying at 40°C, (b) Submergence for 24 hours, and (c) Tensile strength test.

The guide for Bitumen Stabilized Material (TG2) indicates that the optimum of foamed asphalt content will be that which provides at least a TSR of 75%. In this case, the optimum was 2.2%.

After obtaining the optimum percentage of foamed asphalt, the mixtures were prepared to compact specimens of 15 cm in diameter and 30 cm in height. The compaction procedure was the same followed for specimens with lime or cement. But in this case, the specimens were compacted with 130 impacts in each layer

4.5 Unconfined compressive strength

The unconfined compressive strength (UCS) test was performed at a constant strain rate of 1.2% per minute, in accordance with ASTM D5102-09.

4.6 Resilient modulus test

The resilient modulus was evaluated following the NCHRP 1-28A protocol for granular base materials. The test consisted of 30 loading sequences combining different levels of confining and deviator stresses. Each sequence included 100 load cycles, with the average resilient modulus calculated from the final five cycles of each sequence.

4.7 Permanent deformation Test

Permanent deformation testing was conducted over 20,000 load cycles under a confining pressure of 69 kPa and a deviator stress of 207 kPa. Each load was applied for 0.1 s, followed by a 0.9 s rest period, consistent with the loading protocol specified for resilient modulus evaluation.

5 RESULTS

5.1 Physical Properties

Table 1 summarizes the physical properties of the RAP aggregate, while Figure 11 presents its grain size distribution along with the recommended gradation limits for RAP granular bases as specified in the TG2 guideline. The aggregate was tested in its as-received condition, except for the removal of particles larger than one inch. Consequently, the gradation curve does not conform to the specified limits, with sand and fines fractions falling below the lower boundary. Figure 12 provides images of the material retained on each sieve.

Table 1. Summary of physical properties and classification

Property	Value
USCS Classification	GW
LL (%)	NP
PL (%)	NP
PI (%)	NP
Gs material passing sieve No. 4	2.458
Gs of gravel	2.446
% passing sieve 200 (%)	0.2

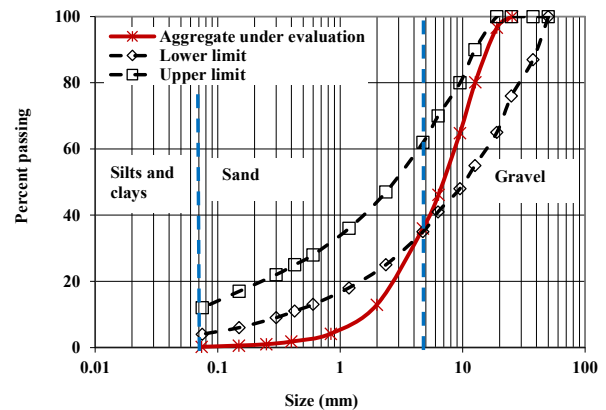


Figure 11. Gradation curve of aggregate under evaluation.

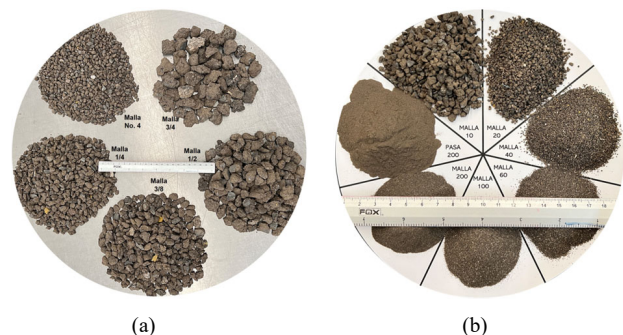


Figure 12. Aggregates in each sieve. (a) Particles retained on sieve No. 4 and (b) Particles passing sieve No. 4.

5.2 Compaction characteristics

Figure 13 illustrates the compaction curves for RAP, RAP stabilized with lime, and RAP stabilized with cement. The optimum conditions summarized in Table 2 served as the target

parameters for specimen compaction. Mixtures incorporating foamed asphalt were controlled using the optimum moisture content (wopt) and maximum dry unit weight (γ_{dmax}) determined for RAP.

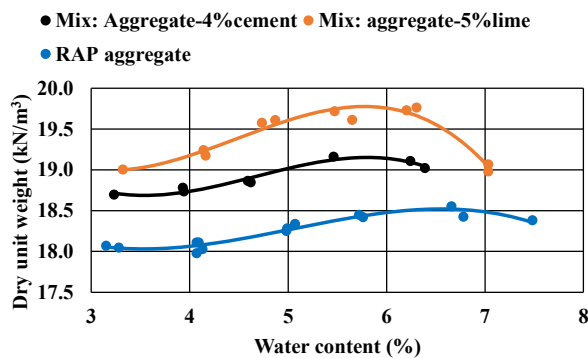


Figure 13. Summary of compaction curves

Table 2. Summary of compaction properties (ASTM D1557-12)

Mixture	wopt (%)	gdmax (kN/m ³)
Aggregate of RAP	6.60	18.52
Aggregate-5%lime	5.77	19.78
Aggregate-4%cement	5.78	19.16

5.3 Unconfined compressive strength

Stress–strain curves were generated for all unconfined compressive strength (UCS) tests; however, the comparisons presented in this section focus exclusively on maximum strength values (q_u). Figure 14 depicts the average q_u results for specimens subjected to curing under storage conditions and Table 4 shows the standard deviations of testing. In all graphs, the notation “AE” refers to foamed asphalt, while “CH” denotes hydrated lime.

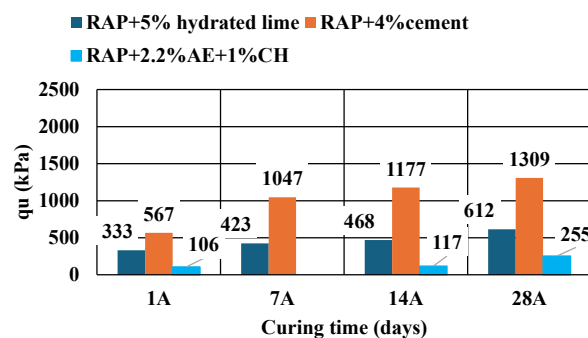


Figure 14. Unconfined compressive strength (q_u) of specimens cured under storage conditions.

Figure 14 shows that specimens stabilized with 5% lime exhibited an 84% increase in strength from 1 to 28 days, while those stabilized with cement increased by 130%, and foamed asphalt by 140%. Although foamed asphalt demonstrated the highest relative gain, it yielded the lowest strength values. For cement stabilization, the Mexican specification N.CMT.4.02.0003/21 requires a minimum strength of 2500 kPa at 28 days for bases treated with 4–5% cement; the RAP aggregate evaluated in this study achieved approximately 50% of this requirement. Similarly, for lime stabilization, the specification mandates 690 kPa at seven days, which was not met by the tested material. It is important to note that these requirements were developed for conventional granular bases and do not account for RAP aggregates. Therefore, the results presented herein, together with findings from previous studies, provide a basis for revising or developing new specifications tailored to RAP-based materials.

Table 3. Unconfined compression strengths and standard deviations for the three additives.

Curing (days)	q_u (kPa)	s (kPa)	q_u (kPa)	s (kPa)	q_u (kPa)	s (kPa)
	Mixture with lime		Mixture with cement		Mixture with foamed asphalt and lime	
1A	333	23	567	11	---	---
7A	423	30	1043	79	---	---
14A	468	35	1177	52	117	5
28A	612	29	1309	54	255	21

Unconfined compressive strength was also assessed on specimens subjected to curing followed by wetting. Since cement hydration requires water, specimens that absorbed moisture through capillarity exhibited higher strength than those cured for 28 days under. Furthermore, longer curing periods prior to wetting resulted in greater strength gains (Figure 15). For lime-stabilized specimens, additional moisture did not reduce strength; on the contrary, a slight increase was observed compared to specimens stored for 28 days (Figure 15). In lime-treated mixtures, the duration of storage prior to wetting had minimal influence on strength. Standard deviations are shown in the same figure, except for the 14A-14H-14A condition for cement, which corresponds to a single result.

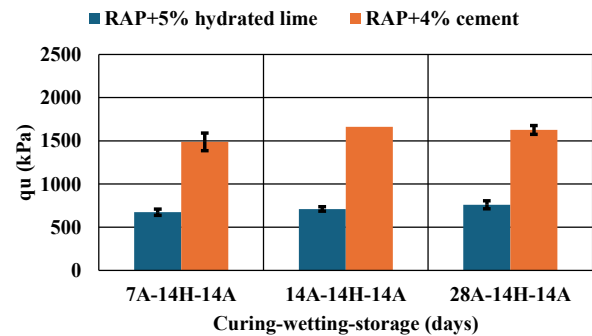


Figure 15. Unconfined compressive strength submergence for 14 days.

5.4 Resilient modulus

Specimens stabilized with cement consistently exhibited higher resilient modulus values (Figure 16). The lowest modulus was observed after one day of curing, whereas values for 7, 14, and 28 days were relatively similar (Figure 17). According to the TG2 guideline, the maximum allowable stiffness for bitumen-stabilized materials is 700 MPa. The resilient modulus of RAP stabilized with foamed asphalt ranged between approximately 400 MPa and 700 MPa, indicating its suitability for base construction. In contrast, TG2 specifies a maximum stiffness of 400–500 MPa for cement-stabilized natural gravel; however, RAP stabilized with cement exceeded these limits, resulting in an overly rigid mixture. Excessive stiffness in base layers increases susceptibility to cracking.

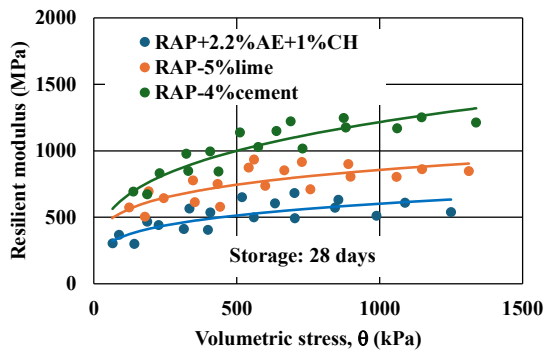


Figure 16. Resilient modulus stored for 28 days

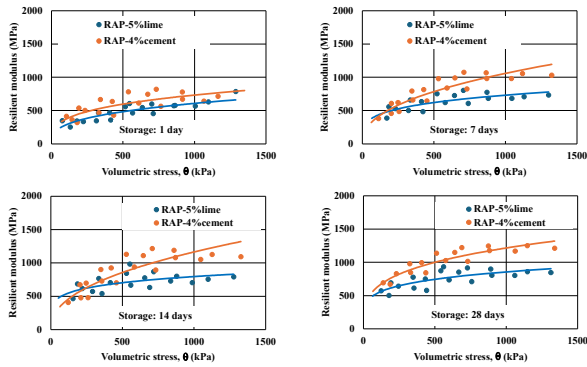


Figure 17. Resilient modulus for specimens cured for 1, 7, 14 or 28 days.

Resilient modulus values did not decrease after specimens were subjected to wetting; on the contrary, they improved compared to those obtained for specimens cured (stored) (Figure 18). Once again, cement-stabilized mixtures exhibited higher resilient modulus values than those stabilized with lime.

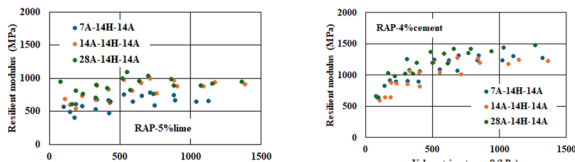


Figure 18. Resilient modulus for specimens stored-capillary suction

5.5 Permanent deformation

Figure 19 illustrates a typical curve from the permanent deformation test, showing total, permanent, and recoverable deformation throughout the loading cycles.

To compare stabilizing additives, only the permanent deformation at cycle 20,000 was considered as a standardized reference.

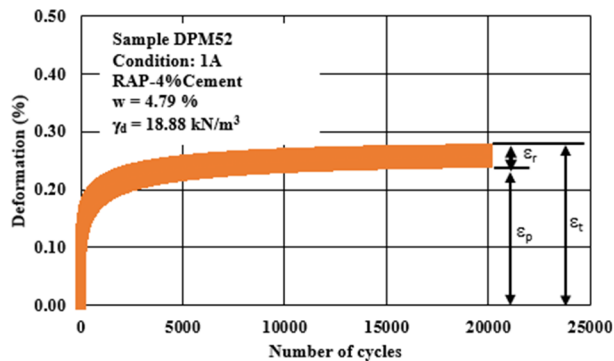


Figure 19. A typical result of a permanent deformation test

For materials used in the subgrade, subbase, and base layers of a pavement, it is essential to evaluate both permanent and recoverable deformation. Ideally, materials should exhibit low values for both types of deformation.

In this context, incorporating certain additives into the aggregates can significantly reduce these deformations. For the aggregate evaluated, the three additives: foamed asphalt, lime, and cement, led to a decrease in permanent deformation with storage time (Figure 20).

Among them, the most effective was 4% cement, which achieved the greatest reduction in permanent deformation. However, when stabilizing with cement, it is important to avoid producing an excessively rigid or brittle mixture, as this could lead to surface cracking problems in the pavement.

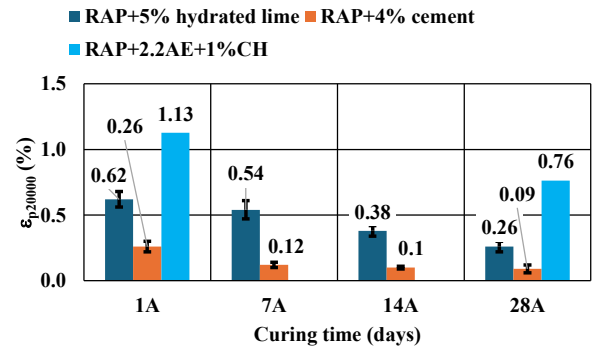


Figure 20. Results of permanent deformation (storage condition)

5.6 Strength parameters

According to the TG2 Manual, when designing pavements with a base stabilized using foamed asphalt or emulsion, it is necessary to evaluate the cohesion and internal friction angle of the mix.

As part of this evaluation, foamed asphalt samples were prepared and tested under dry and saturated conditions. Figure 21 presents the corresponding Mohr diagrams, showing that the material's strength did not degrade with increased water content, as both cohesion and internal friction angle remained nearly identical in both testing conditions

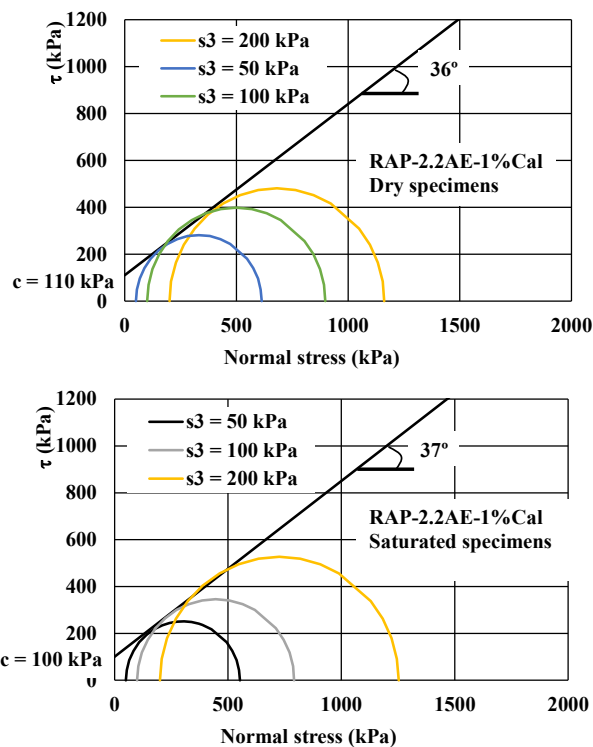


Figure 21. Strength parameters

6 CONCLUSIONS

The incorporation of RAP in pavement layers promotes sustainability but requires performance-based design criteria to ensure reliability. This study evaluated 100% RAP aggregate stabilized with lime, cement, and foamed asphalt under controlled laboratory conditions. The main conclusions are:

- UCS increased with curing time for all stabilizers, with cement achieving 130% from 1 to 28 days, followed by lime (84%) and foamed asphalt (140%), although foamed asphalt exhibited the lowest absolute strength.
- Wet curing enhanced strength for lime and cement mixtures, confirming the benefit of moisture conditioning in field applications.
- Resilient modulus values ranged from 299–682 MPa for foamed asphalt, 503–934 MPa for lime, and 673–1251 MPa for cement, indicating that cement stabilization produces a stiffer matrix, which may increase brittleness and cracking susceptibility.
- Permanent deformation was minimized with cement stabilization; however, mix rigidity must be considered to avoid premature distress.
- Shear strength parameters (cohesion and friction angle) were unaffected by saturation, suggesting adequate moisture resistance for foamed asphalt mixtures.

These findings provide a robust technical foundation for updating existing specifications and advancing the incorporation of RAP in stabilized base layers as part of sustainable pavement design practices.

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