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/ICSMGE2026-230

Experimental laboratory study on the influence of the compaction energy and degree on the mechanical and durability properties of stabilized clays using lime-based binder

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ABSTRACT: The paper presents laboratory experimental studies on the influence of compaction degree and energy on the mechanical and durability performances of stabilized clays. For clay stabilization a lime-based hydraulic binder (3%, 4% and 5%) was used, and the foreseen application is for road earthworks. The experimental results are bringing useful information about the mechanical and durability performances of stabilized clays, as various procedures can be applied on site, where also deviations from the optimum compaction parameters often appear. The results can be directly applied for deciding when to start the operation of the road earthworks by installing the next soil layer or by trafficking, also being linked to the freeze apparition etc. The study is continuing the research regarding procedures for laboratory tests for assessing the freeze – thaw behaviour of stabilized clays, for which there is no consensus at European level.

KEYWORDS: stabilized clay, lime binder, earthworks, freeze – thaw, laboratory tests.

1 INTRODUCTION

This paper presents a detailed laboratory investigation on the influence of compaction degree and compaction energy on the mechanical and durability performance of lime-stabilized clay soils. The study employs a lime-based hydraulic binder at varying dosages (3%, 4%, and 5%) to assess its effectiveness in enhancing clay properties for potential application in road earthworks and subgrade construction.

The experimental program was designed to replicate a range of field compaction conditions, acknowledging that on-site practices often deviate from optimal parameters due to equipment limitations, environmental factors, or execution constraints. The results provide critical insights into how variations in compaction conditions affect the structural integrity and long-term performance of stabilized soils,

Beyond mechanical performance, the study places particular emphasis on durability, especially under conditions relevant to temperate climates, where freeze–thaw cycles can significantly affect material behavior.

The findings are directly applicable to field practice, offering criteria for determining the appropriate timing for subsequent construction phases—such as the placement of additional soil layers or the initiation of light trafficking—based on the achieved compaction and stabilization levels. Additionally, the results inform risk assessments related to early exposure to freezing conditions.

This research continues the previous studies already published (Batali, Andrieș & Popa, 2019, Batali & Andrieș, 2022, Batali, Andrieş & Grégoire, 2024) and further contributes to the broader discussions on the standardization of laboratory methodologies for evaluating the freeze–thaw resistance of stabilized soils. At present, there is no unified European protocol for such testing, leading to inconsistencies in performance evaluation. By proposing a structured approach to assess freeze–thaw behavior, this study supports ongoing efforts to develop harmonized testing standards that ensure reliability and comparability across different regions and projects.

2 PRINCIPLES

Lime stabilization operates through several mechanisms: the hydration of quicklime, cation exchange, and flocculation, which occur in the short term, as well as the pozzolanic reactions with clay minerals that develop over time. The immediate effects are primarily observed as a reduction in the plasticity index and alterations in the particle size distribution. In contrast, the long-term effects are characterized by improvements in strength and durability.

Durability is a critical factor, particularly for earthworks constructed with stabilized soils that are frequently subjected to environmental stressors such as water exposure, wetting–drying cycles, and freeze–thaw conditions.

The durability of lime-stabilized clay is largely governed by the development of pozzolanic reactions over time. The effectiveness of lime stabilization—and consequently its durability—depends on several factors, including the type and activity of the clay minerals, the lime content, curing time and temperature, moisture conditions during curing, and the presence of supplementary materials (e.g., fly ash, slag, or cement).

Our past laboratory and field research on long-term behavior and durability performance of clays stabilized by lime or lime-base binders and on procedures to assess it showed:

- the modifications that the binder produced on the clay: change of the texture, loss of water and mass for some minerals and apparition of a new phase in the clay (Batali, Andrieș & Popa, 2019, Batali & Andrieș, 2022);
- the influence of the compaction energy on the physical, mechanical and, especially, on the durability properties – stability to water, freeze – thaw behavior (Batali, Andrieș & Popa, 2019, Batali & Andrieș, 2022);
- the influence of the curing time, from 3 days up to 60 days (there is still increase in the unconfined compression strength after 60 days of curing, which is enhanced by the compaction energy) (Batali & Andrieș, 2022);
- the assessment of various working procedures for freeze – thaw performance, according to European, Romanian standards and USA standards: loss of mass and strength, sensitivity to freezing by assessing the freezing swelling coefficient and the consistency index after thawing, freeze - thaw behavior by assessing the indirect tensile test (the Brazilian test) (Batali, Andrieș & Popa, 2019, Batali & Andrieș, 2022, Batali, Andrieş & Grégoire, 2024)

3 LABORATORY EXPERIMENTAL PROGRAM

The laboratory experimental program comprised:

- an initial characterization of the soil from physical, mechanical, compaction and durability points of view,
- laboratory tests for the 3 defined binder additions on soil samples prepared using:
  - normal and modified Proctor compaction energy,

  - the optimum water content and various compaction degrees: 90%, 95%, 97%, 100%
  - curing time: 3 ; 7 ; 14 ; 28 ; 60 days
- laboratory tests for mechanical characterization:
  - unconfined compression strength after 28 days (EN 13286-41, on samples prepared according to EN 13286-53 with slenderness ratio 1)
  - California Bearing Ratio test (CBR) (EN 13286-47)
  - compression in oedometer with incremental load (EN 17892-5)
- laboratory tests for durability characterization – freeze – thaw behavior:
  - mass loss after 5 freeze/thaw cycles
  - strength loss after 5 freeze/thaw cycles

The freeze-thaw behavior was studied according a specific procedure according to ASTM D560, with the following particularities: the soil specimens were submitted to freeze – thaw cycles after 28 days of curing, at a temperature range of - 8 ° C and + 20 ° C. Specimens were not soaked in water, but kept in humid atmosphere with more than 90% humidity, laid on water saturated felt pads, according to above mentioned standard. Therefore, were simulated conditions of intermediate seasons, as spring or autumn, when a negative unexpected temperature can appear during the night. Five freeze – thaw cycles were applied, each cycle consisting in maintaining the specimens at -8°C for 24 hours, followed by keeping them in humid atmosphere at + 20°C for 24 hours. After the 5 freeze – thaw cycles the mass loss was determined by:

$$\Delta m_{5ft} = \frac{m_{28} - m_{5ft}}{m_{28}} x100\ (\%) \qquad (1)$$

where: Δm_{5ft} is the mass loss after 5 freeze – thaw cycles, m_{28} is the initial mass after 28 days curing and m_{5ft} is the mass of specimens after 5 freeze – thaw cycles.

4 MATERIALS

The clay on which the experimental program was conducted is a fat clay, with 50% clay fraction (<0.002 mm) and 47 % silt fraction, with very high plasticity (PI = 40 %) and high swelling - 110% free swell, 190 kPa swelling pressure.

The stabilization was performed using a high lime-content hydraulic road binder, with a total amount of CaO+MgO higher than 60%, having also a cement content in order to increase the bearing capacity at short term.

5 EXPERIMENTAL RESULTS

Figure 1 shows the Proctor curves for Normal Proctor (OPN) and Modified Proctor (OPM) energy for the 3 binder additions (3%, 4% and 5%).

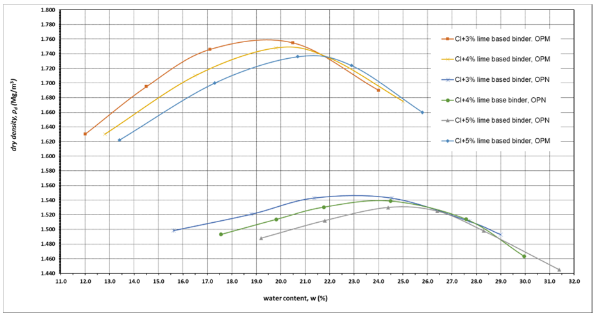

Figure 1. Proctor curves

Tables 1 - 3 show the results in terms of unconfined compression strength, CBR values and oedometric modulus, for the 3 bonder additions (3%, 4% and 5%), for 4 compaction degrees (90%, 95%, 97% and 100%) and 5 curing times (3, 7, 14, 28 and 60 days). Legend for Tables 1 – 3: (1) is the binder addition; (2) is the compaction energy – PM – Modified Proctor, PN – Normal Proctor; (3) is the compaction degree.

Table 1. Unconfined compression strength results

(1)	(2)	(3)	Unconfined compression strength (MPa) for curing time (days):				
			3	7	14	28	60
3%	PM	90%	0.73	0.84	0.99	1.16	1.24
		95%	0.82	0.93	1.17	1.27	1.37
		97%	0.90	1.10	1.33	1.50	1.65
		100%	1.07	1.22	1.40	1.67	1.80
	PN	90%	0.60	0.74	0.85	1.01	1.09
		95%	0.71	0.87	1.00	1.19	1.29
		97%	0.75	0.93	1.17	1.39	1.50
		100%	0.81	0.98	1.23	1.46	1.58
4%	PM	90%	0.80	0.90	1.19	1.21	1.30
		95%	0.90	1.00	1.20	1.40	1.46
		97%	0.99	1.19	1.49	1.65	1.75
		100%	1.18	1.32	1.57	1.84	1.91
	PN	90%	0.66	0.80	0.95	1.11	1.16
		95%	0.77	0.97	1.12	1.30	1.38
		97%	0.85	1.00	1.32	1.54	1.60
		100%	0.90	1.06	1.38	1.60	1.70
5%	PM	90%	0.86	0.98	1.25	1.33	1.40
		95%	0.96	1.18	1.36	1.54	1.66
		97%	1.24	1.33	1.54	1.72	1.84
		100%	1.40	1.55	1.73	2.00	2.12
	PN	90%	0.71	0.83	0.97	1.10	1.20
		95%	0.85	1.00	1.23	1.44	1.53
		97%	1.00	1.22	1.38	1.50	1.60
		100%	1.15	1.30	1.45	1.57	1.76

Table 2. CBR values

(1)	(2)	(3)	CBR (2.5 mm) for curing time (days):				
			3	7	14	28	60
3%	PM	90%	34.10	36.76	44.28	49.16	54.47
		95%	42.96	49.16	62.00	69.08	77.50
		97%	46.06	56.68	66.87	73.51	84.14
		100%	53.58	64.21	68.64	76.61	90.34
	PN	90%	26.58	30.25	36.22	40.11	43.79
		95%	34.64	41.23	51.64	60.08	66.7
		97%	37.20	46.53	51.64	59.88	64.45
		100%	41.28	48.52	55.31	66.31	74.20
4%	PM	90%	37.70	39.27	46.55	51.42	59.73
		95%	47.11	55.29	64.15	75.00	83.47
		97%	51.81	60.23	70.82	81.53	90.27
		100%	61.56	70.86	79.27	88.57	98.31
	PN	90%	32.13	34.90	39.24	44.66	51.00
		95%	41.05	47.83	56.86	63.81	71.20
		97%	46.14	52.14	61.33	70.90	80.44
		100%	54.36	61.27	70.52	73.85	82.68
5%	PM	90%	38.71	41.93	49.00	55.2	63.07
		95%	51.28	57.96	70.93	81.37	89.40
		97%	56.44	63.38	78.31	91.00	97.41
		100%	70.29	77.36	87.20	98.33	111.12
	PN	90%	35.20	38.45	43.12	50.85	57.80
		95%	45.12	50.78	60.27	71.33	78.62
		97%	50.47	58.20	68.93	81.60	67.20
		100%	60.77	68.35	74.88	86.92	95.11

Table 4 presents the results for the durability tests – loss of mass after 5 freeze – thaw cycles, unconfined compression strength and loss of compression strength after 5 freeze – thaw cycles. The legend is the same as for Tables 1 – 3. The loss of strength was computed in a similar way as the loss of mass:

$$\Delta R_{c\,5ft} = \frac{R_{c\,28} - R_{c\,5ft}}{R_{c\,28}} x100\ (\%) \qquad (2)$$

Table 3. Oedometric modulus values

(1)	(2)	(3)	Eoed (kPa) for curing time (days):				
			3	7	14	28	60
3 %	PM	90%	10363	11000	12903	14100	14286
		95%	13333	14210	16987	17000	17052
		97%	14286	16667	18333	19000	20890
		100 %	15385	17912	20412	22820	23710
	PN	90%	8500	9100	10750	11562	12000
		95%	10973	11752	13975	14111	14500
		97%	11910	13820	15511	16280	17400
		100 %	12800	14810	16992	18000	19245
4 %	PM	90%	11236	11880	12000	12410	13890
		95%	14270	15478	17150	18500	19000
		97%	15890	16942	19300	21400	22222
		100 %	16214	18000	21440	23156	24980
	PN	90%	9420	10000	10424	10527	11880
		95%	12000	13100	14550	15625	16100
		97%	13444	14120	16000	17986	18667
		100 %	14210	15227	18333	19450	21000
5 %	PM	90%	11986	12100	13111	13870	14286
		95%	15748	16230	19045	20765	21888
		97%	16000	17050	20130	23100	23175
		100 %	16667	18182	22222	25000	25470
	PN	90%	10280	10500	11275	11958	12500
		95%	13520	14000	16225	17775	18800
		97%	13800	14750	17500	19800	20500
		100 %	14334	15667	19109	21440	21900

Table 4. Results for durability tests – after 5 freeze – thaw cycles

(1)	(2)	(3)	Loss of mass (%)	R_{c5ft} (MPa)	Loss of strength (%)	R_{c5ft} / R_{c60}
3%	PM	90%	7.20	0.80	31.03	0.64
		95%	5.50	1.20	5.51	0.87
		97%	5.00	1.40	6.66	0.85
		100%	4.10	1.50	10.18	0.83
	PN	90%	10.10	0.62	36.61	0.58
		95%	7.50	0.94	21.00	0.73
		97%	6.10	1.22	12.23	0.81
		100%	5.50	1.30	10.95	0.82
4%	PM	90%	6.00	0.92	23.96	0.71
		95%	5.10	1.26	10.00	0.86
		97%	4.70	1.50	9.09	0.85
		100%	3.80	1.67	9.24	0.87
	PN	90%	8.60	0.71	36.03	0.61
		95%	6.30	1.04	20.00	0.75
		97%	5.80	1.25	18.83	0.78
		100%	5.00	1.34	16.25	0.79
5%	PM	90%	5.50	1.11	16.54	0.79
		95%	4.80	1.44	6.49	0.87
		97%	4.10	1.70	1.16	0.92
		100%	3.00	1.95	2.50	0.92
	PN	90%	7.50	0.85	22.72	0.71
		95%	5.50	1.20	16.66	0.78
		97%	5.30	1.30	13.33	0.81
		100%	4.80	1.35	14.01	0.77

6 COMMENTS ON THE RESULTS

The results of the unconfined compression tests showed that the compression strength varied from a minimum value of 0.60 MPa (for 3% addition, 3 days of curing and 90% of Normal Proctor compaction) up to a maximum value of 2.12 MPa (for 5% addition, 60 days of curing and 100% of Modified Proctor compaction).

After 5 freeze - thaw cycles, for Modified Proctor energy and more than 95% compaction degree, the compression strength at 28 days is equal to around 0.8 – 0.9 of the compression strength at 60 days and around 0.9 of the compression strength at 28 days. In case of 5 % binder addition the compression strength loss compared to $R_{c\ 28\ days}$ is very low (1 – 2%) for modified Proctor energy, while for normal Proctor compaction energy the loss is higher, of 13 – 14%.

The requirements for the various uses of the stabilized soils for roads are varying depending on country, standard or technical norm, practice, local ground conditions etc. In Romania the local standard (STAS 10473/1-87) is imposing the following conditions for the use of stabilized soils for roads in terms of compression strength:

- R_{c7} > 0.8 MPa for sub-base layers, >1.2 MPa for foundation layers and >1.5 MPa for base layers for flexible systems
- R_{c28} > 1.2 MPa for sub-base layers, >1.8 MPa for foundation layers and > 2.2 MPa for base layers for flexible systems

Depending on the lime-based binder addition and the compaction energy, these conditions are fulfilled for the various uses, for higher binder dosage and higher compaction energy these are fulfilled even for less curing time or compaction degree.

In terms of durability, the conditions for mass loss after freeze-thaw imposed in Romania are: Δm_{ft} < 7% for foundation layers and <10% for base layers for flexible systems (no condition imposed for sub-grade layers). Even though the conditions in which the samples were prepared and kept are not according to the Romanian standard (not being soaked with water), one can note that a good compaction degree is required (min. 95%), while, as expected, the higher the binder addition and the compaction energy, the better the freeze – thaw behaviour.

The Belgian Code CRR (2010) is imposing to have a compression strength, R_c, for a curing time corresponding to the one on site when freeze can appear, higher or equal to 2.5 MPa.

Also, CRR is imposing a condition regarding the strength after immersion: R_{ci} / R_{c60} > 0.8, where R_{ci} is the compression strength at 28 days of normal cure and 32 days of water immersion, and R_{c60} is the compression strength after 60 days of normal cure. The normal cure is at air at 20°C.

If we are extending now this condition to our case to assess the durability, as the ratio $R_{c\ 5ft}$ / R_{c60} (but in the curing conditions described here above, not the normal cure), we can see in the last column of Table 4 that the values of this ratio are higher than 0.80 for higher compaction degrees (> 95%) and modified Proctor compaction energy. In case of normal Proctor compaction energy, a higher binder dosage is necessary to reach this extended condition.

In terms of CBR values (Table 2) one can note that after 3 days the CBR values are already significantly increased, from 2 – 3 % for the non-stabilized clay (value that cannot be allowed for road earthworks), to values 26 – 70 % that are specific for mediocre (but not bad) soils for earthworks. In can also be seen that a higher compaction degree (100 % compared to 90 %) is almost doubling the CBR value. Generally, it was observed that after 7 days CBR values are comparable to values for granular materials.

The oedometer tests have been added to this experimental program to see if this can be used as an indicator for the freeze – thaw durability. Analyzing the results presented Table 3 in association with the durability results in Table 4, we can conclude that oedometer moduli higher than 20000 kPa correspond to a good durability for freeze – thaw. These values are obtained for high compaction degrees (>95%), high compaction energy and high curing times. Of course, the higher the binder dosage, the better, but good results are also obtained for medium dosage (4%), modified Proctor compaction energy, full curing (28 days) and more than 97% compaction degree.

7 CONCLUSIONS

The presented experimental program was conducted as part of a general approach of investigating methods and procedures for assessing mechanical and durability performances of clays stabilized by lime – based binder, for road applications.

In terms of laboratory tests, in this experimental program was applied a slightly different procedure for assessing the freeze – thaw behavior and the evaluation of the results was performed according to various norms and extending some of them to the actual testing conditions of this program.

Also, the assessment of the durability performance was conducted based not only on the compression strength and loss of mass, but also on the oedometric modulus and CBR value. This is part of the general objective of this research on stabilized clays with lime-based binders, to find applicable, easy-to-use and effective procedure to evaluate when the stabilized layer is ready to support traffic, next layers execution or freeze-thaw cycles,

The condition $R_{c\,5ft} / R_{c60}$ has to be further investigated to see if it can be imposed in a technical norm or standard,

The obtained results show that for better and more rapid results a medium – high binder dosage, a high compaction energy and a high compaction degree are required. This is somehow contradicting the practice, as for stabilized clays normal Proctor compaction energy is used. And, in site conditions often the compaction degree is not fulfilling the requirements.

For the given clay, for at least 4% of lime-based binder addition and modified Proctor compaction a good freeze – thaw behavior is obtained in terms of good compression strength values and low mass losses, but it cannot be considered as an insensitive to freezing material, but it can be used for sub-grades. Even for lower compaction energy good results are obtained if compared to the non-stabilized clay, which exhibits total loss of strength after freeze – thaw. Everything depends on the intended use and the stabilization conditions, and these results can give an orientation during the site works, especially if lower – medium binder dosages are used to optimize costs.

As expected, and already seen in the previous experiments, the lime-base binder stabilization helps significantly to improve the mechanical performances, with values that, in some conditions, approaches those of granular materials (CBR, E_{oed}),

8 ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by CARMEUSE GROUP and for the logistical support offered by CCF Laboratory.

9 REFERENCES

American Society for Testing and Materials, 2016. *ASTM D560/D560M-16 Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures*

Asociația Română pentru Standardizare, 1987, *STAS 10473/1-87 Lucrări de drumuri. Straturi din agregate naturale sau pământuri stabilizate cu ciment. Condiții tehnice generale de calitate*

Batali, L., Andrieș, G. and Popa, H., 2019. Assessment of physico – mechanical and durability characteristics of difficult soils improved by mixing with special lime-based hydraulic binders. *Proceedings of the 17th European Conference on Soil Mechanics and Geotechnical Engineering*

Batali, L. and Andrieș, G., 2020. Experimental analysis of physical, mechanical and durability performances of a clay treated with special lime-based hydraulic binder. *Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering*, Rahman and Jaksa (Eds), Vol. 2, 2813-2814

Batali, L and Andrieș, G., 2024. Use of the Brazilian test and Frost sensitivity test for determining the aptitude for earthworks of difficult soils stabilized by special lime-based binder, *Proceedings of the XVIII ECSMGE 2024 Geotechnical engineering challenges to meet current and emerging needs of society*, Lisbon, 2093-2096

CRR (2010). *Code de bonne pratique pour le traitement des sols à la chaux et/ou aux liants hydrauliques*. Centre de recherches routières.

European Committee for Standardization, 2021. *EN 13286-41 Unbound and hydraulically bound mixtures - Part 41: Test method for the determination of the compressive strength of hydraulically bound mixtures.* Brussels: CEN.

European Committee for Standardization, 2004. *EN 13286-53 Unbound and hydraulically bound mixtures - Part 53: Methods for the manufacture of test specimens of hydraulically bound mixtures using axial compression.* Brussels: CEN.

European Committee for Standardization, 2021. *EN 13286-47 Unbound and hydraulically bound mixtures - Part 47: Test method for the determination of California bearing ratio, immediate bearing index and linear swelling.* Brussels: CEN.

European Committee for Standardization, 2021. *EN 13286-47 Unbound and hydraulically bound mixtures - Part 47: Test method for the determination of California bearing ratio, immediate bearing index and linear swelling.* Brussels: CEN.

European Committee for Standardization, 2017. *EN ISO 17892-5 Geotechnical investigation and testing — Laboratory testing of soil — Part 5: Incremental loading oedometer test.* Brussels: CEN.