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DETERMINATION OF THE PHYSICAL-MECHANICAL CHARACTERISTICS OF NON-COHESIVE SUB-GRADE LAYERS STABILIZED WITH FLY ASH (PART I)

BY

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Abstract. In the execution of the foundation layers and the road base it is necessary to reduce the costs of their construction by using local materials (ballast or crushed stone). In some cases, the physical-mechanical characteristics of the local materials do not satisfy the conditions for dimensioning the road structure. Therefore, to improve these characteristics, they are stabilized with hydraulic binders (fly ash or various mixtures based on lime and cement). By using hydraulic binders, the aim is to obtain a speed in execution, to increase the physico-chemical and mechanical characteristics of the local aggregates and implicitly to reduce the overall costs of the work (Zarojanu, 1976).

Keywords: fly ash; earthworks; stabilisation; road structures, lime.

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1. Introduction

Choosing the type of binder that will be used is determined by laboratory tests. These tests are performed on unsuitable sub-grade layers (tests that take into account the type, humidity, the presence of various chemicals and the characteristics of the sub-grade layers) (Boboc and Zarojanu, 2000). So, in general, for highly cohesive soils with relatively high humidity, it is recommended to use lime as a binder, and in the case of weakly cohesive soils a binder, in the composition of which, will be a significant percentage of cement. The alternative solutions for replacing natural aggregates, binders, as viable alternatives to traditional technologies, the adoption and continuous development of recycling technologies are concerns of researchers, designers and road builders. Therefore, the stabilized mixtures successfully form the foundation layers of the rigid road structures or both the foundation layers and the base layers of the semi-rigid structures (STAS 10473/2-86).

Internationally, there are researches based on the same material, the mixture of ash and lime being between 10% and 20% (Arvind *et al.*, 2007). The results of the research are influenced by the chemical composition of the ash. Our case study is based on both international and previous national research, which has studied the use of thermal power plant ash in stabilized layers with various activators (Boboc, 1995).

2. Fly ash - chemical and mineralogical comparison of fly ash in Romania

Table 1 shows the chemical composition of the ashes from CET, Romania, which ensures dry capture, but also the ashes from the two thermal power plants, as well as the current eligibility conditions in our country (Boboc, 1995; Nicolescu, 1978; Jercan, 1980).

From the comparison with the admissibility conditions, regarding the ashes from the two sources (Holboca-Iași and Vaslui), it results that:

- the ash meets the requirements for the main oxide components (SiO_2 , Al_2O_3 , Fe_2O_3);
- the CaO content is within the permissible limits for Iași ash and slightly below the limit for Vaslui ash;
- the SO_3 content, although higher than the permissible limit for use as an additive in concrete and mortar, falls within the proposed value (maximum 4) for the use of ash in stabilized road layers, which ensures a wide range of uses.

Depending on the oxide composition, the evaluation of the hydraulic activity is performed based on the following indices (Voinea, 1981; SR EN 14227-1; 4:2015):

- Basicity index, calculated with relation 1:

$$I_b = \frac{(\%) \text{CaO}}{(\%) \text{SiO}_2} \quad (1)$$

– Basicity module, calculated with relation 2:

$$M_b = \frac{(\%) \text{CaO} + (\%) \text{MgO}}{(\%) \text{SiO}_2 + (\%) \text{Al}_2\text{O}_3} \quad (2)$$

Table 1
The chemical composition of C.E.T. ashes from Romania

Provenance fly ash C.T.E.	Chemical composition (average values), %								
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	SO ₃	Na ₂ O	K ₂ O	PC	MgO
Govora (coal)	Σ = 98.10			5.90	0.91	0.90	1.95		2.1
	50.90	38.50	10.70						
Ocnița (lignite)	Σ = 79.11			9.16	3.66	0.44	1.67	1.36	3.0
	48.00	23.00	8.11						
Rogojelu (lignite)	Σ = 73.69			8.06	5.63	0.45			2.1
	41.60	23.26	8.83						
Oradea (lignite)	Σ = 79.90			6.70	7.15		2.05		2.1
	47.21	19.51	13.18						
Onești (lignite)	Σ = 77.52			10.21	4.18	1.08	2.09	2.35	3.5
	47.20	18.98	11.36						
Comănești (lignite)	Σ = 72.29			7.03	0.93	1.60	3.46		3.1
	51.60	19.43	11.26						
Holboca-Iași (lignite)	Σ = 90.05			5.60	3.76			2.29	2.20
	50.05	32.42	7.58						
Vaslui (lignite)	Σ = 88.76			4.06	3.05			2.18	2.10
	53.28	27.50	7.98						
Admissibility conditions	SiO₂+Al₂O₃+Fe₂O₃ ≥ 70			Min 5.0	Max 3	1.3	1.3	≤10	Max 5

– Activity index, calculated with relation 3:

$$I_a = \frac{(\%) \text{SiO}_2}{(\%) \text{Al}_2\text{O}_3} \quad (3)$$

– Quality index, calculated with relation 4:

$$I_c = \frac{(\%) \text{CaO} + (\%) \text{CaS} + (\%) 0.5 \text{MgO} + (\%) \text{Al}_2\text{O}_3}{(\%) \text{SiO}_2 + (\%) \text{MgO}} \quad (4)$$

Depending on these indices and the CaO content presented in Table 2, it results that the ashes from CET 2 Holboca - Iași and CET Vaslui are aluminosiliceous ashes (Boboc, 1995).

Table 2
The chemical composition of C.E.T. ashes from Romania

C.T.E.	Index			Module basicity	CaO %	Ash type
	basicity	activity	quality			
Holboca - IAȘI	0.112	1.54	0.78	0.095	5.60	alumino -siliceous
VASLUI	0.076	0.93	0.61	0.076	4.06	alumino-siliceous

3. Case study

The ashes from CET 2 Holboca - Iași were used to stabilize the natural aggregates used in the foundation / base layers of the semi-rigid road structures.

The source of the natural aggregates used in this study is the Tupilați gravel pit, and the granulometric analysis for this material can be found in Fig. 1.

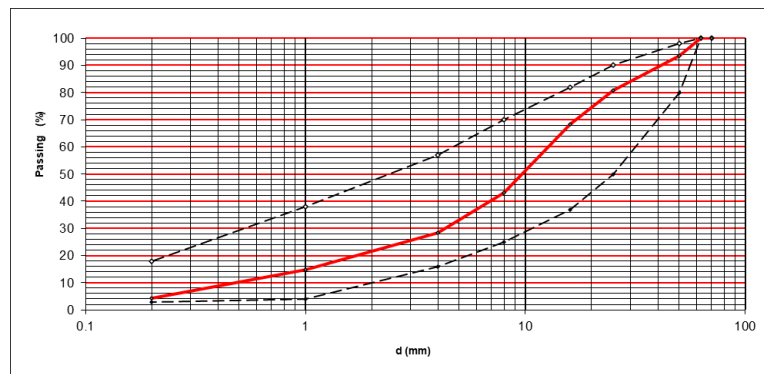


Fig. 1 – Granulometric analysis of the natural aggregates.

Natural hydraulic lime is in accordance with UNI-EN 459, and the variant used is NHL 3.5.

To determine the composition of the mixture from stabilized sub-grade layers, the available materials will be taken into account. The laboratory test determines the optimum binder dosage and modified Proctor compaction characteristics (ρ_{dmax} , W_{optim}), with a rate of compaction of at least 95% (Andrei *et al.*, 2012; STAS 1913/3 – 86; SREN 13286-2/2011).

A mixture of ballast, ash and lime was used to determine the parameters of the modified Proctor test (W_{opt} , γ_d).

The specimens ($d = 51$ mm; $h = 7,5$ mm) were made using the appropriate Proctor energy and maintaining an approximately optimal amount of water. Six test pieces from each recipe were made. Six specimens from each recipe were made.

The tests were performed between 15.02.2021 - 10.06.2021 and we made 3 recipes for mixing the ballast (taken from the Moța gravel pit) with

pozzolanic binders (ash and lime): Variant I (20% ash + 2% lime), Variant II (25% ash + 2% lime), Variant III (30% ash + 2% lime) (SR EN 14227-5:2015, SR ENV 13282 – 2002).

Based on the compaction characteristics and the water content, the values of the Modified Proctor test were determined, the result being: for variant I (Table 3, Table 4, Table 5), for variant II (Table 6, Table 7, Table 8) and for variant III (table 9, Table 10, Table 11). Figure 2 shows the variation of the compaction characteristics of the Modified Proctor for all 3 studied variants.

Based on the values that were determined with the Proctor Modified test, 3 test bodies were made for each variant studied. Tensile strength and compressive strength at 14 days and 28 days were determined on these samples.

The values obtained for variant I can be found in Table 12, Table 13, Table 14, Table 15, for variant II in Table 16, Table 17, Table 18, Table 19, and for variant III in Table 20, Table 21, Table 22, Table 23. Figure 3, Fig. 4, Fig. 5, Fig. 6 shows the comparison of the results for each determination.

Variant I: 20% ash + 2% lime

- Modified Proctor test – Proctor B pattern;
- tamper: "B", mass = 4.5 kg
- total amount of material = 40.000 g
- $m = 0.112$
- amount of material over $D_{\max} = 4.480$ g
- $\rho_{ssD} = 2.7 \text{ Mg/cm}^3$
- $W_0 = 0.019$

Table 3

Compaction characteristics - variant I

Characteristics	Sym.	U.M.	Number of test					
			1	2	3	4	5	6
Mass empty pattern + base plate	m_1	g	9724	9724	9724	9724	9724	9724
Mass pattern with material + base plate	m_2	g	13850	13926	14004	14082	14046	14009
Volume pattern	V	ml	2120	2120	2120	2120	2120	2120
Apparent density $\rho = (m_2 - m_1)/V$	ρ	Mg/m ³	1.946	1.982	2.019	2.056	2.039	2.021
Water content	w	%	7.2	7.8	8.4	9.0	9.6	10.2
Dry density $\rho_d = (100\rho)/(100+w)$	ρ_d	Mg/m ³	1.816	1.839	1.863	1.886	1.860	1.834
Water content revised $w' = w(1-m) + w_0m$	w'	%	6.4	6.9	7.5	8.0	8.5	9.1
Dry density revised $\rho_{d'} = \rho_d(1-m) + 0.9m\rho_{ssD}$	$\rho_{d'}$	Mg/m ³	1.884	1.905	1.926	1.947	1.924	1.901

Table 4
Test values Proctor - Modified Proctor - variant I

Compaction characteristics	Symbol	Value	U.M.
Optimal humidity in moist domain, %	W_{opt}	8,0	%
Dry density, maximal moist domain, Mg/m^3	ρ_{dmax}	1.947	g/cm^3

Table 5
Water content - variant I

Characteristics	Symbol	Determination					
		1	2	3	4	5	6
		(g)					
Container	M_2	2870	2910	2812	2650	2880	2656
Mass of tray+ moist test portion	$M_1 - M_2$	4870	4910	4812	4650	4880	4656
Mass of tray + dry test portion	$M_{d1} + M_2$	4736	4765	4657	4485	4705	4471
Second weighing of tray and dry test portion	$M_{d1} + M_2$	4736	4765	4657	4485	4705	4471
Difference of weighing data	(line3 – line4)	0	0	0	0	0	0
(line3 – line4) / (line 3 – line1) x 100	-	0	0	0	0	0	0
Mass of water (line2 – line4)	-	134	145	155	165	175	185
Mass of dry test portion (line 4 – line1)	M_3	1866	1855	1845	1835	1825	1815
Water content (line7/line8) x 100	%	7.2	7.8	8.4	9.0	9.6	10.2

Variant II: 25% ash + 2% lime

- Modified Proctor test – Proctor B pattern;
- tamper: "B", mass = 4.5 kg
- total amount of material = 40.000 g
- $m = 0.112$
- amount of material over $D_{max} = 4.480$ g
- $\rho_{ssD} = 2.7 Mg/cm^3$
- $W_0 = 0.019$

Table 6
Test values Proctor - Modified Proctor - variant II

Compaction characteristics	Symbol	Value	U.M.
Optimal humidity in moist domain, %	W_{opt}	8.3	%
Dry density, maximal moist domain, Mg/m^3	ρ_{dmax}	1.888	g/cm^3

Table 7
Compaction characteristics - variant II

Characteristics	Sym.	U.M.	Number of test					
			1	2	3	4	5	6
Mass empty pattern + base plate	m ₁	g	9724	9724	9724	9724	9724	9724
Mass pattern with material + base plate	m ₂	g	13745	13807	13875	13944	13912	13880
Volume pattern	V	ml	2120	2120	2120	2120	2120	2120
Apparent density $\rho = (m_2 - m_1)/V$	ρ	Mg/m ³	1.897	1.926	1.958	1.991	1.975	1.960
Water content	w	%	7.6	8.2	8.8	9.4	10	10.6
Dry density	ρ_d	Mg/m ³	1.763	1.780	1.800	1.820	1.796	1.772
$\rho_d = (100\rho)/(100+w)$	w'	%	6.8	7.3	7.8	8.3	8.9	9.4
Water content revised	$\rho_{d'}$	Mg/m ³	1.837	1.853	1.87	1.888	1.867	1.846

Table 8
Water content - variant II

Characteristics	Symbol	Determination					
		1	2	3	4	5	6
		(g)					
Container	M ₂	2880	2910	2812	2650	2870	2656
Mass of tray+ moist test portion	M ₁ – M ₂	4880	4910	4812	4650	4870	4656
Mass of tray + dry test portion	M _{d1} +M ₂	4739	4758	4650	4478	4688	4464
Second weighing of tray and dry test portion	M _{d1} +M ₂	4739	4758	4650	4478	4688	4464
Difference of weighing data	(line3 – line4)	0	0	0	0	0	0
(line3 – line4) / (line 3 – line1) x 100	-	0	0	0	0	0	0
Mass of water (line2 – line4)	-	141	152	162	172	182	192
Mass of dry test portion (line 4 – line1)	M ₃	1859	1848	1838	1828	1818	1808
Water content (line7/line8) x 100	%	7.6	8.2	8.8	9.4	10.0	10.6

Variant III: 30% ash + 2% lime

- Modified Proctor test – Proctor B pattern;
- tamper: "B", mass = 4.5 kg
- total amount of material = 40.000 g
- $m = 0.112$
- amount of material over $D_{\max} = 4.480$ g
- $\rho_{ssD} = 2.7 \text{ Mg/cm}^3$
- $W_0 = 0.019$

Table 9
Compaction characteristics - variant III

Characteristics	Sym.	U.M.	Number of test					
			1	2	3	4	5	6
Mass empty pattern + base plate	m_1	g	9724	9724	9724	9724	9724	9724
Mass pattern with material + base plate	m_2	g	13621	13698	13769	13840	13798	13762
Volume pattern	V	ml	2120	2120	2120	2120	2120	2120
Apparent density $\rho = (m_2 - m_1)/V$	ρ	Mg/m ³	1.838	1.875	1.908	1.942	1.922	1.905
Water content	w	%	8.2	8.8	9.4	10	10.6	11.2
Dry density	ρ_d	Mg/m ³	1.699	1.723	1.744	1.765	1.738	1.713
$\rho_d = (100\rho)/(100+w)$	w'	%	7.3	7.8	8.3	8.9	9.4	9.9
Water content revised	ρ_d^*	Mg/m ³	1.781	1.802	1.821	1.839	1.815	1.793

Table 10
Test values Proctor - Modified Proctor - variant III

Compaction characteristics	Symbol	Value	U.M.
Optimal humidity in moist domain, %	w_{opt}	8.9	%
Dry density, maximal moist domain, Mg/m ³	$\rho_{d\max}$	1.839	g/cm ³

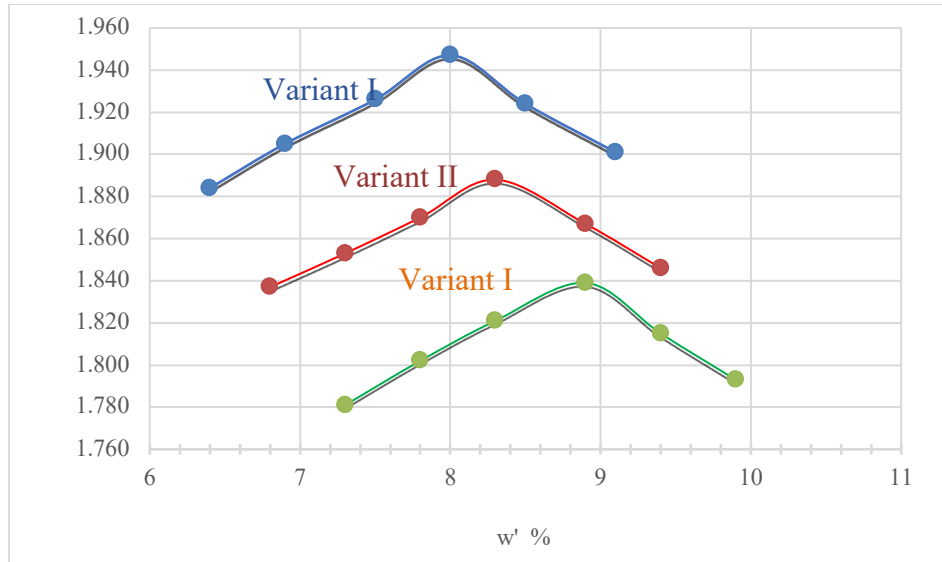


Fig. 2 – Proctor Test Diagram modified.

Table 11
Water content - variant III

Characteristics	Symbol	Determination					
		1	2	3	4	5	6
		(g)					
Container	M ₂	2656	2880	2650	2812	2870	2910
Mass of tray+ moist test portion	M ₁ – M ₂	4656	4880	4650	4812	4870	4910
Mass of tray + dry test portion	M _{d1} +M ₂	4504	4718	4478	4630	4678	4709
Second weighing of tray and dry test portion	M _{di} +M ₂	4504	4718	4478	4630	4678	4709
Difference of weighing data	(line3 – line4)	0	0	0	0	0	0
(line3 – line4) / (line 3-line1) x 100	-	0	0	0	0	0	0
Mass of water (line2 – line4)	-	152	162	172	182	192	201
Mass of dry test portion (line 4 – line1)	M ₃	1848	1838	1828	1818	1808	1799
Water content (line7/line8) x 100	%	8.2	8.8	9.4	10.0	10.6	11.2

Determination of compressive strength R_c and tensile strength R_t
Variant I: 20% ash+ 2% lime

Table 12
Physical - mechanical characteristics (R_{t14}) - variant I

Physical - mechanical characteristics	U.M.	Characteristics / Specimen value								
		Specimen 1			Specimen 2			Specimen 3		
		D cm	H cm	V cm ³	D cm	H cm	V cm ³	D cm	H cm	V cm ³
Specimen characteristics	-	7.14	10.3	412.2	7.14	10.4	416.2	7.14	10.4	416.2
Specimen mass	g	818.7			834.1			848.9		
Specimen density	g/cm ³	1.986			2.004			2.040		
Surface density	mm ²	4002			4002			4002		
Load of failure	N	4482			4482			4402		
R _t 14 days	N/mm ²	1.12			1.12			1.10		
R _t average	N/mm ²	1.11								
Admissibility STAS 10473/1-87		Base layer R _t 14 days = 1.9 – 2.8								
		Sub-base layer R _t 14 days = 1.5 – 2.3								
		Capping layer R _t 14 days = 1.0 – 1.5								

Table 13
Physical - mechanical characteristics (R_{c14}) - variant I

[illegible]

Physical - mechanical characteristics (R_{t28}) - variant I

[illegible]

Physical - mechanical characteristics (R_{c28}) - variant I

[illegible]

Variant II: 25.0% ash + 2% lime

Table 16

Physical - mechanical characteristics (R_{t14}) - variant II

[illegible]**Table 17**

Physical - mechanical characteristics (R_{cl4}) - variant II

[illegible]

Physical - mechanical characteristics (R_{t28}) - variant II

Physical - mechanical characteristics	U.M.	Characteristics / Specimen value								
		Specimen 1			Specimen 2			Specimen 3		
		D cm	H cm	V cm ³	D cm	H cm	V cm ³	D cm	H cm	V cm ³
Specimen characteristics	-	7.14	10.3	412.2	7.14	10.4	416.2	7.14	10.4	416.2
Specimen mass	g	816.6			813.9			814.4		
Specimen density	g/cm ³	1.981			1.956			1.957		
Surface density	mm ²	4002			4002			4002		
Load of failure	N	4402			4682			4882		
R _t 28 days	N/mm ²	1.10			1.17			1.22		
R _t average	N/mm ²	1.16								
Admissibility STAS 10473/1-87		Base layer R _t 28 days = 2.2 – 5.0								
		Sub-base layer R _t 28 days = 1.8 – 3.0								
		Capping layer R _t 28 days = 1.2 – 2.0								

Physical - mechanical characteristics (R_{c28}) - variant II

[illegible]

Variant III: 30.0% ash + 2% lime

Table 20

Physical - mechanical characteristics (R_{tl4}) - variant III

[illegible]

Table 21

Physical - mechanical characteristics (R_{cl4}) - variant III

[illegible]

Table 22

[illegible]

Table 23

[illegible]

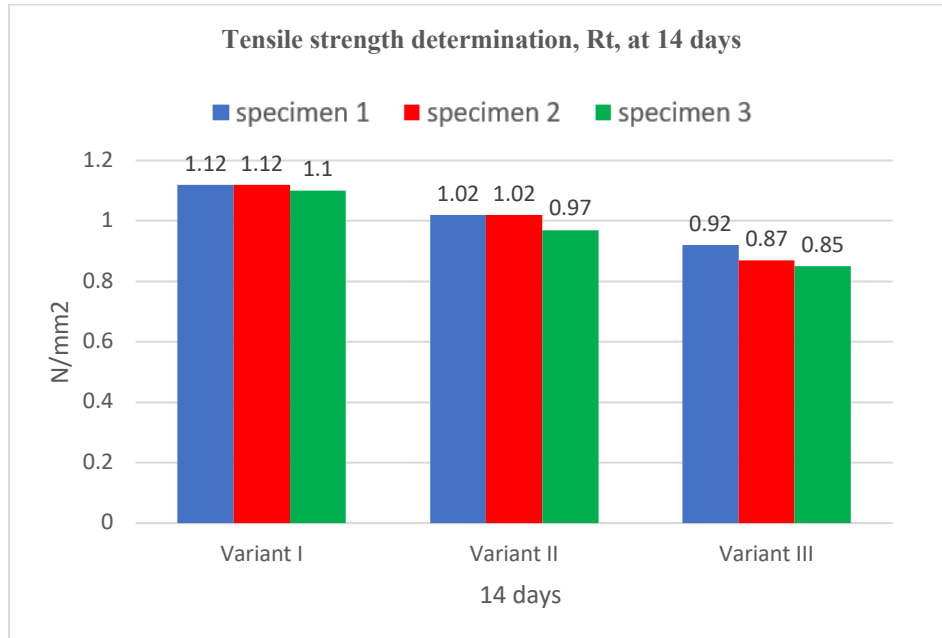


Fig. 3 – Diagram of tensile strength at 14 days.

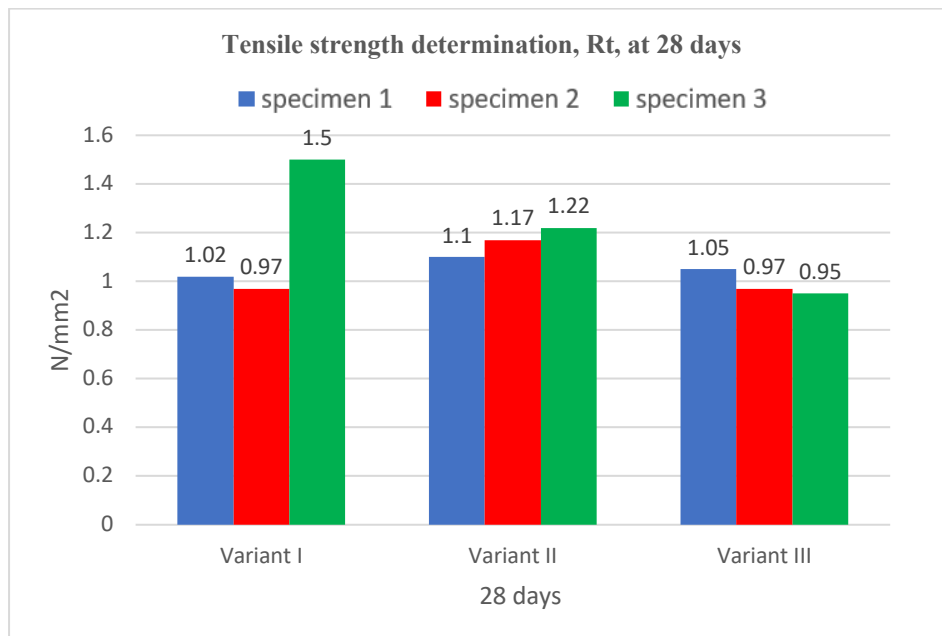


Fig. 4 – Diagram of tensile strength at 28 days.

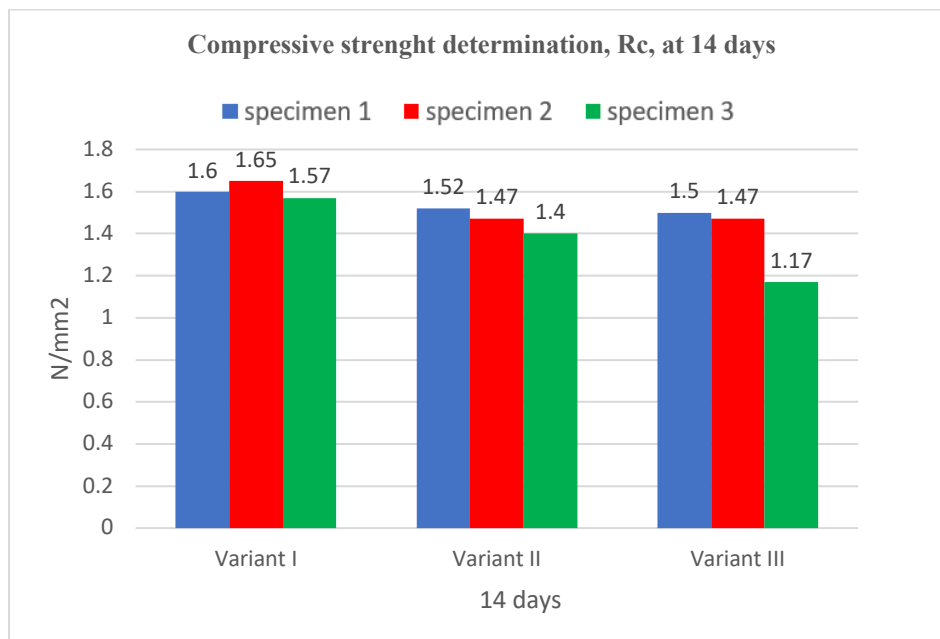


Fig. 5 – Diagram of compressive strength 14 days.

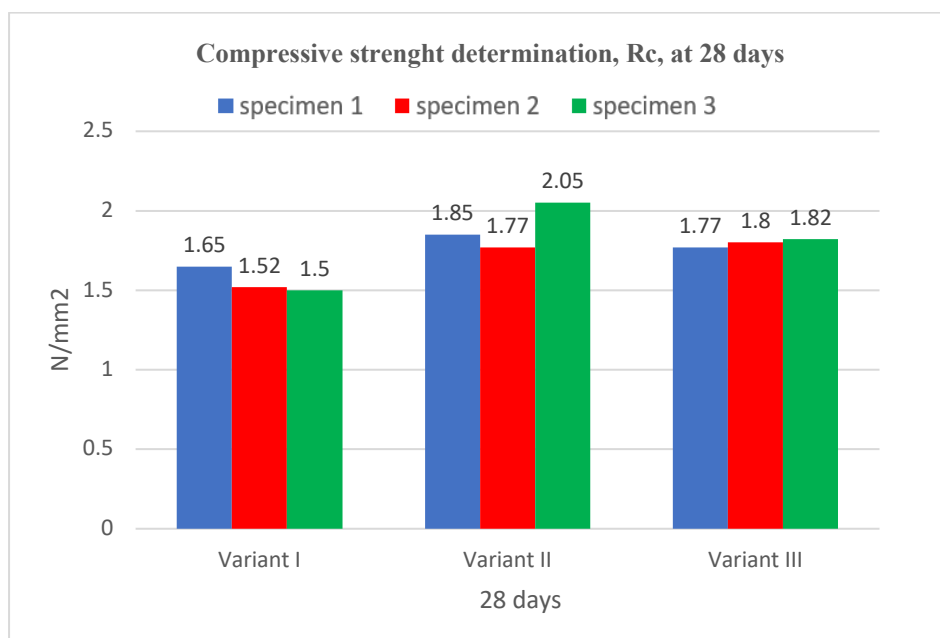


Fig. 6 – Diagram of compressive strength 28 days.

4. Conclusions

In order to modify the inadequate properties of sub-grade layers were implemented several methods. Chemical stabilization as a common technique was applied by addition of some additives such as lime, fly ash to the sub-grade layers.

The numerous studies were established about the effect of lime and fly ash on soil properties; however, the obtained results were extremely different about the efficiency and affectivity of stabilization with lime and fly ash.

The fly ash, caught dry, meets the conditions to be used to stabilize the mixtures used in the semi-rigid road structure as a foundation layer and a base layer.

The stabilized mixture with pozzolanic binder type fly ash strengthens over time, so that after 360 days it has higher characteristics than the stabilization with cement.

Mixtures stabilized with 20% fly ash + 2% lime show higher resistance to R_c compression and R_t tensile strength than other mixtures, with average values $R_c = 1.61 \text{ N / mm}^2$, $R_t = 1.11 \text{ N / mm}^2$ for 14 days, and for 28 days the best values of stabilized mixtures are with 25% fly ash + 2% of having $R_c = 1.89 \text{ N / mm}^2$ and $R_t = 1.16 \text{ N / mm}^2$.

Using the process of improving the foundation ground with binders brings us great savings in the total cost of execution of a project. These savings come from the fact that it is no longer necessary to excavate the weak foundation soil and replace it with a good foundation soil, all these operations being large consumers of financial resources.

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DETERMINAREA CARACTERISTICILOR FIZICO-MECANICE A PĂMÂNTURILOR NECOEZIVE STABILIZATE CU CENUȘĂ VOLANTĂ DE TERMOCENTRALĂ (PARTEA I)

(Rezumat)

În execuția straturilor de fundație și bază la drumuri, deseori este necesar pentru reducerea costurilor de realizare a acestora, folosirea materialelor locale (balast sau piatră spartă). În unele cazuri, caracteristicile fizico-mecanice ale materialelor locale nu satisfac condițiile de dimensionare a structurii rutiere. De aceea pentru îmbunătățirea acestor caracteristici se recurge la stabilizarea lor cu lianți hidraulici (cenușă volantă sau diverse amestecuri pe bază de var și ciment). Prin folosirea lianților hidraulici se urmărește obținerea unei rapidități în execuție, creșterea caracteristicilor fizico-chimice și mecanice ale agregatelor locale și implicit reducerea costurilor globale ale lucrării.

