The Effect of the Portland and Eco-cement Stabilization on the Physical and Mechanical Behaviour of the Bahlui Clay

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Abstract. The research program developed by the authors and presented in this paper designate the Bahlui clay – Romania fitting the clays with specific behaviour such as the Addis Ababa clay, London clay, Dharwad clay, New Yorkshire clay, Ankara clay and Weald clay. Its behaviour is mainly characterized by high swells and shrinkages at moisture variations. The utilization of the Bahlui clay as good foundation soil or material for compacted soil cushion required the determination of the parameters characterizing its behaviour during moisture variation: swell-shrinkage, compressibility and respectively shear strength. The research experiments to define the physical and mechanical behaviour of the Bahlui clay were performed on both natural and remoulded samples with 2.5÷10% mix from the dry soil mass with Portland with/or eco-cement. The paper presents graphs and tables displaying the Portland/eco-cement stabilization influence on the main physical and mechanical indices characterizing the Bahlui clay behaviour during moisture variations as well as conclusions its usage.

Introduction

Expansive soils have a high content of clay rich in montmorillonite and illite, as strong hydrophilic minerals, with the liquidity limit higher than 40% and the plasticity index higher than 20% and thus both of them more than those for regular/inactive clays [1].

Swell-shrinkage cycles due to moisture variations induce differential movements of the foundation soil, becoming the reason of many structural damages of constructions founded on expansive soils. Some approaches in foundations design on expansive clays are referring to the exceeding of the active zone and foundation anchorage with deep elements in the soil layer acting with reduced potential or totally inactive. Other frequently used approaches consider beneficial to excavate and remove the expansive soil zone and replace it with a cushion.

In this last approach category, the expansive clay is fully or partially replaced with a soil/material with no volume variations due to moisture variations. Using the soil transferred from another location to perform the cushion is possible as long as the distance from the construction site is not too large to prove the solution economically ineffective.

The chemical stabilization of the expansive clay from the construction site and incorporating the resulted material within the cushion is current practice, since the utilization of good or inactive soils to moisture variations is costly enough.

Katti (1979) [2] [3] suggests based on its own work, the use of certain variation limits of the geotechnical characteristics, correlated with the cushion thickness made of inactive soil. These restrictive values are presented in Table 1.

The reduction of the swell-shrinkage potential by chemical stabilization of the expansive clays can be obtained using in addition to soils various materials: lime, fly ash, Portland and eco-cements. Many research works focused on using waste based materials in stabilizing these soils. This research program carried out by the authors of this paper obtained results regarding the efficient use of some eco-cement made of the waste material from thermal power plants on the improvement of the physical and mechanical behaviour of the Bahlui clay – Romania.

Table 1. Geotechnical parameters that need to be satisfied by the soil cushion material [3]

S. no.	Properties		Specification range
1	Grain size analysis	Clay (<0.002mm) [%]	15÷25
		Silt (0.002÷0.075 mm) [%]	30÷45
		Sand (0.075÷4.75 mm) [%]	30÷40
		Gravel (4.75÷80mm) [%]	10
2	Consistency Limits	Liquid limit, w_L [%]	30÷50
		Plastic limit, w_P [%]	20÷25
		Plasticity index, I_P [%]	10÷25
		Shrinkage limit, w_s [%]	≥ 15
3	Swelling pressure when compacted to standard Proctor maximum dry density at no volume change condition (kPa)		< 10
4	Clay minerals		Preferably Kaolinit and Illite
5	Shear Strength of sample compacted to standard Proctor optimum conditions, after saturation	1/2 UCS (kPa) (*) Consolidated direct shear test 0.0125mm/min	15÷35
		c_u (kPa)	10÷30
		Φ_u (deg)	8÷15
6	Approximate thickness of cohesive non-swelling soils layer for swelling pressure (kPa)	100÷150 (kPa)	0.75÷0.85 m
		200÷300 (kPa)	0.90÷1.00 m
		350÷500 (kPa)	1.05÷1.15 m
(*) UCS – unconfined compressive strength			

Materials

Soil. The expansive clay investigated in this study originated from the Bahlui river plain, from the city of Iasi – Romania. Its physical properties with comparative values characterizing other expansive clays worldwide are displayed in Table 2. Comparing the physical properties values from Table 2 it results that the variation range of each physical characteristic of the Bahlui clay is similar with those for the Addis Ababa clay -Ethiopia followed by the London clay – U.K.; Dharwad clay – India; New Yorkshire clay – U.K.; Ankara clay – Turkey and Weald clay – U.K.

Table 2. Characteristic geotechnical values of expansive clays

S. no.	Representative clays	Geotechnical characteristics					References
		w_L [%]	w_P [%]	I_P [%]	$A_{2\mu}$[%]	A [%]	
1	Bahlui clay- Romania	83÷98	26÷31	57÷67	51÷87	0.77÷1.12	[4]
2	London clay – U.K.	60÷95	24÷30	36÷65	42÷64	0.67÷1.25	[5,6,7,8]
3	Weald clay–U.K.	41÷82	18÷31	21÷51	38÷74	0.6÷0.7	[8,9,10]
4	New Yorkshire clay – U.K.	53÷70	20÷29	29÷41	41÷70	0.46÷0.72	[11]
5	Ankara clay - Turkey	64÷75	25÷43	29÷34	39÷55	056÷0.94	[12]
6	Addis Ababa clay - Ethiopia	100÷105	40÷43	58÷65	57÷76	0.42÷0.56	[13]
7	Dharwad clay - India	48.2÷72	10.7÷23.2	35÷45.2	52÷59	0.66÷0.81	[11]

According to the Unified Soil Classification System, the majority of the soil samples were inorganic clays of high plasticity (CH), and highly compressible inorganic silt and organic clays (ML) (Fig. 1a). Based on the Van der Merwe's diagram, all clays exhibit high to very high swell potential (Fig.1b).
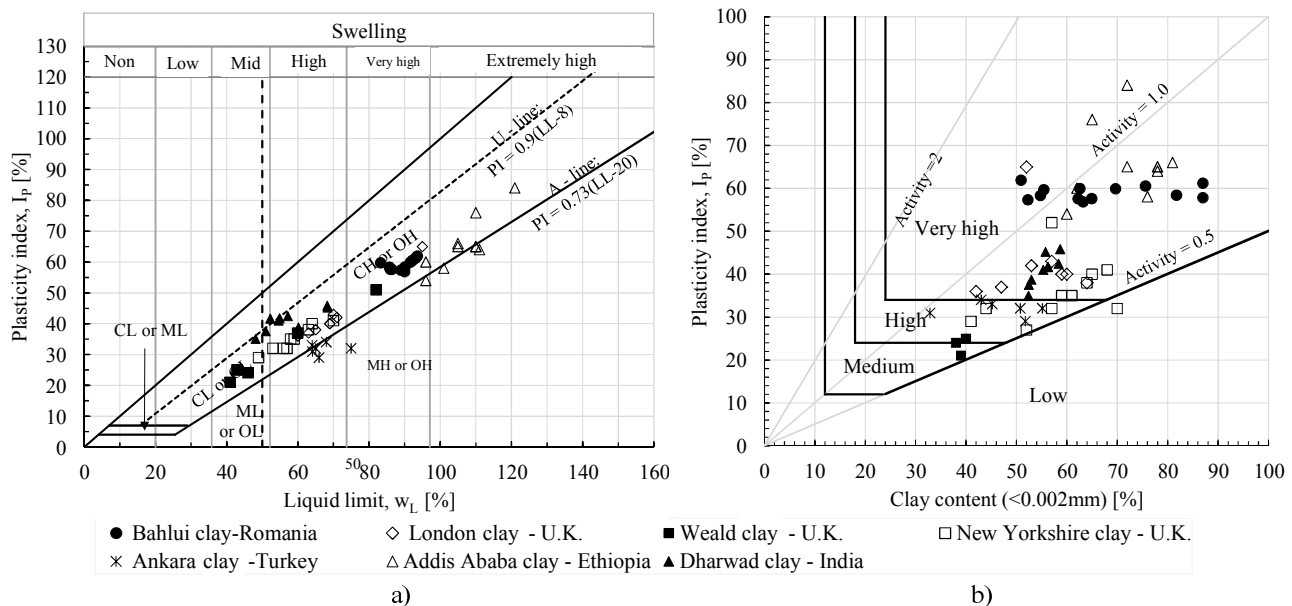

Fig. 1. a) Unified Soil Classification System of the studied clay; and b) identification of swelling potential using the Van der Merwe chart.

Using these clays in natural state for a soil cushion would be inappropriate because of the high swell potential they posse on moisture variation.

Portland cement. The Portland cement (PC) used for this study has the chemical composition given in Table 3 and it was purchased in the regular construction materials market.

Eco-cement. Eco-cement has the chemical composition presented in Table 3 and it is made from a by-product of the production of iron in a blast furnace where iron ore, limestone and coke are heated to about 1500°C [14]. These two types of cement have the same chemical composition, but the proportion of the oxide compounds is different. By consequence, the rate of the eco-cement reaction with water is slower, and Portland cement is used as an activator. In this research work, the two cements, the Portland and the eco-cement are used in equal parts (1:1).

Table 3. The chemical composition of the hydraulic binders used in this research program

Oxide	Portland cement	Eco-cement
CaO	63 %	40 %
SiO_2	20 %	35 %
Al_2O_3	6 %	10 %
MgO	2 %	8 %
Reference	[16]	[14]

Experimental program. The objective of this program is to reduce the swell potential of the Bahlui clay – Romania and to improve the behaviour of the stabilized soil as foundation soil, by analyzing comparatively the effect of the cement percentage increase (using both Portland cement as well as a 1:1 mix, Portland cement and eco-cement) for the chemical stabilization of this clay.

Results and Discussion

The influences of expansive clay Eco cement stabilization on the physical properties. The cement stabilization effect on the physical properties of the Bahlui clay has been studied in these two options (Portland cement stabilization and 1:1 mix of Portland and eco-cement stabilization).

The binder content has been 0%, 2.5%, 5%, 7.5% and 10% of the dry soil mass. The obtained results for the grain size distribution, Atterberg limits and linear shrinkage are presented in Table 4. Diagrams in Figure 2 a ÷ d emphasize the effect of the Portland cement substitution as 50% with eco-cement as mix acting like binder in the Bahlui clay stabilization.

Table 4. The influence of the ecologic/Portland cements on the main geotechnical indices of the Bahlui clay-Romania

S. no.	Mix	w_L [%]	Decrease in w_L [%]	I_P [%]	Decrease in I_P [%]	$A_{2\mu}$ [%]	Decrease in $A_{2\mu}$ [%]	LS [%]	Decrease in LS [%]
1	Natural clay	86.1	-	57.8	-	89	-	20.1	0
2	2.5% (EC+PC) *	86.2	0	41.9	27.51	63	29.21	19.4	3.48
3	5% (EC+PC) *	75.1	12.78	30.4	47.40	55	38.20	14.7	26.87
4	7.5% (EC+PC) *	75	12.89	30.8	46.71	48	46.07	14.3	28.85
5	10% (EC+PC) *	65.6	23.93	22.6	60.90	26	70.79	10.3	48.75
6	2.5% (PC)	88.3	0	52.8	8.65	78	12.36	20.8	0
7	5% (PC)	79.7	7.43	42.1	27.16	51	42.70	16.4	18.41
8	7.5% (PC)	69.6	19.16	25.1	56.57	47	47.19	15.0	25.37
9	10% (PC)	63.2	26.6	22.9	60.38	23	74.16	9.8	51.24

w_L – liquid limit; I_P – plasticity index; $A_{2\mu}$- colloidal clay fraction; LS – linear shrinkage; (*) 50% eco-cement (EC) and 50% Portland cement (PC)
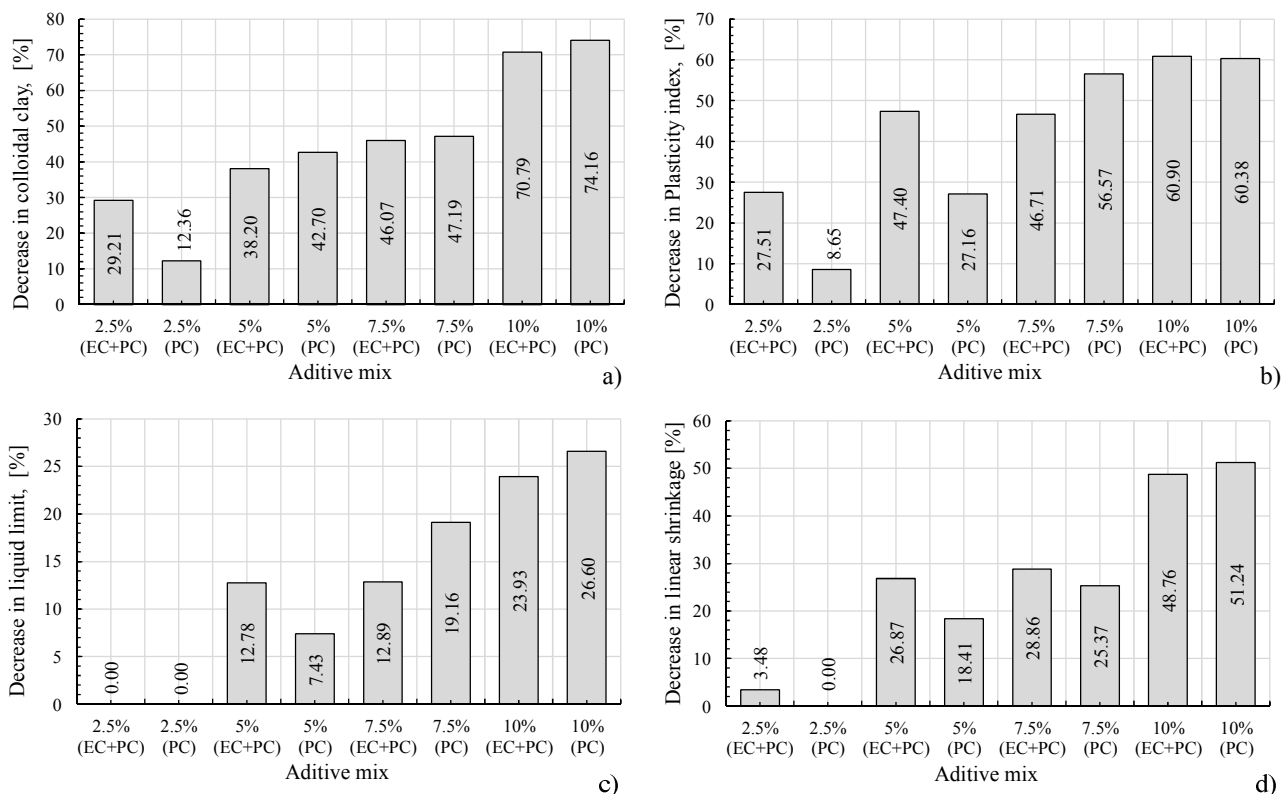

Fig. 2. Variation of the geotechnical indices with the chemical stabilizing agent

Figure 2 a ÷ d presents the percentage decrease of the geotechnical indices: liquid limit (w_L), plasticity index (I_P), colloidal clay fraction ($A_{2\mu}$) and linear shrinkage (LS) with the increase of the PC and PC+EC mix.

The evaluation of the swell potential for the stabilized expansive soil is made indirectly based on the following geotechnical indices: liquid limit, plasticity index, colloidal clay fraction and linear shrinkage. Using this empirical correlation, the Bahlui clay – Romania develops a very high swell potential (Table 5). By the chemical stabilization of the Bahlui clay with Portland cement and 1:1

mix of Portland and ecological cement, the swell potential is constantly decreased with the increase of the cement percentage, from very high for the natural clay to medium for 10% cement (PC or PC+EC mix). Van der Merwe [15] developed the correlation between the swell potential and heave per meter of the expansive (Table 5). Thus, the natural clay would display a heave of 80mm/m while being used as cushion material that can induce degradation for light structures founded on this soil without chemical stabilization. The Bahlui clay would reduce the potential heave from 80mm/m to 40mm/m by chemical stabilization with a binder mix of PC and EC.

Table 5. The swell potential of the stabilized Bahlui clay with Portland and eco-cement

S. no.	Mixes	Swell potential depending on				Heave/meter of soil profile [mm]
		w_L [%]	I_P [%]	$A_{2\mu}$ [%]	LS [%]	
1	Natural clay	High	Very high	Very high	Very high	80
2	2.5% (EC+PC) *	High	Very high	Very high	High	80
3	5% (EC+PC) *	High	High	Very high	Medium	40
4	7.5% (EC+PC) *	High	High	Very high	Medium	40
5	10% (EC+PC) *	High	Medium	Medium	Low	40
6	2.5% (PC)	High	Very high	Very high	High	80
7	5% (PC)	High	Very high	Very high	Medium	40
8	7.5% (PC)	High	High	Very high	Medium	40
9	10% (PC)	High	Medium	Medium	Low	40

References: w_L [17]; I_P [18,19]; $A_{2\mu}$ [20]; LS [21]; Heave/m meter of soil profile [15]

The requirements imposed for the soil cushion as values for the geotechnical indices presented in Table 1, are not fully satisfied by the chemical stabilization with cement (Portland cement (PC) and Eco-cement-Portland cement (EC+PC)). For 10% cement, for both cases of stabilization, with Portland cement and ecological/Portland cement mix, the colloidal clay content and the plasticity index decrease sufficiently to meet the requirements for a soil cushion (Table 1), but the other parameters, plastic limit and liquid limit develop still higher values than the demanded ones for the use of the material in cushion compaction (Table 1 and Table 4).

The influences of expansive clay Eco cement stabilization on the mechanical properties. The value increase of the shear strength parameters with the necessary binder addition for chemical stabilization can be designated to the initiated cation exchange by the chemical composition of the Portland and ecological cements. Clays consisting predominantly of montmorillonite present a residual internal friction angle decreasing with the increase of the liquid limit, approximated by the following function [22]:

$$\tan \phi_r = 22.26 \cdot w_L^{-1.094} \tag{1}$$

where: Φ_r is the predicted value of the residual internal friction angle, w_L – the liquid limit of the investigated clay (the correlation coefficient is R =0.837 and it was determined using 142 soil samples). Using this correlation for the Bahlui clay both natural and stabilized with cement (PC and PC+EC mix) one can notice (Table 6) an increase of the residual internal friction angle with the increase of the utilized cement. For percentages of 7.5% and 10% of PC, the stabilized clay will display higher values of the residual internal friction angle, by comparison with the PC+EC binder mix.

Regarding the compressibility determined by oedometer laboratory tests and following the value of the compressibility index (C_c - Table 6), the natural Bahlui clay displays a high compressibility (C_c>0.4), while by stabilization with 10 % cement PC and PC+EC mix the compressibility decrease to medium (C_c=0.2÷0.4).

Table 6. The mechanical properties of the stabilized Bahlui clay with cement (PC and EC+PC)

S. no.	Parameters	Natural clay	(EC+PC) stabilization				PC stabilization			
			2.5%	5%	7.5%	10%	2.5%	5%	7.5%	10%
1	Φ_r [^{0}]	9.65	9.64	11.17	11.19	12.9	9.39	10.48	12.11	13.41
2	C_c	0.573	0.54	0.457	0.424	0.385	0.552	0.498	0.456	0.399

Φ_r - residual friction angle; C_c – compression index; EC – eco-cement; PC- Portland cement

Swelling properties of treated expansive soil. The literature presents correlation techniques of the geotechnical properties indices to obtain an estimation of the swell potential S and the swell pressure P_s [19].

Eq. 2 is proposed for the swell pressure and Eq. 3 for the swell potential, both obtained by the method of least squares applied on the results from the laboratory tests, with a very high coefficient of correlation, R, of the fitted regression lines (R>0.8) [23]:

$$P_S = (6.9820 \cdot 10^{-4}) \cdot (I_p)^{1.92} \cdot \frac{A_{2\mu}^2}{w_i^2} + 9.1191 \tag{2}$$

where: P_S is the predicted value of the swell potential in psi, utilizing the initial value of the moisture content for the soil sample, w_i.

$$S = (4.4938 \cdot 10^{-3}) \cdot (I_p)^{1.74} \cdot \frac{A_{2\mu}}{w_i} + 14.722 \tag{3}$$

in which: S is the predicted value of the swell potential, expressed as percentage, using the natural moisture content of the soil sample w_i.

The predicted swell pressure for the natural Bahlui clay using the equation (2) resulted in P_s = 177.85 kPa, which is approximately the same value obtained by oedometer tests performed according to ASTM D 4546-90, method A, P_s = 187kPa.

The swell pressure and swell potential values for the stabilized Bahlui clay with 2.5% ÷ 10% PC and PC+EC mix are presented in Table 7.

The 75% decrease of the swell pressure (P_s) (Table 7) for only 2.5% EC+PC cement mix or just PC, continues at a smaller rate with the increase of cement participation to the stabilization process, recording decreases up to 10% for 10% cement percentage.

Table 7. The swelling potential of the stabilized Bahlui clay with Portland and eco-cement

S. no.	Mixes	Swell potential (S) [%]	Decrease in swell potential [%]	Swell pressure (P_s) [kPa]	Decrease in swell pressure [%]
1	Natural clay	31.16465	-	177.85	-
2	2.5% (EC+PC) *	18.97018	39.12917	75.55118	57.51973
3	5% (EC+PC) *	16.82514	46.01208	67.99937	61.7659
4	7.5% (EC+PC) *	16.62094	46.66733	66.96804	62.34578
5	10% (EC+PC) *	15.33897	50.78085	63.57446	64.25389
6	2.5% (PC)	24.53638	21.26854	110.0464	38.12403
7	5% (PC)	18.80752	39.65112	74.51216	58.10394
8	7.5% (PC)	16.01555	48.60987	65.48824	63.17783
9	10% (PC)	15.31787	50.84858	63.51405	64.28786

S - Swell potential; P_s - Swell pressure kPa; (*) 50% eco-cement (EC)+50% Portland cement (PC)

The initial moisture content of the soil (w_i) plays an important role in the estimation of the swell pressure. In Figure 4 a ÷ d the variations of the swell pressure and swell potential are presented depending on the natural moisture content of the soil.
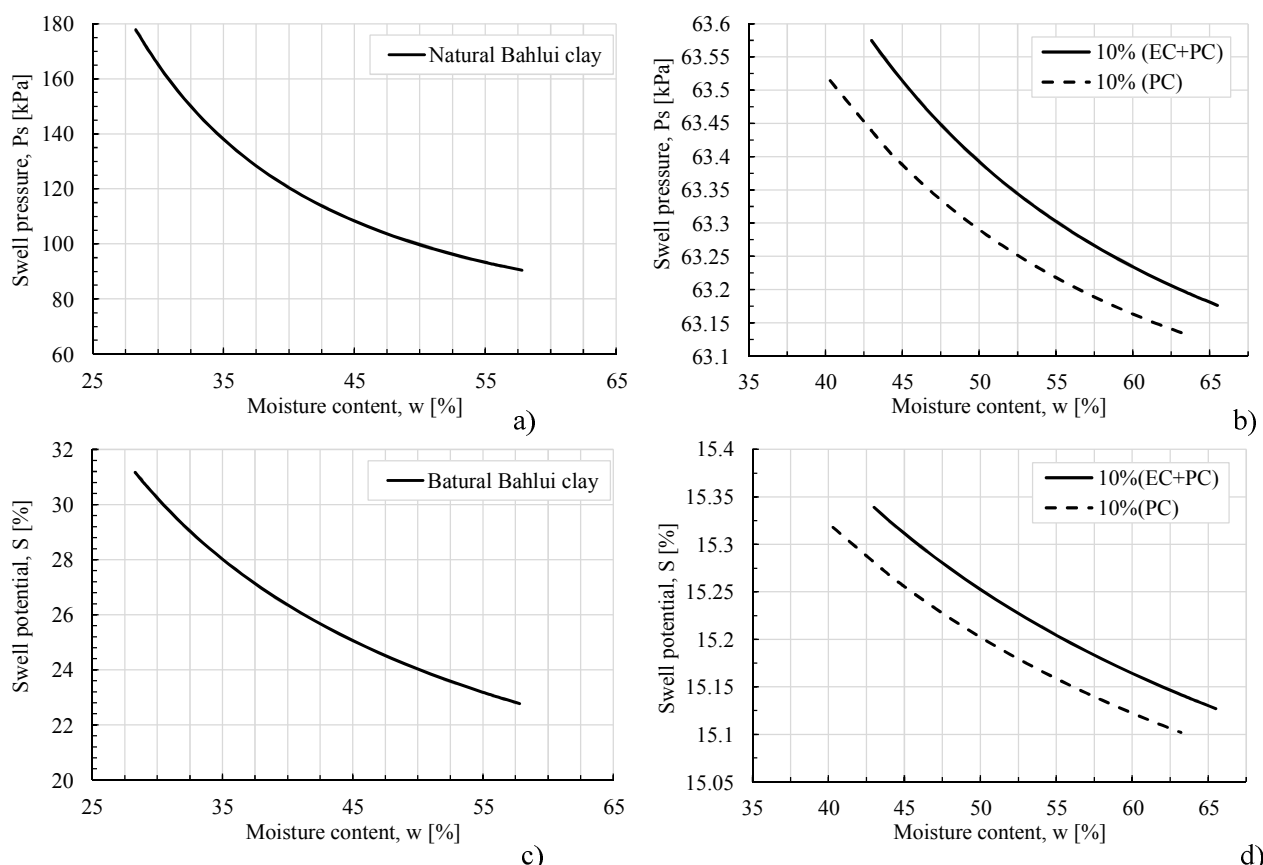
Fig. 3. Variations of a), b) swelling pressure and c), d) swelling potential, with the moisture content, for the Bahlui clay - Romania

Conclusions

The Bahlui clay – Romania is spread on a relatively large zone within the city of Iasi area. Founding construction on this clay as well as its utilization as material for soil cushions required the necessity to develop an extensive research program to obtain its main physical and mechanical properties. This research work performed by the authors classified this clay as being an expansive one, similar with other representative clays in the world (Addis Ababa clay – Ethiopia, London clay – U.K.; Dharwad clay –India; New Yorkshire clay – U.K.; Ankara clay – Turkey and the Weald clay from the U.K.). The Bahlui clay has been investigated to build without any structural risk exposure, establishing its behaviour and potential improvement based on the physical and mechanical characteristics, by chemical stabilization with Portland cement or cement mix, Portland and eco-cement. It is noted based on the laboratory test results that stabilization by 10% cement (PC and PC+EC mix) reduces the swell potential from very high to medium.

The very high swell pressure of the natural Bahlui clay (177.85kPa) decreases as well by 57.52% for only 2.5% cement (PC+EC mix) and with only 38.12% for 2.5% stabilization with Portland cement (PC). The influence of the eco-cement participation in the binder mix utilized in the stabilization is more pronounced at small values (up to 2.5%) while the increase from 2.5% to 10% cement is not providing significant decreases of the swell pressure and swell potential. The partial substitution of the Portland cement with eco-cement lead to a significant influence on the environment protection by consequence of the reduction of non-renewable resources and CO_2 emissions resulted from the manufacturing process.

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