INFLUENȚA CENUȘII PROVENITE DIN ȘISTURI BITUMINOASE ASUPRA CARACTERISTICILOR ARGILELOR BRUNE NISIPOS-PRĂFOASE STABILIZATE

THE INFLUENCE OF BITUMINOUS OIL SHALE ASHES ON THE CHARACTERISTICS OF STABILIZED SILTY-SANDY BROWN CLAYS

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The western part of Amman, the capital of Jordan, holds a layer of 4 to 5 meters depth of problematic brown clay that exhibits a wide range of plasticity, swelling, settlements and low shear resistance. On the other hand, south Jordan holds large deposits of bituminous oil shale that extend to considerable depths. The government of Jordan has decided to start using the bituminous oil shale for power generation and oil production resulting large amounts of ash. This research work studies the effect of bituminous oil shale ash, rich in lime, on the characteristics of the silty-sandy brown clay that spreads on large areas in the middle and northern areas of Jordan. The oil shale ash has been mixed with brown clay in different percentages and some geotechnical parameters of the resulted mixtures have been measured and analysed. The outcomes of this work show that there is a significant effect of the bituminous oil shale ash on reducing the plasticity index of the mixture, on decreasing its dry unit weight, as well as on increasing its compressive strength and permeability to a certain percentage of added ash. In addition, the mixture has a positive effect on reducing the compression index (Cc) and the swelling index (Cs) of brown silty-sandy clays.

Vestul orașului Amman, capitala Iordaniei, prezintă o stratificație de 4 până la 5 metri în adâncime de argilă brună care este considerată un teren dificil de fundare datorită variațiilor mari de plasticitate și de umflare-contracție, precum și a tasărilor diferențiate, având o capacitate portantă scăzută. Pe de altă parte, sudul Iordaniei dispune de depozite impresionante de șisturi bituminoase care se extind până la adâncimi considerabile. Guvernul iordanian a dat startul utilizării șisturilor bituminoase pentru producerea curentului electric și a petrolului rezultând cantități importante de cenușă. În această lucrare de cercetare se analizează efectul cenușii provenite din şisturi bituminoase, cenuşă bogată în var, asupra comportării argilei brune prăfos-nisipoase care ocupă zone întinse în centrul și nordul Iordaniei. Cenușa provenită din șisturile bituminoase a fost amestecată cu argilă brună, în diferite procente, analizându-se parametrii geotehnici ai amestecurilor obținute. Rezultatele arată efectul semnificativ de reducere a indicelui de plasticitate și a greutății specifice pe care cenușa provenită din șisturile bituminoase îl are asupra amestecului, precum şi creşterea rezistenței la compresiune și a permeabilității până la un anumit procent de adaos. În ceea ce privește compresibilitatea, amestecul are un efect pozitiv în reducerea indicelui de compresiune (Cc) și al celui de umflare (Cs) ale argilei brune nisipos-prăfoase.

Keywords: *bituminous oil shale ash, silty-sandy brown clay, plasticity index, compressive strength.*

1. Introduction

The design of new pavements or the reconstruction of the existing ones to facilitate the quick increase of vehicles weight and traffic requires relatively low-cost solutions such as using materials with moderate or weak engineering and physical characteristics [1, 2]. The soil stabilization method by treating natural soils and aggregates with additives to obtain properties according to the appropriate standard specifications is the most commonly employed method aiming to increase the physical and mechanical properties of soils [3 - 5]. In this research work, the authors investigate several geotechnical properties of the expansive silty-sandy brown clay collected from Madaba area, near Amman City, to predict the effect of oil shale ash stabilization on its characteristics.

The term of oil shale refers to Jordanian lithologic bituminous limestones and marls [6]. The Jordanian oil-shale deposits are marinites of Late Cretaceous (Maastrichtian) to early Tertiary age when Jordan was closed to the southern margin of Neo-Tethys Ocean and the sedimentation happened on a broad shallow shelf [7] bringing a thick sequence of chalks, marls and limestones over the northern and central areas of Jordan [8].

Jordanian oil shale is usually brown, grey or black weathering to a distinctive light bluish-grey. It consists of unconsolidated gravel and silt with some stringers of marlstone and limestone as well as basalt in isolated areas [8]. Among the 26

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known Jordanian deposits of oil shale totalizing more than 4 billion tonnes, the most important eight are in west central Jordan within 20 to 75 km east of the Dead Sea in the marine Chalk-Marl unit (Fig.1), which is underlain by phosphatic limestone and chert of the Phosphorite unit [9].

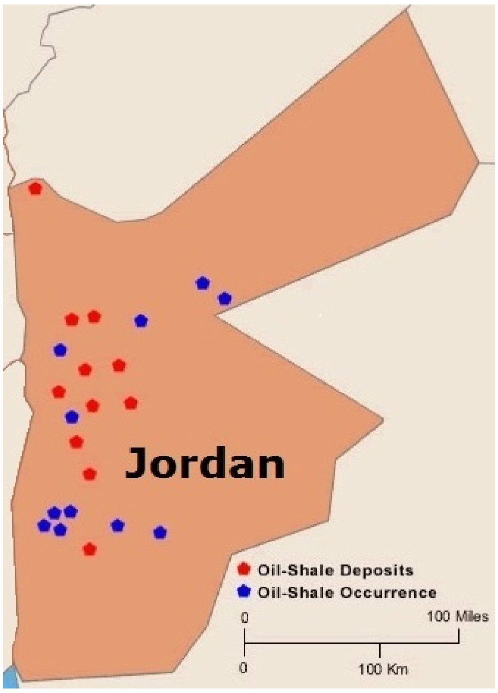

Fig.1 - Map of oil shale deposits in Jordan, locations after Jaber and others, 1997; and Hamarneh, 1998 (after the reprint of: United States Geological Survey Scientific Investigations Report 2005-5294 by John R. Dyni)/ *Harta depozitelor de şisturi bituminoase în Iordania, locaţii stabilite de Jaber ş.a., 1997; Hamarneh, 1998 (după United States Geological Survey Scientific Investigations Report 2005-5294, autor: John R. Dyni).*

The government of Jordan decided to start burning the bituminous limestone for power production purposes as about 80 billion tons of such stockpiles are distributed in the southern part of the country so that large amounts of fly ash are expected to be generated from this process [10]. This waste has complex characteristics and composition so that its safe management and disposal is also intricate and complex. The disposal and storage of oil shale ashes without treatment leads to surface and groundwater contamination and disturbs the environmental balance [11]. Therefore, finding methods and techniques so that to use the bituminous oil shale ash for several geotechnical engineering purposes [12] would have a significant impact on the environment. The solution of this problem may be achieved through the utilization of the oil shale ash as a building material in different civil engineering and infrastructural projects and several research scientists have reported the influences of the addition of fly ash on soil properties [13, 14].

Soils in the vicinity of Amman City are formed by the breaking up of the Cretaceous bedrock that inserted the nodules of soft calcium carbonate in the brown silty clay [9]. The upper 2m layer consists of soft to stiff fissured silty clay dark to greyish brown with pebbles, cobbles and boulders of chert and limestone [9] with high shrinkage and swelling characteristics causing severe damage to civil engineering structures whose geotechnical properties are investigated to predict the effect of oil shale ash on the stabilized mix.

Expansive brown silty-sandy clays derived mainly from marl, limestone and chert bedrocks formed during the Cretaceous Age, spread over 40% of the area located in the central part of the country, in the vicinity of west Amman City [7, 15, 16]. This clay is a problematic soil as it exhibits excessive differential settlements and deformations while its swelling and shrinkage potential affected by mineralogical constituents and surrounding environment induces building cracks [17].

The smectite, which is the main component of the sandy-silty brown clay [8], is responsible for the volume change and shear failure. A while back, lime was utilised as an additive for soil stabilization to improve the plasticity behaviour and increase the workability level of the treated soil. Although the hydrated lime proved safe, effective, and easy to mix with water [18], it is already proved that mixing fly ash with any expansive clay similarly results in improving the engineering properties of the stabilized product [19]. The improvement develops in respect with:

1) A good effect on the plasticity and compressibility of the expansive soil determined by the compression index (Cc), which describes the variation of the void ratio according to effective stresses [20] and by the rich content of lime in the fly ash [21].

2) A decrease in permeability with the increase in ash content [22].

The calcium content is different for various types of fly ash, and even though the greater part of ashes has particular effects on the treated soil [23], there is no ash able to improve all physical and mechanical properties of a certain soil. Extensive research has been performed on the effect of the fly ash on compressibility, but the optimal percentage of the stabilizing ash is still unclear. The objective of this paper is to use different percentages of bituminous oil shale ash by weight to improve the engineering behaviour of the problematic silty-sandy brown clay, especially for pavement foundation, by controlling its compressibility, permeability and compressive strength during the stabilization processes [24].

Oil shale is the most abundant fossil energy resource discovered in Jordan; in terms of oil shale reserves, Jordan is ranked immediately after the USA and Brazil. The Jordanian reserves of oil shale are huge and sufficient to satisfy the national energy needs for hundreds of years. The burnt oil shale produces ash that usually can be utilised as additives for cement and other building materials [25]. However, it is well known the fact that some ashes can stabilize clays. Expansive brown silty-sandy clays spread in the central part of the country, in the vicinity of Amman City, induce differential settlements and deformations causing cracks of the building elements. The current study summarizes the test results and discusses the optimum percentage of oil shale ash that can be used to improve the stabilization process of brown clays in Jordan, minimising the cost of cement-like materials and reducing the residual deposits of ash for a safe built environment.

Fig. 2 - Location of silty-sandy brown clay about 30 km South of Amman and Al-lajjun deposit of bituminous oil shale (after "Al-lajjun Oil Shale Project" – Jordan Energy and Mining Limited)/ *Localizarea argilei brune prăfos-nisiopase la circa 30 km sud de Amman şi a depozitului de şisturi bituminoase Al-lajjun (conform "Al-lajjun Oil Shale Project" – Jordan Energy and Mining Limited).*

2. Materials and methods

2.1. Materials

2.1.1. Bituminous oil shale ash

The bituminous limestone has been collected from the surface or near-surface deposits located in Al-lajjun area, South of Karak City, the Jordanian most extensively explored deposit (Fig. 2), and burned at 950^o C in the laboratories of the American University of Madaba, Jordan. The chemical components of the by-product are given in Table 1 [26]. The outcome shows that the resulted ash contains considerable amounts of lime, calcium oxide, and many pozollanic materials such as silica and iron oxide with an apparent specific gravity of 2.70 g/cm^3. The major mineral components of the El Lajjun oil shale are calcite, quartz, kaolinite, apatite, along with small amounts of feldspar, illite, dolomite, goethite, pyrite, and gypsum. The sulfur content of Jordanian oil shale usually ranges from 0.3 to 4.3 percent, but it was found larger on the tested site [10].

The specific surface area for ash: Initially, the surface area of oil shale ash combusted at 550 °C increased to about 2.5 times compared to that of the raw oil shale sample, from 12 m^2/g to 29 m^2/g [27], which can be explained by the opening of new pores due to the devolatilisation combustion of organic matter. A further increase of combustion temperature to 950 °C results in a decrease of the surface area with values below those of raw sample. This demonstrates that sintering of oil shale ash may have started beyond 600 °C, giving a significant reduction in surface area, i.e. 7 m^2/g over this temperature [27].

2.1.2. Brown clay

Disturbed samples of silty-sandy brown clays have been undertaken from a shallow borehole of 1 m depth from the vicinity of the campus of The American University of Madaba, about 30 km south of Amman City that is the most developed area in the country facing many geotechnical issues as building cracks and damages (Fig. 2). The samples taken from this area were prepared in the University's laboratory for testing their main physical and mechanical properties as well as the effect of oil shale ash stabilizer on these properties.

Table 1

Chemical composition of the bituminous oil shale ash/ *Compoziţia chimică a cenuşii provenite din bituminoase [26]*

Oxide/ *Oxid*	SiO_2	Fe_2O_3	Al_2O_3	CaO	K_2O	MgO	P_2O_5	SO_3
Percentage/ *Procentaj* [%]	32	3.15	1.45	46.3	1.47	2.46	5.62	5.78

Table 2

Physical properties of silty-sandy brown clay / *Proprietățile fizice ale argilei brune nisipos-prăfoase*

Parameter/ Parametru	**Value/ Valoare**
Liquid limit/ *Limita de curgere* [%]	56
Plastic limit/ *Limita de plasticitate* [%]	32
Plasticity index/ *Indicele de plasticitate* [%]	24
Max. compacted dry density/ *Greutatea volumică maximă în stare uscată compactată* [kN/m^3]	15.1
Clay fraction/ *Fracţiunea de argilă* [%]	22
Apparent specific gravity/ *Densitatea aparentă* [g/cm^3]	2.61
Sample classification/ *Clasificarea probelor* (USCS)	CL

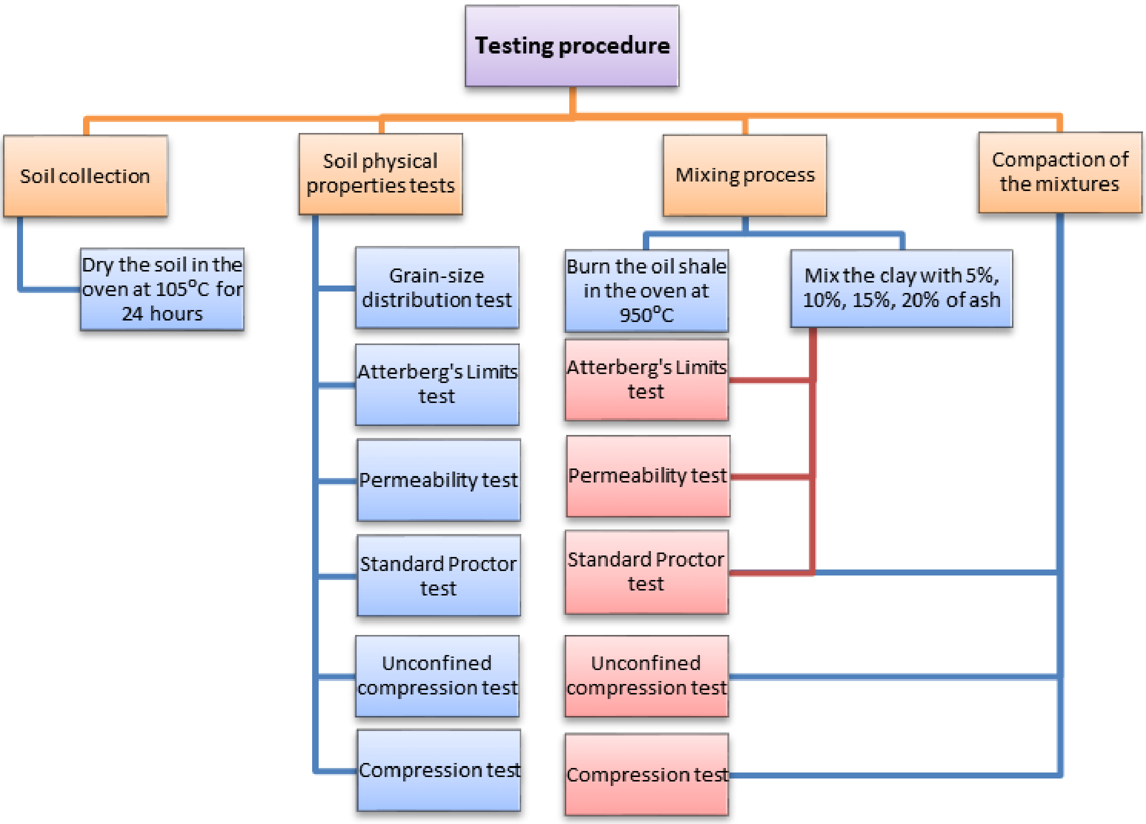

Fig.3 - Testing procedure/ *Procedura de încercare.*

Table 2 shows the physical properties of unstabilized silty-sandy brown clay.

2.2. Methods

The purpose of the bituminous oil shale ash addition in different percentages (5%, 10%, 15%, 20%) to brown silty-sandy clays is to identify its influence on the geotechnical properties of the mixed soil minimizing the plasticity index and increasing its permeability.

Tests were carried out to determine the geotechnical properties of the brown silty-sandy clay.

2.2.1. Grain-size distribution curve

After conducting the sieve analysis test of the silty-sandy brown clay according to ASTM C136/C136M-14 [28], the particle-size distribution curve has been obtained, as shown in Figure 4.

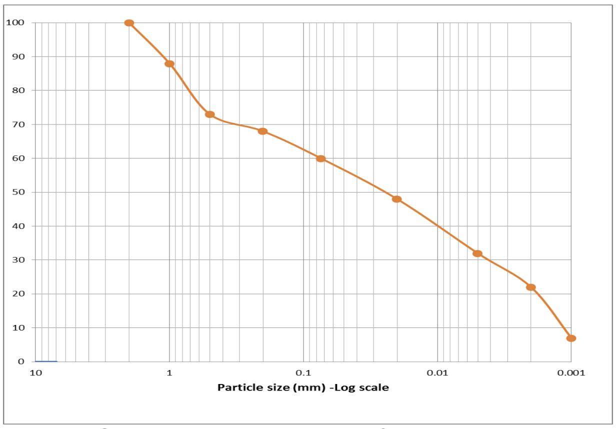

Fig. 4 – Grain-size distribution curve of the silty-sandy brown clay / Curba granulometrică a argilei brune nisipos-pufoase.

2.2.2. Atterberg Limits

Liquid limit (LL) and plastic limit (PL) tests have been performed for the determination of soil plasticity of the clay sample passing sieve #40 mixed with different percentages of fly ash. Casagrande device serves for the liquid limit test while the hand rolling method determines the plastic limit. Both tests use distilled water. The Plasticity Index (PI) of the brown clay is 25%. Hence, the difference between the liquid limit and the plastic limit is equal to 15%. Results in Figure 5 show a 7% decrease in the plasticity index at 20%

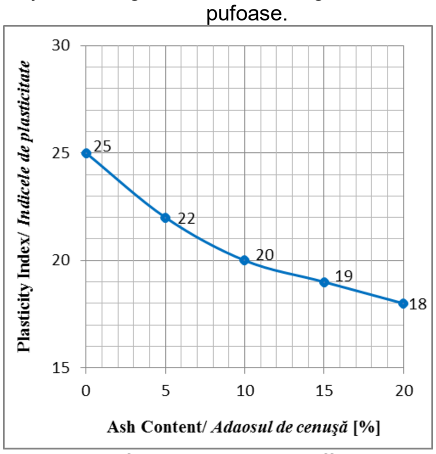

Fig. 5 - Variation of plasticity index at different added ash percentages/ *Variația indicelui de plasticitate pentru diferite procente de adaos de cenușă.*

Table 3

Maximum dry unit weight and optimum moisture content of brown clay with different oil shale ash percentages/ *Greutatea specifică maximă în stare uscată şi umiditatea optimă de compactare ale argilei brune cu diferite procente de adaos de cenuşă provenită din şisturi bituminoase*

Sample/ Probă	Maximum Dry Unit Weight/ *Greutatea specifică maximă în stare uscată* [kN/m^3]	Optimum Moisture Content/ *Umiditatea optimă de compactare* [%]
Brown clay/ *Argilă brună*	15.1	26
Brown clay with 5% oil shale ash/ *Argilă brună cu adaos de 5% cenuşă provenită din şisturi bituminoase*	14.7	28
Brown clay with 10% oil shale ash/ *Argilă brună cu adaos de 10% cenuşă provenită din şisturi bituminoase*	14.3	31
Brown clay with 15% oil shale ash/ *Argilă brună cu adaos de 15% cenuşă provenită din şisturi bituminoase*	14.1	33
Brown clay with 20% oil shale ash/ *Argilă brună cu adaos de 20% cenuşă provenită din şisturi bituminoase*	13.8	34

added oil shale ash. This is mainly due to the reduction in the liquid limit and a slight increase in the plastic limit [29].

2.2.3. Compaction test

Standard compaction tests using the Proctor apparatus and added water have been performed to determine the maximum dry density (MDD) and optimum moisture content (OMC) of brown silty-clay and of brown silty-clay mixed with different percentages of oil shale ash (5%, 10%, 15% and 20%, respectively). The additive content, expressed as percentage, is defined by the ratio of the dry weight of the additive to the dry weight of the natural clayey soil. Samples having the same percentage of oil shale ash were repeatedly used (remolded) for compaction at different moisture contents. The material was thoroughly mixed to achieve uniform mixing of water before compacting in the mould and tests were carried out using the equipment and procedure as specified in ASTM D698 for Proctor test [30]. Accordingly, the uniform stabilized soil admixture was transferred to a cylindrical mould and compacted in three equal

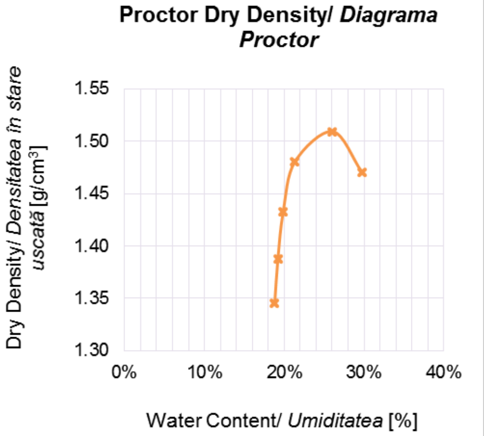

Fig. 6a - Compaction curve for brown clay/ *Curba de compactare pentru argila brună.*

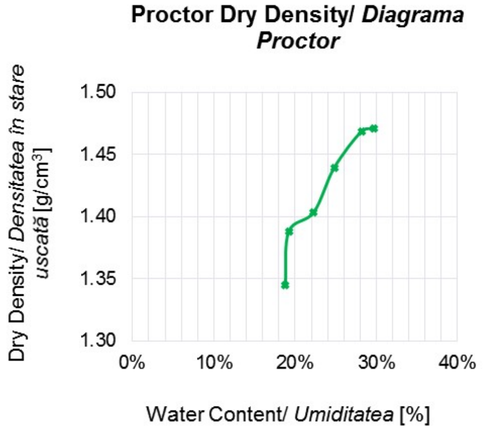

Fig. 6b - Compaction curve for brown clay with 5% oil shale ash/ *Curba de compactare pentru argila brună cu adaos de 5% cenuşă provenită din şisturi bituminoase.*

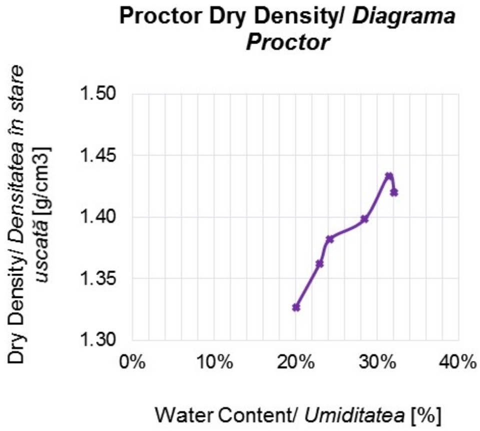

Fig. 6c - Compaction curve for brown clay with 10% oil shale ash/ *Curba de compactare pentru argila brună cu adaos de 10% cenuşă provenită din şisturi bituminoase.*

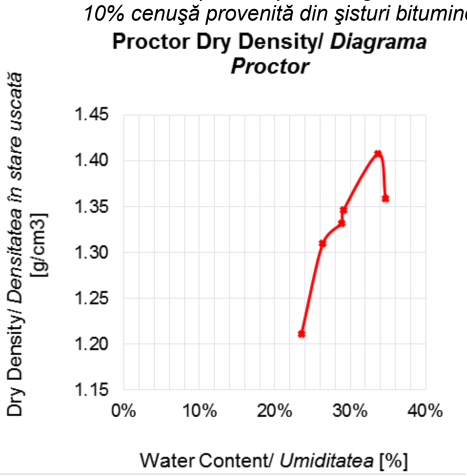

Fig. 6d - Compaction curve for brown clay with 15% oil shale ash/ *Curba de compactare pentru argila brună cu adaos de 15% cenuşă provenită din şisturi bituminoase.*

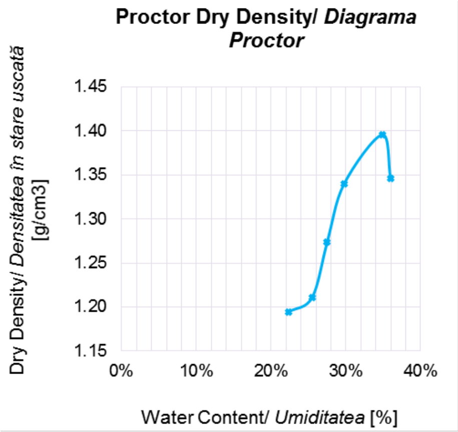

Fig. 6e - Compaction curve for brown clay with 20% oil shale ash/ *Curba de compactare pentru argila brună cu adaos de 20% cenuşă provenită din şisturi bituminoase.*

layers. Table 3 shows the complete results of the compaction test. Typical compaction curves of these tests are illustrated in Figures 6 a to e.

The effect of increasing the fly ash content on the coefficient of consolidation, compression index [31], permeability [32], and preconsolidation pressure were also investigated [33].

Five samples were prepared by compacting the clay and the clay with oil shale ash in the Proctor standard mould at the maximum density and optimum moisture content and were cured inside a tight plastic bag for one week before subjected to a falling head permeability test. The complete results of this test are illustrated in Figure 7.

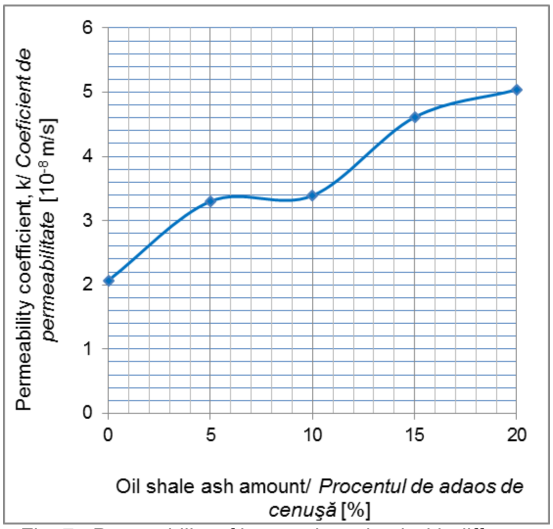

Fig. 7 - Permeability of brown clay mixed with different percentages of oil shale ash/ *Permeabilitatea argilei brune amestecate cu diferite procente de cenusă provenită din şisturi bituminoase.*

2.2.4. Permeability test

Even though the plasticity index increases with the percentage of oil shale ash, also specific to normally consolidated conditions, the maximum allowable value of the permeability coefficient, k_{all}, for sandy clays of low plasticity (CL) is 5 x 10^{-8} m/s, similarly to the initial brown sandy-clay analysed in this study. Consequently, a percentage of 15% of oil shale ash is acceptable, ranging the mixture in the Moderate to Slow zone (Fig. 8), like the initial brown sandy-clay for which the permeability coefficient, *k,* is less than k_{all}. However, specific conditions for some engineering problems often need to be considered for an appropriate choice of geotechnical parameters.

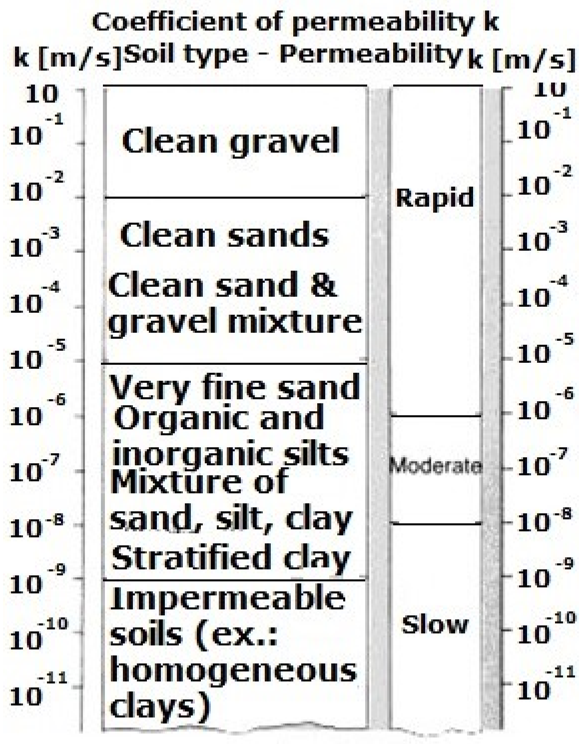

Fig.8 - Classification of the coefficient of permeability/ *Clasificarea coeficientului de permeabilitate [34].*

2.2.5. Unconfined compression test

Samples of brown clay mixed with different percentages of oil shale ash were compacted in a small mould at the maximum dry density and optimum moisture content. They were prepared in laboratory and self-cured in tight plastic bags for 7 and 21 days [35].

The samples sizes were 100mm length and 50mm diameter. The results are illustrated in Figures 9 a and b.

2.2.6. Consolidation test

Several one-dimensional consolidation tests were performed according to ASTM D2435/ D2435M [36] provisions to analyse the effect of oil shale ash on the brown clay. Different samples of brown clay and brown clay with various percentages of oil shale ash in the range of 5%-20% by weight, were prepared. The clay was disturbed and all the samples passed the sieve #100. All the saturated samples were subjected to an effective stress of 50 kPa up to 800 kPa, immediately followed by un–loading process for two consecutive readings. The results of these tests are shown in Figures 10 a to e, while Table 4

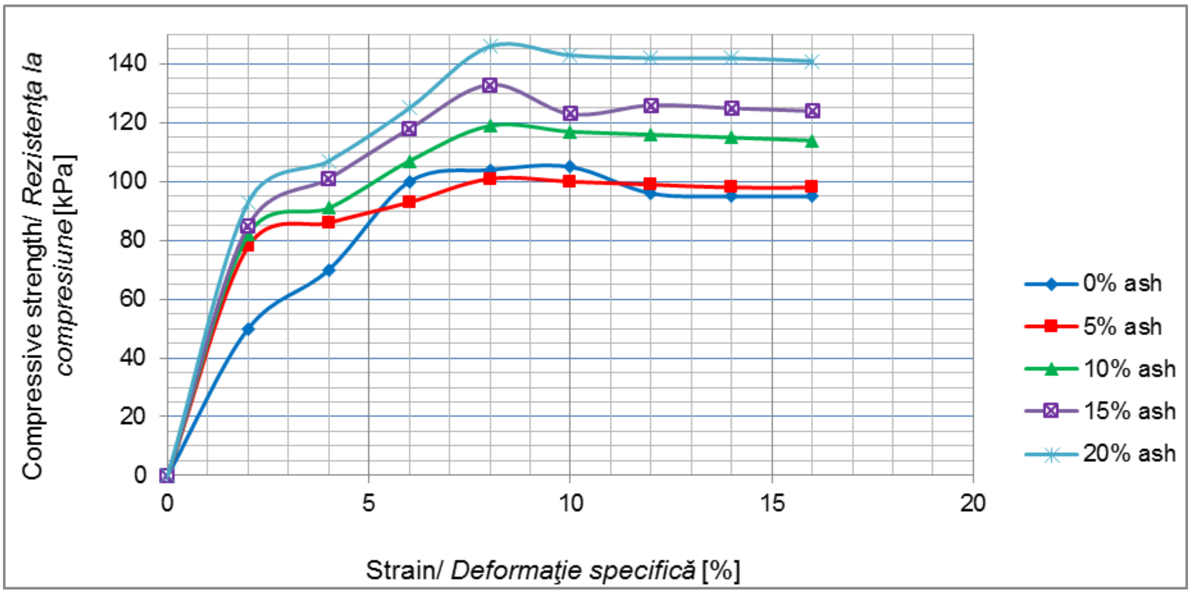

Fig. 9a - Unconfined compressive strength of the brown clay mixed with different percentages of oil shale ash at age of 7 days/ *Rezistenţa la compresiune monoaxială a argilei brune amestecate cu diferite procente de cenușă provenită din şisturi bituminoase, determinată la 7 zile.*

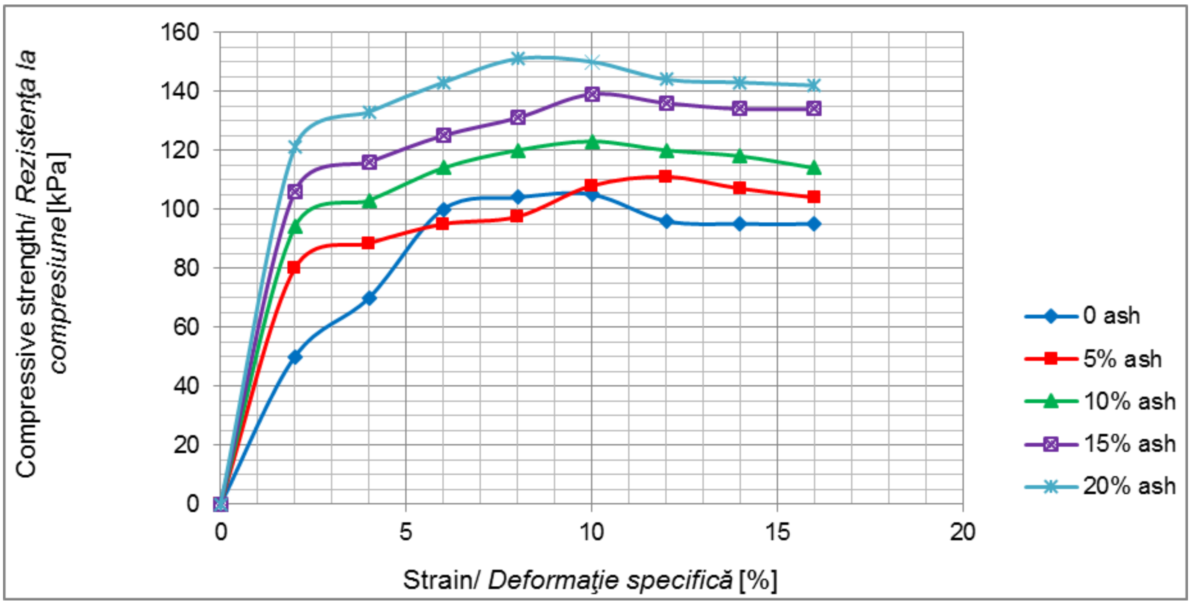

Fig. 9b - Unconfined compressive strength of the brown clay mixed with different percentages of oil shale ash at age of 21 days/ *Rezistenţa la compresiune monoaxială a argilei brune amestecate cu diferite procente de cenușă provenită din şisturi bituminoase, determinată la 21 zile.*

Table 4

Compression index and swelling index of brown clay with different oil shale ash percentage/ *Indicele de compresiune şi indicele de umflare ai argilei brune cu diferite procente de adaos de cenuşă provenită din şisturi bituminoase*

Sample/ Probă	**Compression Index/ *Indicele de compresiune* (Cc)**	**Swelling Index/ *Indicele de umflare* (Cs)**
Brown clay/ *Argilă brună*	0.233	0.014
Brown clay with 5% oil shale ash/ *Argilă brună cu adaos de 5% cenusă provenită din şisturi bituminoase*	0.171	0.010
Brown clay with 10% oil shale ash/ *Argilă brună cu adaos de 10% cenusă provenită din şisturi bituminoase*	0.142	0.007
Brown clay with 15% oil shale ash/ *Argilă brună cu adaos de 15% cenusă provenită din şisturi bituminoase*	0.131	0.0031
Brown clay with 20% oil shale ash/ *Argilă brună cu adaos de 20% cenusă provenită din şisturi bituminoase*	0.122	0.0014

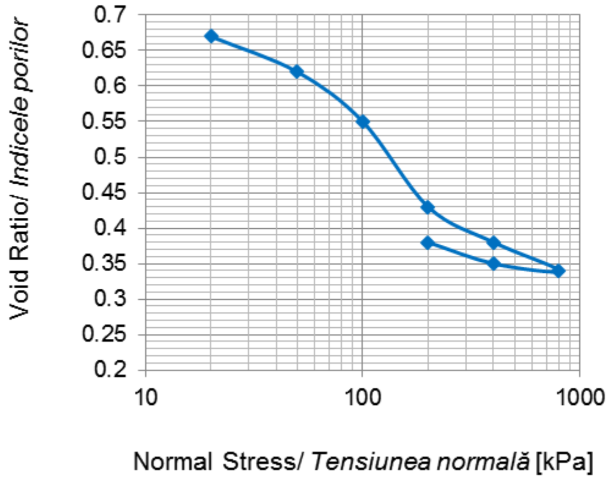

Fig. 10a - Consolidation curve of clay without bituminous oil shale ash/ *Curba de consolidare a argilei brune.*

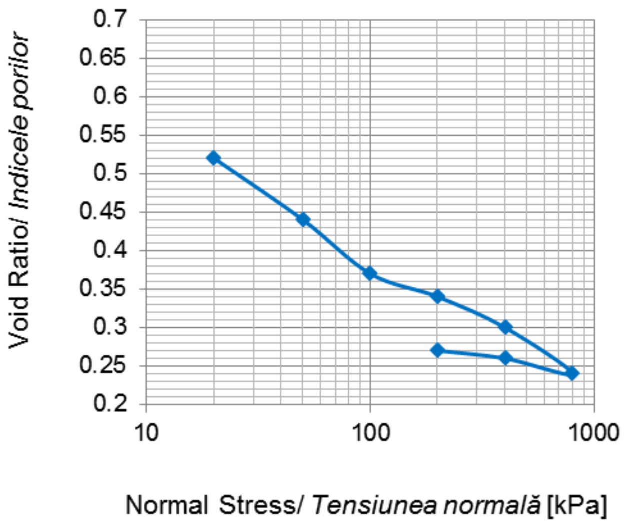

Fig. 10b - Consolidation curve of clay with 5% ash/ *Curba de consolidare a argilei brune cu adaos de 5% cenuşă provenită din şisturi bituminoase.*

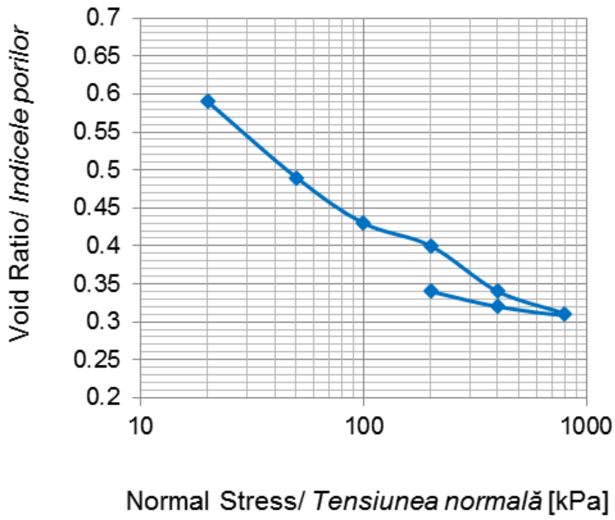

Fig. 10c - Consolidation curve of clay with 10% ash/ *Curba de consolidare a argilei brune cu adaos de 10% cenuşă provenită din şisturi bituminoase.*

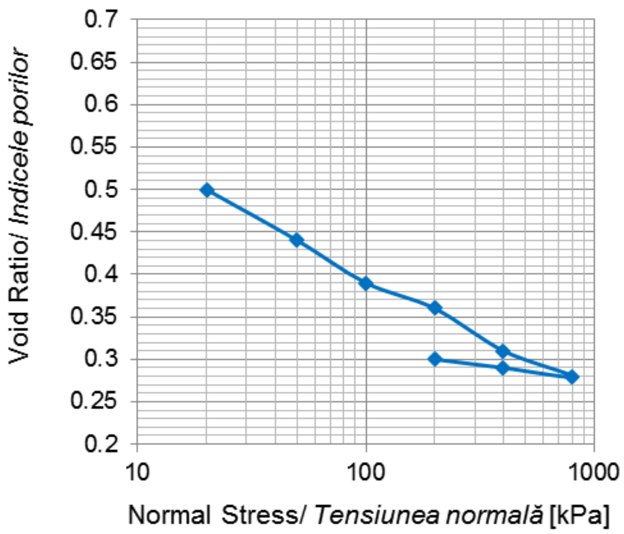

Fig. 10d - Consolidation curve of clay with 15% ash/ *Curba de consolidare a argilei brune cu adaos de 15% cenuşă provenită din şisturi bituminoase.*

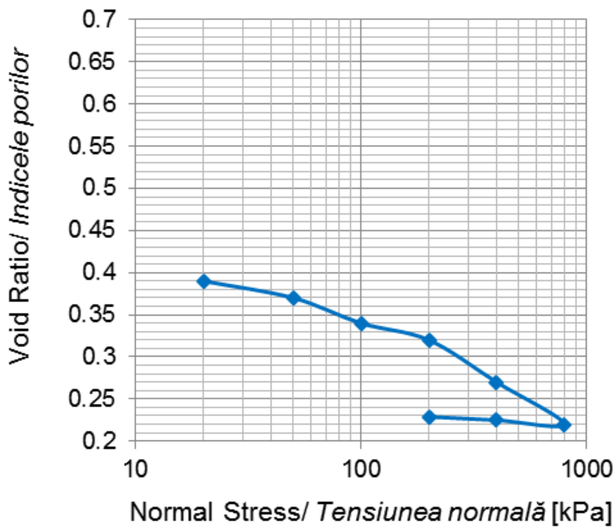

Fig. 10e - Consolidation curve of clay with 20% ash/ *Curba de consolidare a argilei brune cu adaos de 20% cenuşă provenită dir şisturi bituminoase.*

gives the summarized results of the consolidation test. Figure 14 shows the consolidation behaviour of the brown clay without any addition of oil shale ash. A compression index (Cc) of 0.233 and a swelling index (Cs) of 0.014 were determined for the brown clay, Table 4.

Adding the bituminous oil shale ash as self-cementing material to the brown clay creates a calcination process starting from the beginning of the consolidation test. At the onset of the compression stage, its effect was very low, but still noticeable. During the unloading process, which took place after 2-3 days, the effect of calcination appeared clearly in reducing the swelling pressure. This indicate that the clay lost much of its plasticity due to presence of the bituminous oil shale ash.

3. Results and discussion

The plasticity index decreases from 25% for the brown clay to 18% for the mix with 20% of oil shale ash. A plasticity index in the range of 10% to 20% indicates a medium plastic behaviour of the tested soil. A soil with the plasticity index less than 20% needs stabilization, either with a cement content or with an environmentally friendly substitute, like the oil shale ash.

The compaction test results show that the increase of the oil shale ash content in ash-brown clay mixtures leads to a decrease in the dry density due to the low specific gravity of the oil shale ash. The addition of oil shale ash to the expansive brown silty-clay soil results in a decrease of the maximum dry unit weight (γ_{dmax}) and an increase of the optimum moisture content (OMC) of the brown clay - oil shale ash mixtures. This is because the oil shale ash larger surface absorbs much water, while its density is less than that of the brown clay. Another reason might be the flocculation of oil shale ash particles and of brown clay particles. Table 3 shows that percentages of 15-20% of oil shale ash added in the brown sandy-clay represent the optimum required to minimize the plasticity index and the swelling potential.

The results of the compaction test show that the consistency limits, compaction characteristics and swelling potential of expansive clay–oil shale ash mixtures are significantly modified and improved. It can be noticed that the 15% and 20% of oil shale ash is the optimum to improve the plasticity characteristics of a brown clay. The oil shale ashes exhibit low dry unit weight compared to the brown clay. Therefore, the main objective of the study is to reveal the effect of oil shale ashes on the physical, compaction, and swelling potential of brown clays, and to encourage the utilization of this industrial waste by-product without adversely affecting the environment.

The results obtained for the permeability analysis show a slight increase of the permeability coefficient for low oil shale content, and a noticeable increase for 15% and 20% of added oil shale ash to a maximum value of 5.1 x 10^{-8} m/s, while the permeability index of the brown clay was only 2.07 x 10^{-8} m/s.

The samples subjected to the unconfined compression testing show a quite similar behaviour for distinct percentages of oil shale ash. The determined value of the compressive strength for the samples with 20% of oil shale ash reaches 146 kPa in case of curing for 7 days, while this property attains 151 kPa in case of curing for 21 days.

Adding the oil shale in different percentages is proved to decrease the indices of compression (Cc) and swelling (Cs). A sharp decrease of both the compression index and the swelling index is observed up to 10% of clay mixed with oil shale and, after that, the decrease is negligible. This behaviour is mainly due to the high calcium content of the oil shale resulting in more cementitious material inside the body of the clay.

4. Conclusions

Soil stabilization as a cost-effective method is utilized in order to improve the properties of weak foundation soils by adding binders and by-products. Experimental results confirm the availability of using the bituminous oil shale ash waste to enhance the geotechnical properties of brown clay minimizing the environmental impact of the output of solid waste resulted from the combustion of bituminous oil shale.

An extensive experimental work was conducted by the authors to study the effect of the bituminous oil ash addition on the geotechnical behaviour of silty-sandy brown clay from Jordan. Based on the test results and due to nature of the oil shale ash and its high lime content, the following conclusions can be formulated:

1. The bituminous oil shale ash it is more effective due to the rich lime content compared with other types of ashes.

2. Various percentages of oil shale ash have been used for the preparation of brown clay-bituminous oil shale ash mixtures. Along with the increase in the percentages of bituminous oil shale ash in brown clay specimens, the optimum moisture content increases and the maximum dry density decreases.

3. The admixture of brown clay with bituminous oil shale ash shows a gradual reduction of the maximum dry density indicating an increased resistance to compaction. This effect is determined by the flocculated structure. In addition, the increase of the optimum moisture content is derived from the excess water embedded in the open units of the flocculated structure.

4. The plasticity index of the clay was sharply decreased by adding the oil shale ash.

5. The permeability coefficient of the clay increased proportionally with the ash percentage.

6. The highest strength values obtained for the stabilized brown clay with bituminous oil shale ash are associated to the moisture content, as both maximum compressive strength and maximum dry density have been achieved when the specimens were compacted with the optimum moisture content.

7. The addition of oil shale can noticeably reduce both compression and swelling indices.

8. The compaction of the brown clay with oil shale ash additive places the mixture in areas of lower densities and higher moistures than those of the untreated soil. After adding different percentages of oil shale ash, the compaction characteristics are only slightly modified.

9. For additive contents ranging from 5% to 20%, the maximum dry density of the brown clay mixtures with oil shale ash is smaller than the corresponding of mixtures without ash. Graphs show that bituminous oil shale ash contents greater than 10% have a insignificant effect on the maximum dry density.

10. The unconfined compressive strength is proportional to the amount of added ash.

Conclusively, the percentage of oil shale ash mixed with the brown clay influences the optimum moisture content, the maximum dry density (compaction) and the permeability. Based on these findings, 10-15% of bituminous oil shale ash mixed with bituminous brown clay could be recommended as an effective agent for the improvement of swelling brown clays. It also has the benefit of reducing the negative impact on the environment by reducing the landfill of an industrial by-product like bituminous oil shale ash.

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