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Stabilization of sandy soil with high content of asphalt emulsion

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Abstract

The purpose of this article is to evaluate the shear strength parameters of mixtures of sandy soil with high asphalt emulsion contents for their use in geotechnical structures, such as zoned earth dams, embankments, etc. The methodology adopted consisted of: collecting and characterizing samples of sandy soil to be laboratory tested; compacting the mixtures between soils and asphalt emulsion with contents varying between 13% and 28% in weight by using different compaction methodologies; and performing direct shear tests to evaluate the parameters governing the shear strength behavior of the manufactured mixtures. Results showed that the use of a high asphalt emulsion content contributed to greater homogeneity of the mixtures. It was also found that the presence of residual asphalt gave a bilinear behavior to the sandy soil for the failure envelopes obtained from direct shear tests. At normal stresses usually less than 100 kPa, the mixtures present a cohesive intercept due the existing residual binder, while for normal stresses higher than 200 kPa, the mixtures presented a friction angle equal to the matrix of sandy soil used.

Keywords: soil, asphalt emulsion, stabilization, shear strength.

1. Introduction

Stabilizing soil involves altering some of its properties to improve its behavior and guarantee that the material's new characteristics meet the requirements of an engineering project, the most common being mechanical and chemical stabilizations. Mechanical stabilization consists of adding materials to soil that modify its properties with no chemical interactions between the elements in contact, or of modifications to its properties over time (pozzolanic reactions). In general, expansibility, mechanical strength, durability and permeability are properties of a soil that is to be improved in order to deploy it in engineering projects. Some mechanical stabilization techniques worth mentioning are particle stabilization and modification of the soil properties by incorporating other materials, including natural or synthetic fibers, asphalt materials and so on (Suarez, 2008; Belchior *et al*., 2017; Silveira *et al*., 2018; Silveira, 2018; Consoli *et al*., 2019; Silva *et al*., 2019). In pavement applications, there are reports in several emulsion-soil studies (Miceli Junior, 2006; Soliz, 2007; Suarez, 2008; Gondim, 2008; Sant'Ana, 2009), so that soil stabilization studies with asphalt emulsion, in order to increase the bearing capacity and durability of the paving layers, are to some extent advanced. On the other hand, little progress has been made in terms of using emulsion-soils as materials for other applications in geotechnics, such as impervious cores in zoned dams, landfill liners, embankments, etc, where the hydraulic properties or shear strength behavior are important (Jacintho 2005, 2010). In some specific studies, lumps were found to have formed between the asphalt emulsion and fines present in the soil, when emulsion contents of 8% or less in weight led to an increase in macroporosity of the material, thereby damaging its hydraulic and mechanical behavior (Jacintho 2005, 2010). Thus, no consensus was reached on soil stabilization by adding 8% or less in weight of asphalt emulsion.

Accordingly, the aim of this study is to assess the influence of adding high asphalt emulsion content to the shear strength behavior of mixtures of sandy soils with asphalt emulsion. The intention then is to check if the use of high asphalt emulsion contents produces greater homogeneity in emulsion soil mixtures. Thus, finding conclusive results on possible soil stabilization, represented by a lower permeability coefficient and a larger cohesion intercept of the studied mixtures in relation to the granular soil used, would help obtain material with characteristics that could be used in building homogeneous dams, impervious cores in zoned dams, embankments, or even landfill liners.

2. Stabilization of soils with asphalt emulsion

The stabilization process consists of applying a stabilizing factor to the soil, in order to modify its properties so that it can satisfactorily meet a certain design requirement (Falcão, 2007; Gouveia *et al.*, 2007; Dantas Neto *et al.*, 2016; Lima, 2016). In general, expansibility, mechanical strength, durability and permeability are properties of a soil that is to be improved in order to deploy it in engineering projects.

Soliz (2007) reports that soil stabilization with asphalt materials first began with the use of medium and rapid curing diluted asphalt, being the use of cationic asphalt emulsions in France in 1951. In Brazil in 1952, anionic asphalt emulsions started to be used and it was only ten years later that the cationic emulsions appeared in the market. However, research on soil stabilization with diluted asphalt in the 1950s and early 1960s did not provide enough information to be able to establish specifications and standards for soil-bitumen mixtures, and it was only in 1976 in Brazil that a low-cost road construction program began, including the study of soil stabilization by adding asphalt emulsions.

The main role of asphalt material in the emulsion-soil mixture is to strengthen the material and help reduce its permeability (Jacintho, 2005; Gondim, 2008; Sant'Ana, 2009; Jacintho, 2010; Verma, 2015; Linsha *et al.*, 2016). According to Sant'Ana (2009), in the case of sandy soils, shear strength grew by increasing the cohesion between particles caused by the bitumen film coating, and permeability dropped by reducing the number of voids between the soil particles, thus hindering the water flow.

The bitumen film coating around the soil particles is of the utmost importance for soil stabilization and the hydraulic and mechanical behavior of the resultant material. Some of the main factors that influence the efficiency of the bitumen film are viscosity and rupture time of the asphalt emulsion, as well as the adhesive characteristics of the residual asphalt with mineral grains (Sant'Ana, 2009). If the emulsion breaks before completely coating the soil particles with the bituminous material, this will result in forming lumps made by the residual asphalt and the finest fraction of the soil (Jacintho, 2010). It may be considered that the lump formation inside the emulsion-soil mixture hinders the stabilization process, since it gives the structure greater heterogeneity and, in many cases, may increase the volume of voids in the material, leading to an unwanted increase in soil permeability, or even a drop in its shear strength.

The fact that the asphalt emulsion breaks before or after the complete coating of the mineral grains of the soil should be considered extremely important when studying emulsion-soil mixtures, and the chemical interaction between the soil particles and the emulsion is a key factor in this process. Depending on the chemical components of the mixture, they could act as catalysts of the emulsion's coalescence process, accelerating the binding between the asphalt globules dispersed in the emulsifying agent and, therefore, influencing the bitumen's adhesion to the soil particles, which is very relevant in the stabilization process (Sant'Ana, 2009).

In general, most applications and studies on soil stabilization with asphalt emulsions are found in pavements (Miceli Júnior, 2006; Lima, 2016). Few studies have been undertaken regarding the behavior of the emulsion-soil mixture for building dams (Sampaio, 2008; Sant'Ana, 2009; Santos, 2009). In all studies, the maximum asphalt emulsion contents added to a wide variety of soil types to stabilize them were 8% in weight (Nascimento *et al.*, 2003; Miceli Júnior, 2006; Gondim, 2008; Sampaio, 2008; Sant'Ana, 2009).

The emulsion-soil with emulsion contents of 8% or less in weight have shown that the increase in emulsion content produces in the mixtures a reduction in apparent dry specific mass and optimum moisture content in compaction studies of different types of soil and compaction energies (Sampaio, 2008; Sant'Ana, 2009; Jacintho, 2010). From the viewpoint of hydraulic and mechanical behavior, the studies for these materials have shown to be inconclusive regarding the gain achieved in the behavior of the materials by adding asphalt emulsion. This problem of stabilization may be attributed to lump formation in the structure of the emulsion-soil with low asphalt emulsion content, as already mentioned.

Preliminary studies on the compaction of mixtures of sandy soils with high asphalt emulsion contents, 13% to 31%, in weight, have already been performed (Lima, 2016; Lima and Dantas Neto, 2019). These studies involved mixtures prepared by adding a low-breaking cationic asphalt emulsion, classified according the Brazilian standardization as RL-1C type (IPR, 2013), to a soil classified as poor graded sand (SP) and consisted of assessing the compaction energy (standard and modified Proctor) and the viscosity of the asphalt binder. All mixtures were compacted immediately and 24 hours after their preparation. The time of 24 hours was chosen by the authors to ensure the complete break of asphalt emulsion before the mixture compaction. Their results demonstrated that for the high asphalt contents, the mechanisms of compaction of studied mixtures are quite different from those responsible for compaction of granular materials, or even emulsion-soil mixtures, with emulsion contents below 10% in weight previously mentioned.

The results of the studies performed with mixtures of sandy soil with high asphalt emulsion contents also revealed that the stiffness of the formed asphalt film exerts a strong influence on the compaction process of emulsion-soil mixtures (Lima, 2016; Lima and Dantas Neto, 2019). The efficiency of the compaction was obtained only in situations where the emulsion viscosity was significantly low, or with increased compaction energy. Moreover, it has been demonstrated that the physical parameters, such as unit dry weight and optimum moisture content traditionally used in granular and fine soil compaction studies, should not be applied in the compaction and design of emulsion-soil mixtures with high emulsion. Instead, using the physical parameters as unit weight, void content, and void content in relation to the mineral grain structure can be used to better represent the influence of the asphalt emulsion added to the compaction characteristics of emulsion-soil mixtures.

Lima (2016) and Lima and Dantas Neto (2019) also present results of scanning electronic microscopic tests carried out to verify the homogeneity of the emulsion-soil mixtures made with high asphalt emulsion contents. According to these authors, the homogeneity of the compacted mixtures improved with the increase in the asphalt emulsion content used, causing the formation of fewer lumps in the mixture. Therefore, this could lead to a decrease in the permeability and to an appearance of some cohesive intercepts of the mixtures manufactured with sandy soil and asphalt emulsion contents in comparison to those made with emulsion content up to 8% in weight (Jacintho, 2005; Jacintho, 2010). The influence of the use of high asphalt emulsion contents on the shear behavior of the produced mixtures is the lack of knowledge which intends to be fulfilled by the results presented herein.

3. Materials and methods

3.1 Soil samples

To prepare the mixtures in this study, two samples of a sandy soil classified by the Unified Soil Classification System (USCS) as a poor graded sand - SP were used. Table 1 presents the average values of the soil parameters obtained by laboratory tests performed pursuant to the following standardization: ASTM D421-85 - Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants; ASTM D854 – Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer; ASTM D4318 – Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils; ASTM D422-63 – Standard Test Method for Particle-Size Analysis of Soils; and ASTM D698 – Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort.

Table 1 - Geotechnical properties for the reference sandy soil.

Parameters	Value
$\gamma_{d,max}$ – Modified Proctor (kN/m³)	19.7
Optimum moisture content (%)	8,1
Liquid Limit, %	-
Plastic Index, %	-
Specific gravity (G_s)	2.65
USCS classification	SP

3.2 Asphalt emulsion

In this study, the mixtures were prepared with a slow-breaking cationic emulsion termed RL-1C, and its results from the characterization tests are shown in Table 2. This type of emulsion was chosen in order to have enough time to coat the aggregates during the mixing operation without breaking the emulsion.

Table 2 - Physical properties for the used RL-1C asphalt emulsion.

Properties	Brazilian specifications (IPR, 2013)	Value
Saybolt–Furol viscosity, sSF, at 50°C	Max. 70	44
Sifting, 0.84mm, % weight	Max. 0.10	0.01
Residue, % weight	Min. 60	63.2

3.3 Manufacturing of emulsion-soil mixture

The methodology used to compact the soil-emulsion mixtures was the Marshall procedure standardized by ASTM D6926, with the compaction made immediately and 24 hours after the mixing process of the soil with asphalt emulsion, resulting in a total of two different types of mixtures, as shown in Table 3. The compaction of the mixtures after 24 hours was done in order to ensure the complete breaking of asphalt emulsion before compaction as also proceeded in the studies of Lima (2016) and Lima and Dantas Neto (2019).

Table 3 - Description of the studied emulsion-soil mixtures.

Compaction methodology	Code	Compaction time
Marshall	M-I	Immediately after mixing
Marshall	M-24	24 hours after mixing

Figure 1 presents the compaction curves showing the variation in unit weight of the mixtures with the asphalt emulsion content used. The results indicate that the viscosity of the bitumen film coating of the soil particles plays a major role in the compaction of mixtures made with high asphalt emulsion contents. In general, the immediately compacted mixtures after their preparation had higher values for the unit weight and lower optimum emulsion contents than those compacted 24 hours after the mixing procedure.

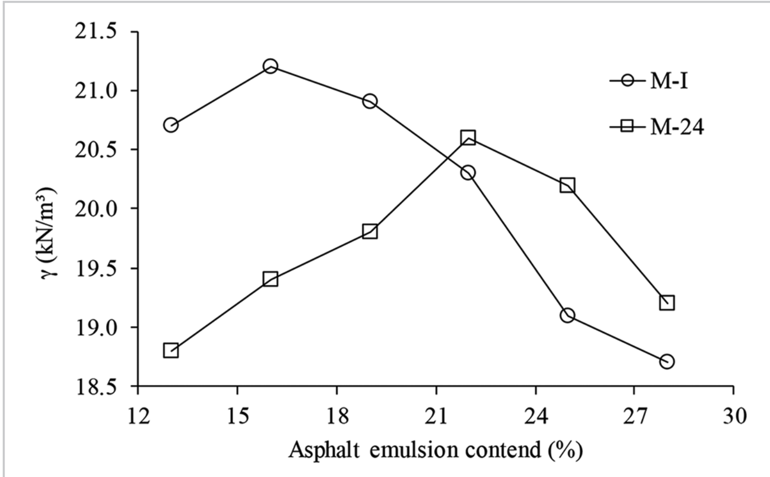

Figure 1 - Results of compaction tests of emulsion-soil mixtures.

3.4 Shear strength testing

The shear strength parameters of the soil specimens compacted under modified Proctor energy and the mixtures studied were assessed by the direct shear test carried out according to ASTM D3080 – Standard Test Method for Direct Shear Test of Soil under Consolidated Drained Conditions.

The emulsion-soil specimens used in the shear strength tests were based on physical parameters obtained from the compaction curves for the studied materials. The direct shear tests were performed on specimens of emulsion-soil mixture M-I under drained conditions after first being flooded with water, as well as under unsaturated conditions, although the suction was not measured during the rupture of the test specimens. The emulsion-soil mixture M-24 was tested only under unsaturated conditions. This test procedure was intended to check the influence of the suction, even without its measurement, in the shear behavior of the mixtures of the sandy soil with high asphalt emulsion content.

4. Results and discussion

The specimens used for studying the shear behavior of emulsion-soil mixtures were prepared using the maximum dry unit weight of the mixtures with their corresponding emulsion contents obtained by compaction in methodologies M-I and M-24 as shown in Figure 1. To mold the soil specimen, the maximum dry unit weight was used with its corresponding optimum moisture content under modified Proctor energy, presented in Table 1.

Figure 2 presents the results of the direct shear test for: 1) the specimens of M-I mixture tested saturated and non-saturated, 2) of the M-24 mixture tested non-saturated, and 3) the SP sandy soil, for normal stresses of 50 kPa, 100 kPa, 200 kPa and 400 kPa.

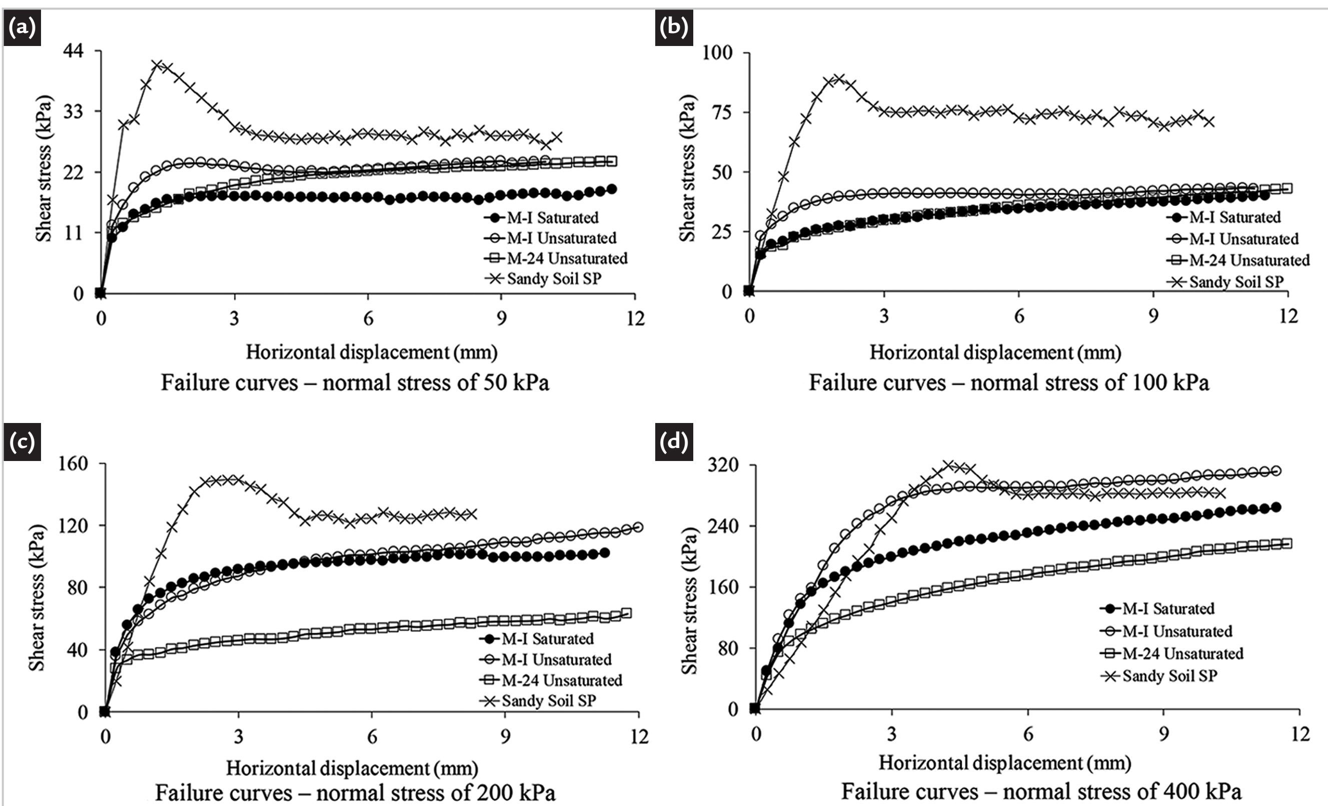

Figure 2 - Comparison between the shear behavior of the emulsion-soil mixtures and sandy soil SP.

According to the results given in Figure 2, it is evident that the compacted SP sandy soil has peak and residual strengths well defined for all levels of the normal stresses applied, contrary to what happens with the emulsion-soil mixtures (M-I and M-24) tested with and without saturation. It is also found for the emulsion-soil mixtures that, except for the M-24 mixture under a normal stress of 400 kPa (Figure 2d), in every other specimen there is no significant increase in shear strength after failure. The results also show that the emulsion-soil mixtures have peak shear strength and lower shear stiffness than those obtained for the compacted SP soil. The drop of shear stiffness of the emulsion-soil mixtures in relation to the compacted SP soil, mainly found in the pre-peak horizontal displacements, can be attributed to the viscous nature of the residual asphalt film surrounding the soil particles in the emulsion-soil mixtures.

Results presented in Figure 2 also show that saturation influences the shear strength of the studied mixtures. In general, the mixtures tested without saturation present higher shear stiffness and shear strength than those tested with saturation of the specimens. Such a rise in rigidity and shear strength may be attributed to the matric suction present in the specimens tested without saturation. It is worth mentioning that this is only a preliminary assessment, since the tests were conducted without measuring the suctions during the failure.

The comparison between the shear behavior of the emulsion-soil mixtures and the SP compacted soil may also be better understood from the analysis of the shear strength envelopes shown in Figure 3, which were built considering the peak strength values for the sandy soil (SP), and the maximum values of shear strength of the emulsion-soil mixtures, which occurred normally for 10 mm horizontal displacements. These results indicate that there is bilinearity of the strength envelopes of the emulsion-soil mixtures, which helps to define the behavior of those materials for two different loading levels.

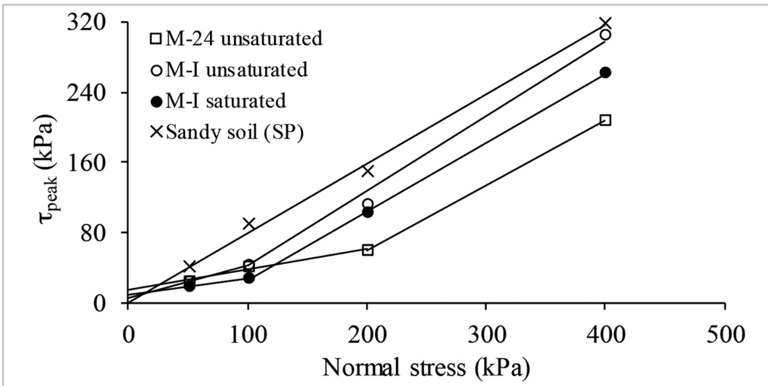

Figure 3 - Failure envelope curves for the studied materials.

In general, the results show that to apply low loading levels to the mixtures between soil and high emulsion contents, the mechanism responsible for the shear of the mixtures is the residual asphalt film. It conveys to the materials a cohesive intercept due to the bonding action of the emulsion and friction by the interlocking of the grains duly wrapped by the residual asphalt film, as illustrated in Figure 4a. From a certain normal stress value, the failure envelopes of the emulsion-soil mixtures are parallel to that of the compacted SP sandy soil, and therefore the mechanism responsible for the shear strength is the friction between the soil particles in the mixtures. Therefore, for high levels of normal stresses, there probably is a complete removal of the asphalt film in the contacts, so that the grain-grain friction exceeds in relation to the possible bonding action caused by the residual asphalt, as illustrated in Figure 4b.

In the M-I mixtures, the stress level on which the envelope is parallel to that of the SP compacted soil is less than in the M-24 mixtures, tested under the same flooding condition. This occurs because in M-I mixtures, the residual asphalt film is thinner due to the smaller emulsion content used in their preparation, so that the grain-grain contact occurs at lower normal stress levels.

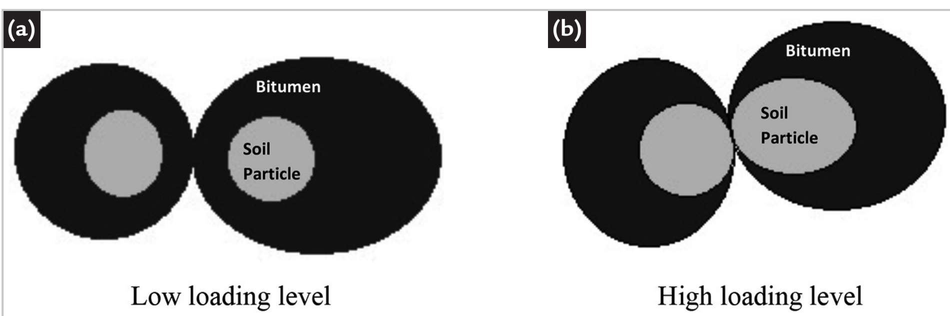

Figure 4 - Interaction between the soil particles and bitumen.

It should be stressed that the behavior noted in the strength envelopes of the emulsion-soil mixtures presented in Figure 3 is the inverse of that presented by soils reinforced with other materials, such as, for example, by natural and synthetic fibers (Consoli et al. 2009; Silva dos Santos et al. 2010; Silveira et al. 2018; Silveira 2018). The results obtained for these types of compounds indicate that the failure envelopes have in some cases a well-defined linearity, and in others, a curvilinear or bilinear behavior, in which the fiber-soil mixtures present a cohesive intercept for high loading levels, due to a greater fiber-soil interaction.

Table 4 provides the shear strength parameters for the sandy soil (SP) and of the emulsion-soil mixtures studied for the aforementioned low and high stress level situations. These results show that there is a gain in cohesive interception in the emulsion-soil mixtures in relation to the primarily granular sandy soil. Such results confirm the parallelism between the envelopes of the studied emulsion-soil mixtures and that presented by the compacted sandy soil, as already discussed above. The results in Table 4, therefore, corroborate the interpretation made of the direct shear tests results.

Table 4 - Parameters of shear strength of the studied materials.

Material	Emulsion Content (%)	Low stress level		High stress level
		c (kPa)	ϕ (°)	ϕ (°)
Soil SP (benchmark)	0	0.0	38.5	-
M-I (unsaturated)	16	5.3	20.5	40.4
M-I (saturated)	16	8.7	10.9	38.0
M-24 (unsaturated)	22	14.2	13.6	37.7

Note: c = cohesive intercept; ϕ = friction angle.

5. Conclusions

The direct shear test results enabled the conclusion that the addition of high asphalt emulsion contents to the sandy soil provided the soil with a cohesion intercept and a decrease in the friction angle for low normal stress levels applied during direct shear testing. This cohesion in the materials was due to the binding action caused by the presence of the residual asphalt binder coating the soil particles, while the internal friction angle in relation to the sandy soil as a benchmark decreased due to the reduced grain-to-grain friction resulting from the presence of the bitumen film coating. In high normal stress levels, it was found that the studied emulsion-soil mixtures had the same internal friction angle values as those obtained for the benchmark sandy soil, very likely due to removal of the residual asphalt film from the contacts grain-to-grain, so that the friction between the mineral particles is the governing mechanism of the shear strength of the mixtures.

Lastly, it was noted that the mixtures of soil with a high asphalt emulsion content that was compacted immediately after its manufacturing process, have slightly more properties to those of mixtures compacted 24 hours later. Even so, the mixtures compacted 24 hours after preparation have properties that would consider soil stabilization with the addition of emulsion. The advantages of mixtures compacted 24 hours after their preparation possibly lies in their preparation, storage and later application, a condition simulated in the manufacturing process of mixtures M-24, which are an alternative that could facilitate their application on a dam site construction.

By analyzing all presented results, it can be observed that the effect of adding high asphalt emulsion content to a sandy soil provokes a change in its shear behavior by adding cohesion to the material and decreasing the internal friction angle. Results obtained indicate that the mixtures of granular soil and high asphalt emulsion content can be used in geotechnical structures as an impervious core in zoned dam, liners in landfills, containing walls, etc. However, a more detailed evaluation of the behavior of this material when used in these applications must be done.

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References

BELCHIOR, I. M. R.; CASAGRANDE, M. D. T.; ZORNBERG, J. G. Swelling behavior evaluation of a lime-treated expansive soil through centrifuge test. ***Journal of Materials in Civil Engineering,*** v. 29, p.04017240-04017240-12, 2017.

CONSOLI, N. C.; BITTAR MARIN, E. J.; QUIÑONEZ SAMANIEGO, R. A.; HEINECK, K. S.; DALLA ROSA JOHAN, A. Use of sustainable binders in soil stabilization. ***Journal of Materials in Civil Engineering,*** v. 31, p. 06018023, 2019. DOI: doi.org/10.1061/(ASCE)MT.1943-5533.0002571.

CONSOLI, N. C.; FESTUGATO, L.; HEINECK, K. S. Strain-hardening behavior of fibre-reinforced sand in view of filament geometry. ***Geosynthetics International,*** v.16, n. 2, 2009. DOI: doi.org/10.1680/gein.2009.16.2.109.

DANTAS NETO, S. A.; LIMA, F. C.; LEME, R. F. Estudo da compactação de misturas solo-emulsão para emprego em núcleo de barragens zoneadas. In: CONGRESSO BRASILEIRO DE MECÂNICA DOS SOLOS E ENGENHARIA GEOTÉCNICA. 18., 2016, Belo Horizonte. ***Anais[...].*** Belo Horizonte: COBRAMSEG, 2016.

FALCÃO, P. R. F. ***Estudo das propriedades mecânicas e hidráulicas de concretos asfálticos para aplicação em barragens.*** 2007. 106 f. Tese (Doutorado em Geotecnia) - Faculdade de Tecnologia, Universidade de Brasília, 2007.

GONDIM, L. M. ***Estudo experimental de misturas solo-emulsão aplicado às rodovias do agropólo do Baixo***

Jaguaribe – Estado do Ceará. 2008. 213 f. Dissertação (Mestrado em Engenharia de Transportes) – Centro de Tecnologia, Universidade Federal do Ceará, 2008.

GOUVEIA, L. T.; FERNANDES JÚNIOR, J. L.; SOARES, J. B. Influência da energia de compactação no comportamento volumétrico e mecânico de misturas asfálticas. ***Transportes,*** v. 15, n.1, june2007.

INSTITUTO DE PESQUISAS RODOVIÁRIAS. ***IPR. DNIT 165/2013:*** emulsões asfálticas para pavimentação: especificação de material. Rio de Janeiro: IPR, 2013.

JACINTHO, E. C. ***Estudo do comportamento de misturas solo-emulsão para uso em barragens.*** 2005. 160 f. Dissertação (Mestrado em Geotecnia) – Faculdade de Tecnologia, Universidade de Brasília, 2005.

JACINTHO, E. C. ***Estudo de propriedades e comportamentos de misturas solo-emulsão aplicado a barragens.*** 2010. 279 f. Tese (Doutorado em Geotecnia) - Faculdade de Tecnologia, Universidade de Brasília, 2010.

LIMA, F. C. ***Estudo dos processos de compactação e dosagem de misturas entre solo arenoso e emulsão asfáltica.*** 2016. 96 f. Dissertação (Mestrado em Engenharia Civil) – Centro de Tecnologia, Universidade Federal do Ceará, 2016.

LIMA, F. C.; DANTAS NETO, S. A. Study of the compaction mechanism in mixtures of sandy soil and high asphalt emulsion contents. ***Geotecnia,*** n. 145, p. 61-80, 2019. DOI: 10.24849/j.geot.2019.145.05.

LINSHA, R. D.; DHARANYA, Y. P.; VINODHINI, V.; PAVITHRA, C. Improvement of shear strength of soil using bitumen emulsion. ***International Journal of Civil Engineering and Technology,*** v. 7, n.6, p.156 – 165, 2016.

MICELI JUNIOR, G. ***Comportamento de solos do estado do rio de janeiro estabilizados com emulsão asfáltica.*** 2006. 267 f. Dissertação (Mestrado em Engenharia de Transportes) – Instituto Militar de Engenharia, Rio de Janeiro, 2006.

SAMPAIO, M. G. ***Comportamento mecânico e hídrico de solos estabilizados com emulsão asfáltica.*** 2008. 157 f. Dissertação (Mestrado em Engenharia Civil) - Faculdade de Engenharia Civil, Arquitetura e Urbanismo, Universidade Estadual de Campinas, 2008.

SANTOS, W. J. ***Avaliação do uso de emulsão asfáltica na estabilização química de três solos de Sergipe.*** 2009. 141 f. Dissertação (Mestrado em Engenharia Civil) - Centro de Tecnologia e Recursos Naturais da Universidade Federal de Campina Grande, 2009.

SANT'ANA, W. C. ***Contribuição ao estudo de solo-emulsão em pavimentos de rodovias de baixo volume de tráfego para o Estado do Maranhão.*** 2009. 341 f. Tese (Doutorado em Engenharia) - Escola Politécnica, Universidade de São Paulo, São Paulo, 2009.

SILVA DOS SANTOS, A. P.; CONSOLI, N. C.; BAUDET, B. A. The mechanics of fibre-reinforced sand. ***Geotechnique,*** v. 60, n. 10, p. 791-799, oct. 2010. DOI: https://doi.org/10.1680/geot.8.P.159 .

SILVA, M. V.; REZENDE, L. R.; MASCARENHAS, M. M. A.; OLIVEIRA, R. B. Phosphogypsum, tropical soil and cement mixtures for asphalt pavements under wet and dry environmental conditions. ***Resources Conservation and Recycling,*** v. 144, p. 123-136, 2019. DOI: https://doi.org/10.1016/j.resconrec.2019.01.029.

SILVEIRA, M. V. ***Análise do comportamento mecânico e da durabilidade em compósitos de areia reforçada com fibras naturais de curauá e sisal.*** 2018. 148 f. Tese (Doutorado em Engenharia Civil) - Pontifícia Universidade Católica do Rio de Janeiro, 2018.

SILVEIRA, M. V.; CALHEIROS, A. V.; CASAGRANDE, M. D. T. Applicability of expanded polystyrene as a soil improvement tool. ***Journal of Materials in Civil Engineering,*** v. 30, p. 06018006, 2018. DOI: https://ascelibrary.org/doi/10.1061/%28ASCE%29MT.1943-5533.0002276.

SOLIZ, V. V. P. ***Estudo de três solos estabilizados com emulsão asfáltica.*** 2007. 140 f. Dissertação (Mestrado em Engenharia Civil) – Coope, Universidade Federal do Rio de Janeiro, Rio de janeiro, 2007.

SUAREZ, D. A. A. ***Estudo do comportamento mecânico de dois solos lateríticos do Estado de São Paulo com adição de emulsão asfáltica.*** 2008. 144 f. Dissertação (Mestrado em Ciências) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2008.

VERMA, S. K. A laboratory study on use of bitumen emulsion in black soil. ***International Research Journal of Engineering and Technology (IRJET),*** v. 02, p. 548-553, 2015.

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