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GEOTECHNICAL PROPERTIES ANALYSIS IN SOIL, RECLAIMED ASPHALT PAVEMENT (RAP) AND PORTLAND CEMENT MIXTURES FOR USE AS PAVEMENT LAYERS

ANÁLISE DE PROPRIEDADES GEOTÉCNICAS EM MISTURAS DE SOLO, MATERIAL ASFÁLTICO FRESADO E CIMENTO PORTLAND PARA UTILIZAÇÃO COMO CAMADAS DO PAVIMENTO

Guilherme ALMEIDA[1], Lucila Costa SALES[2], Erinaldo CAVALCANTE[1]
[1]Universidade Federal de Sergipe, Departamento de Engenharia Civil. Cidade Universitária “Professor José Aloísio de Campos”.
Avenida Marcelo Deda Chagas, s/n, Jardim Rosa Elze. São Cristovão - SE.
E-mail: gboa@academico.ufs.br; erinaldohc@academico.ufs.br
[2]Departamento Nacional de Infraestrutura de Transportes (DNIT). Avenida Maranhão, 1890 - Santos Dumont, Aracaju – SE.
E-mail: lucilacs@gmail.com

RESUMO – É apresentado um estudo de misturas de solo fino e material asfáltico fresado nos teores de 20, 30 e 50% com e sem adição de 5% de cimento Portland. O programa experimental envolveu uma bateria de ensaios os quais constataram que a adição de até 50% do resíduo altera a granulometria, aumenta a massa específica aparente seca máxima, índice de suporte e a permeabilidade, reduz a plasticidade, umidade ótima e a expansão. Em todas as misturas de solo e fresado, ao adicionar 5% de cimento, foram observadas relevantes alterações na granulometria, no aumento do índice de suporte e na redução da expansão e da permeabilidade. Para todas as misturas de solo-fresado-cimento, a resistência à compressão ficou abaixo de 2,1 MPa, valor tomado como referência conforme DNIT 142. Complementando os ensaios dessas misturas aditivadas, a resistência à tração foi considerada satisfatória, apresentando valores superiores a 10% da resistência à compressão. Enquanto a durabilidade, apresentou uma perda de massa máxima pouco abaixo de 5% para a mistura de solo com 20% de fresado e 5% de cimento. A plasticidade se apresentou como maior impedimento de utilização de todas as misturas perante os requisitos das normas técnicas. No entanto, verificou-se que o fresado é promissor na melhoria das propriedades do solo e como material a ser aplicado na pavimentação.
Palavras-chave: Estabilização de solos. Material asfáltico fresado. Cimento Portland. Pavimento.

ABSTRACT - A study is presented of mixes of fine soil and reclaimed asphalt pavement (RAP) in the contents of 20, 30 and 50% with and without the addition of 5% Portland cement. The experimental program involved a battery of tests which found that the addition of up to 50% RAP alters the granulometry, increases the maximum dry density, bearing capacity and permeability, reduces plasticity, optimum moisture and expansion. In all soil and RAP mixtures, when adding 5% cement, relevant changes in particle size were observed, an increase in the bearing capacity and a reduction in expansion and permeability. For all soil-RAP-cement mixtures, the compressive strength was below 2.1 MPa, a value taken as a reference according to DNIT 142. Complementing the tests of these additive mixtures, the tensile strength was considered satisfactory, presenting values greater than 10% of the compressive strength. As for durability, it showed a maximum mass loss of just under 5% for the soil mixture with 20% RAP and 5% cement. Plasticity presented itself as the greatest impediment to the use of all mixtures in view of the requirements of technical standards. However, it was found that the RAP is promising in improving soil properties and as a material to be applied in paving.
Keywords: Soil stabilization. Reclaimed asphalt pavement. Portland cement. Pavement.

INTRODUCTION

When asphalt pavements get deteriorated, is it necessary intervening in part of, or in the whole, coating. In order to do so, it is possible using milling machines equipped with cutting diamond tips to make cuts in the pavement’s structure (Bernucci et al., 2008). Bonfim (2007) defines milling as the act of thinning one or more pavement layers to a pre-set thickness through mechanical process carried out under cold or heating conditions, aimed at their restoration.

Most interventions generate asphalt milling waste, known as RAP (Reclaimed Asphalt Pavement), that oftentimes consists in mineral aggregate fragments and old asphalt binders that can be recycled, a fact that leads to natural-resources optimization. Using this material is a way to help protecting the environment, since it ensures the proper reuse of resources and accounts for construction-cost reduction (Alhaji et al., 2019).

Milling waste recycling to produce new asphalt mix is common, and this subject is broadly approached either in studies (Bańkowski, 2018; Wang et al., 2018; Zhang & Muhunthan, 2017; Noferini et al., 2017) or in handbooks by public bureaus in Brazil and abroad (FHWA, 2018, DNIT, 2006; DNIT 2005; Kandhal & Mallick, 1997). However, the technique based on using thinned material in other pavement layers is not yet consolidated.

Authors like Alhaji et al. (2019), Ruknuddin et al. (2019), Hasan et al. (2018), Alhaji & Alhassan (2018), Mahasneh (2016), Kamel et al. (2016) and Mishra (2015), among others, have assessed RAP using in paving and soil stabilization. They concluded that its use is feasible, be it in base and sub-base layers, or even to adjust subgrade properties. Nevertheless, there is no uniformity in results found by these authors or in the adopted methods; therefore, it is essential gathering more information about the physical and mechanical properties of both the RAP and its mixing to soil in order to outspread knowledge about, and ensure, construction stability.

In this context, this research shows its contribution to RAP studies. It is justified by the large volume of RAP waste generated, by the application of RAP as a pavement layer, in addition to reducing environmental impacts, whether in its disposal or in the smallest extraction of soil from nature. The selection of clayey soil is justified by the finer graining it imparts to the soil-RAP mixture.

The heterogeneity of RAP and the nature of clayey soil motivated the incorporation of an additive to ensure increased strength and reduced plasticity in the soil-RAP mixture. This is pertinent because the selected cement is characterized by minimal raw material additions in its composition and exhibits high-early-strength.

Therefore, the aim of the present study was to assess the physical, chemical and hydraulic properties of soil, RAP and Portland cement mixes to be used in paving structures. It must be done through an experimental program carried out in laboratory environment.

MATERIALS AND METHODS

The herein used materials were soil, RAP and Portland cement. Soil was collected in a field of study located in Sergipe State; it presented a large amount of fine material. The RAP was collected in an asphalt production plant; it results from interventions made in the streets of Aracaju City, Sergipe State. Big-sized milling machine Wirtgen W 200, which cuts thickness ranging from 2.5 cm to 3 cm, was used in the milling operation. Milling waste was ground to allow all the material to be sieved in 19 mm mesh. CP V-ARI type Portland cement (high-early-strength type III according to ASTM) was chosen for the experiment because it presents less additions in its composition, compared to other types of cement, high initial strength and because it is easy to be found in the market. Furthermore, this cement type accounts for higher tricalcium silicate (C3S) content than that found in common cement. This feature can be interesting in clayey soil mixes, since C3S releases calcium hydroxide when it is hydrated. Calcium hydroxide participates in secondary reactions with soil clay-minerals.

The particle size distribution (DNER-ME 051 and DNER-ME 080), specific gravity (DNER-ME 093), Atterberg limits (DNER-ME 122 and DNER-ME 082), compaction using deformed on modified effort (DNER- ME 162), California bearing ratio (CBR), which also includes compaction test with undisturbed samples (DNIT-ME 172), and determining of the permeability coefficient at variable load, according to method B, described in NBR 14545, were used to carry out tests with pure soil (100S).

Particle size distribution applied to pure RAP (100M) tests carried out with aggregates was based on sieving (DNER-ME 083) specific mass using Chapman flask (DNER-ME 194), density in oven-dry condition and density saturated-surface-dry condition (NBR 16916 and NBR 16917), bitumen content (DNER-ME 053) and Los Angeles abrasion (DNER-ME 035).

After materials were featured, in separate, soil and RAP mixes were prepared at the following contents: 20%, 30% and 50%, in comparison to the samples total mass. This procedure led to the following designations: 20M80S, 30M70S and 50M50S. The sequence of particle size distribution, specific gravity, Atterberg limits, compaction (modified effort), CBR and permeability (method B) test was also carried out with these same mixes, based on their respective standards.

Theses soil and RAP mixes were added with 5% Portland cement in comparison to samples total mass. Their representations were named 95(20M80S)5C, 95(30M70S)5C and 95(50M50S)5C.

Mixes added with cement were subjected to compaction tests with undisturbed samples (modified energy), CBR and permeability (method B), based on their respective standards. After the compaction and CBR tests were over, samples that got closer to both maximum dry density and optimum moisture content were subjected to particle size, specific gravity and Atterberg limits tests.

The time-period of seven days to cure the additive after specimens sampling was set for these tests. This same cure-time was adopted to the permeability test.

Strength and durability tests were carried out and strength was based on axial compression of cylindrical specimens (DNER-ME 201); tensile strength of cylindrical specimens (DNIT-ME 136) and durability when submitted to wetting and drying cycles (DNER-ME 203). These tests were conducted seven days after specimens curing in humid chamber. The results of the strength tests were obtained from the average of three tested specimens.

RESULTS AND INTERPRETATIONS

Physical characterization of soil and rap

Soil recorded 2.27% gravel, 21.74% sand, 33.90% silt and 42.09% clay, based on the AASHTO granulometric scale.

In addition, specific gravity 2.66, liquidity limit (LL) was 51%, plasticity limit (PL) was 23% and plasticity index (PI) was equal to 28%. Accordingly, soil was highly plastic and classified as A-7-6 (18); it was not recommended for paving.

The RAP, in its turn, consisted of 54.07% coarse aggregate, 45.65% fine aggregate and 0.27% pulverulent material. It presented coarse granulation, non-plastic and was classified as type A-1-a (0). Table 1 presents properties of the herein assessed waste type.

Table 1 - Properties of the RAP used in this research.

Properties	Values
Density in oven-dry condition (g/cm³)	2,29 (coarse aggregate)
	1,81 (fine aggregate)
Density saturated-surface-dry condition (g/cm³)	2,34 (coarse aggrehate)
	2,18 (fine aggregate)
Specific mass (Chapman flask) (g/cm³)	2,26
Water absorption (%)	2,0 (coarse aggregate)
	1,9 (fine aggregate)
Bitumen content (%)	5,9
Abrasion (Los Angeles machine) (%)	31

Physical characterization of soil-RAP and soil-RAP-cement mixes

Figure 1 depicts the granulometric curves of soil, RAP and soil-RAP mixes with and without Portland cement.

Table 2 provides information on granulometric composition, Atterberg limits, group index (GI) and AASHTO classification.

Increased RAP content turned the mixes more granular. This observation was also found in the studies by Oliveira (2018), Moura et al. (2018), Maciel et al. (2018) and Hasan et al. (2018). Specific gravity values obtained for soil-RAP mixes reached 2.59, 2.59 and 2.48 in mixes 20M80S, 30M70S and 50M50S, respectively. Data have shown reduced density, and it may be justified by lower waste's specific mass. Studies by Alhaji & Alhassan (2018), Mousa et al. (2017) and Mahasneh (2016) showed the same density-reduction behavior.

Similar to the soil, cement-free mixes were classified as highly plastic. However, increase in RAP content led to slight reduction in LL and PI values, a fact that is justified by RAP granular feature. PL, in its turn, was less sensitive to RAP content increase. This behavior can be attributed to high rates of soil passing through #40 sieve (0.42mm) in comparison to RAP rate. Classification, in comparison to pure soil, did not change, even after RAP addition to cement-free mixes (up to 50% content). Fine fraction (small than #200 sieve) prevalence remained, although 50M50S presented sand fraction equated to that of the clay fraction, in terms of rates.

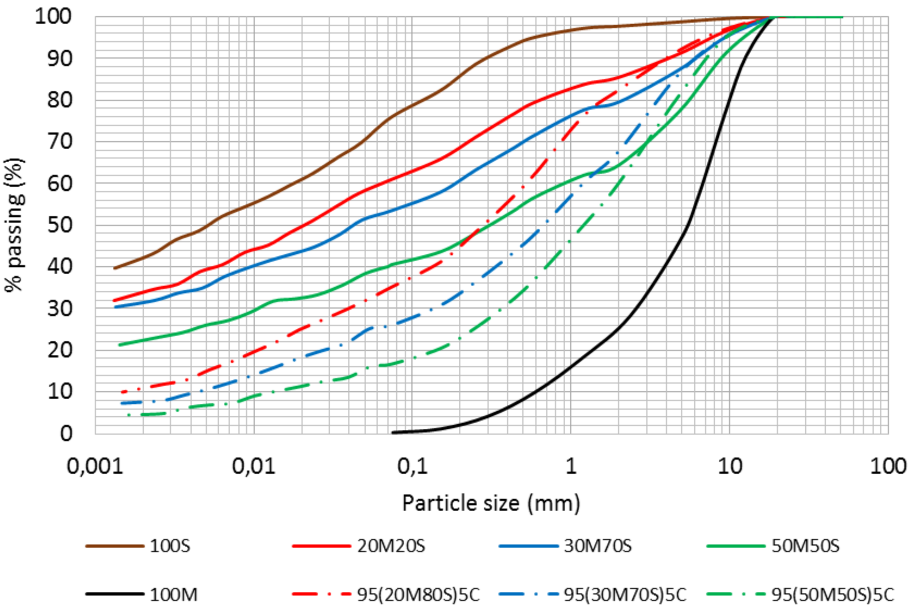

Figure 1 - Grain size distribution of materials.

Table 2 - Granulometric compositions, Atterberg limits, IG and classification of the materials.

Sample	**Granulometric composition**			**LL (%)**	**PI (%)**	**GI**	**Classification AASHTO**
	% passing by weight						
	#10	#40	#200				
100S	97,73	92,97	75,99	51	28	18	A-7-6
20M80S	85,47	76,36	61,00	49	26	13	A-7-6
30M70S	79,56	68,19	53,52	48	27	11	A-7-6
50M50S	64,41	52,11	40,56	46	25	6	A-7-6
95(20M80S)5C	82,44	56,41	35,20	35	13	1	A-2-6
95(30M70S)5C	67,77	43,05	26,06	35	13	1	A-2-6
95(50M50S)5C	60,14	31,86	16,71	34	11	1	A-2-6
100M	25,50	6,40	0,27	-	NP	0	A-1-a

Similar to the soil, cement-free mixes were classified as highly plastic. However, increase in RAP content led to slight reduction in LL and PI values, a fact that is justified by RAP granular feature. PL, in its turn, was less sensitive to RAP content increase. This behavior can be attributed to high rates of soil passing through #40 sieve (0.42mm) in comparison to RAP rate. Classification, in comparison to pure soil, did not change, even after RAP addition to cement-free mixes (up to 50% content). Fine fraction (small than #200 sieve) prevalence remained, although 50F50S presented sand fraction equated to that of the clay fraction, in terms of rates.

Alhaji et al. (2019), Mousa et al. (2017), Kamel et al. (2016), Taha et al. (2002) worked with RAP and observed its non-plasticity, just as herein recorded. The addition of this waste type tends to reduce the mix plasticity and it can lead to non-plastic mixes, such as those in the studies by Kamel et al. (2016).

Cement addition to the mix caused even more significant downward-trend in granulometric curves; in other words, cement mixes presented even coarser granulation. When mixes with and without cement are compared to each other, it is possible observing significant increase in the sand fraction and reduction in the clay.

It is important reinforcing that granulometry records introduced in figure 1 for cement-added samples were obtained with mixes after the compaction and CBR tests, after 7-day cure. This outcome shows the effect of both the additive and the RAP, since this process bonds these grains to one another in order to form bigger ones. Table 2 shows that the rate of grains passing through the aforementioned sieves gets lower as RAP content increases.

With respect to cement-added mixes, can observe LL and PI reduction in comparison to the value recorded for cement-free samples; it is justified by increase in sand-fraction rates in the three mixes. PL in the mixes was little sensitive to 5%-cement addition to them – there was slight upward trend in it. Cement addition turned mixes a little plastic and changed their classification to A-2-6 (1). It is easy observing that, due to the 5%-cement addition to the mixes, the increase in RAP content exerted lower influence on Atterberg limits. This finding points out strong additive influence in comparison to that of the RAP.

Mechanical characterization of soil-RAP and soil-RAP-cement mixes

Table 3 presents the results recorded for soil maximum dry density (ρ_{dmax}) and optimum moisture content (h_{ot}), as well as for mixes with, and without, Portland cement. Also presents some difference in compaction results recorded for cement-free mixes when deformed, and undisturbed, samples are used in the same mix. This difference can be related to treatment applied to the sample to be compacted. In other words, there is RAP fragmentation trend, be it because of undoing lumps or of displacement of asphalt adhered to the aggregate.

Table 3: Compaction test of the materials.

Sample	Deformed sample *		Undisturbed sample **	
	ρ_{dmax} (g/cm³)	h_{ot} (%)	$\rho_{dmáx}$ (g/cm³)	h_{ot} (%)
100S	1,897	13,7	1,894	13,9
20M80S	1,905	13,2	1,920	12,9
30M70S	1,990	9,5	1,920	12,3
50M50S	2,023	8,6	1,940	11,1
95(20M80S)5C	-	-	1,963	12,0
95(30M70S)5C	-	-	1,938	11,3
95(50M50S)5C	-	-	1,967	10,3

* corresponds to a single sample for all of the compaction, according to DNER 162/94.
** corresponds to a sample for each compaction point, according to DNER 172/2016.

Overall increase in RAP content, up to 50%, ended to increase maximum dry density and to reduce the optimum moisture content.

This finding can be attributed to better granulometric stabilization between soil grains and milled material, as well as to fine material part (soil) replacement by low-absorption coarse material (RAP). Yet, cement contributed to change mixes granulometry, as observed in figure 1.

However, RAP content increase effect strongly influenced the drop-trend in optimum moisture content in relation to the increase in mixes maximum dry density.

Alhaji et al. (2019), Alhaji & Alhassan (2018) observed upward trend in maximum dry density and reduction in optimum moisture content after adding RAP to the mix.

However, there is an ideal content of RAP to reach such a trend. The parameters of the compaction can vary after a given content of it. The herein observed behavior was similar to that observed by Mahasneh (2016), i.e., increase in dry density and reduction in moisture content.

The RAP fragmentation trend can be justified by slight changes in granulometry, depending on the rate of RAP added to the tested mixes and to the carried-out compaction. The sequence of granulometric curves shown in figure 2 depicts these changes. Figure 2(a) presents the granulometric curves of the simple soil-RAP mix. Figure 2(b) refers to the 20% content of RAP. It is possible observing almost unperceivable granulometric changes and, consequently, changes in both maximum dry density and optimum moisture content. This is not perceivable because soil content prevails in the mix. Figure 2(c) presents the curves of mixes with 30% RAP, and it is possible observing some changes in the limit corresponding to gravel fraction in comparison to the deformed sample. This change effect was more perceivable in optimum moisture content in comparison to the maximum dry density. Figure 2(d), in its turn, shows the granulometric curves plotted for 50% RAP addition. Granulometric change under this rate was more perceivable in limits set for sand and gravel; there was reduction in this fraction and increase in sand fraction. Accordingly, the effects of such a change are observed in both optimum moisture content and maximum dry density.

Based on this comparative analysis between compaction parameters (Table 3) and granulometric curves (Figure 2), it was possible deducing

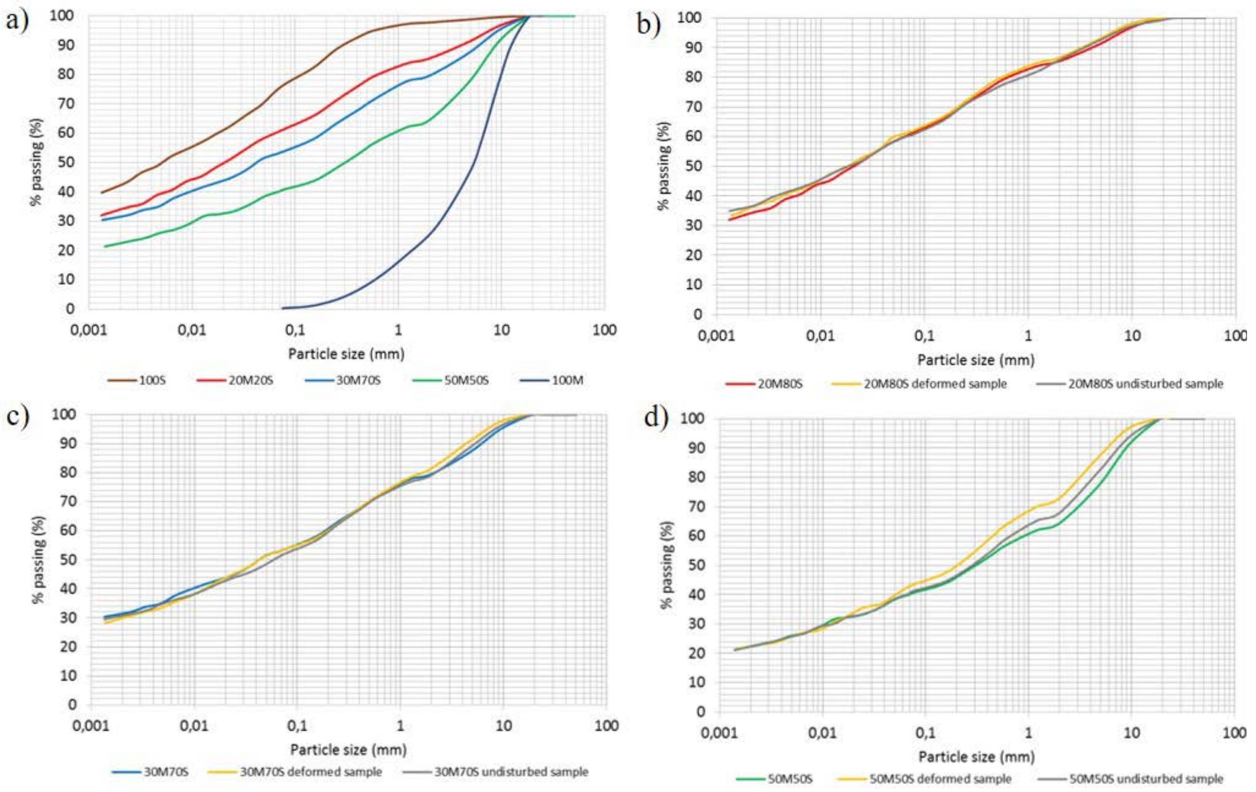

Figure 2 – Grain size distribution: soil, soil-RAP mixes and RAP (a), 80% soil e 20% RAP (b), 70% soil e 30% RAP (c) e 50% soil e 50% RAP (d).

that the blows applied on mixes broke the RAP lumps.

Thus, it reduced the size of the bigger agglomerations, a fact that has contributed to increase the subsequent fraction. Overall, deformed samples presented more significant breaks in lumps than the undisturbed ones.

While the undisturbed samples were subjected to 55 blows per layer (modified effort), the deformed ones were subjected to a sequence of 5-times the number of 55 blows per layer. It is not hard interpreting that this break would be smaller under lower-energy compaction.

Yet, it is possible deducing that soil content in the mix still does influence RAP lump breaking. Compaction parameters and granulometry little change when RAP content is lower (20%) because the soil does not present any fragmentation trend - different from what is observed in the RAP.

When one analyzes the results recorded for compaction parameters applied to mixes added with Portland cement, there is no differences in maximum dry density; it is more outstanding in optimum moisture content. According to O’Flaherty (2002), moisture and maximum dry density are similar to that of pure soil in cement-added mixes. Thus, it is possible confronting data of mixes with and without cement to find such a similarity. Based on studies by Horpibulsuk et al. (2010), using silty clay with different cement contents causes little changes in optimum moisture, even in comparison to pure soil.

Moura et al. (2018) recorded higher maximum dry density results and lower optimum moisture content values in comparison to pure soil. Different cement contents addition to the same RAP content slightly decreased moisture and dry density. Overall, if a certain of RAP rate is exceeded, one can observe low-quality mixes due to more RAP addition, and it leads to new voids.

Table 4 presents CBR results and expansion recorded for soil and mixes (with and without cement) – all of them resulted from undisturbed samples. Increase in RAP content in the mixes showed increased CBR and expansion reduction.

Table 4 - Values of CBR and expansion of the materials

Sample	CBR (%)	Expansion (%)
100S	11	2,5
20M80S	15	2,0
30M70S	18	1,7
50M50S	28	0,4
95(20M80S)5C	197	0,6
95(30M70S)5C	203	0,9
95(50M50S)5C	300	0,2

Despite the few gains in resistance to penetration in cement-free samples, it is possible observing that RAP gave granulometric stability to the soil This same CBR increase trend was observed by Alhaji & Alhassan (2018), Araújo Júnior et al. (2018), Seferoglu et al. (2018) and Kamel et al. (2016) after RAP addition. However, some studies used granulated soils, and it justifies the highest values recorded for resistance in comparison to the results this research. Thus, as recorded by Araújo Júnior et al. (2018), the 50% addition of RAP to the mix led to benefits, since it did not present CBR decrease. Nevertheless, one must not put aside the possibility of finding low values for it when the 50% RAP content is exceeded in the mix.

Data recorded for expansion are justified by the finer fraction found in soil that has higher prevalence in the mix with lower RAP content. This fraction decreases as RAP increases. When the content of such a milled increase, the soil finest fractions decrease, as observed in granulometric curves shown in figure 1. Consequently, mix expansion reduces as cement is added to it.According to Bernucci et al. (2008), soils with significant expansion suffer with deformations when they are requested. There is CBR upward trend as these expansions decrease. Actually, the addition of more RAP led to smaller expansions and to increase in penetration load.

With respect to cement-added mixes, results were higher than those observed for pure soil and cement-free mixes. Cement addition changes material plasticity by changing its granulometry, besides generating strength products. The agglomeration of particles caused by this additive in the mixes guaranteed 10-times higher strength gain in comparison to cement-free samples. Alhaji et al. (2019) and Moura et al. (2018) also recorded higher CBR values in cement-added mixes.

Analysis between compaction parameters applied to undisturbed samples (Table 3) and CBR results (Table 4) showed association between increase in maximum dry density and strength. There was small difference in mix 95(30M70S)5C, which presented small CBR and expansion difference in comparison to the previous and subsequent mixes. However, this discrepancy can be justified by the fact that similarity between the previous mixes only recorded 10% RAP and because of sampling of soil and milled in mix preparation.

A second analysis showed association between lower optimum moisture content values and smaller expansions. Both analyses are valid to increase RAP content and when the mix is added with cement. In this case, RAP addition and the additive lead to granulometric and chemical stabilization, respectively. By observing the Atterberg limitis in table 2, it is possible inferring that RAP and cement addition have reduced plasticity. Such a reduction may be the trace of lower expansions; however, drop in expansion was much more considerable than in plasticity.

Table 5 presents the average of three specimens tested for unconfined compressive strength (UCS) and indirect tensile strength (ITS) for the soil, milled and cement mixes of 7-day cure. Furthermore, the coefficient of variation (cv) was reported. The compression did not react to the same gain trend attributed to those observed for CBR. On the other hand, the tensile presented behavior similar to that of compression.

Table 5 - Values of compressive and tensile strength of the materials.

Sample	UCS (MPa)	cv (%)	ITS (MPa)	cv (%)
95(20M80S)5C	1,23	5,69	0,49	4,08
95(30M70S)5C	1,32	4,55	0,54	1,85
95(50M50S)5C	1,25	6,40	0,47	0,00

Strength gain in mix 95(30M70S)5C, in comparison to mix 95(20M80S)5C, can be attributed to granulometric stabilization caused by RAP addition, which provided some addition of grains to the 30% RAP mixes.

Drop in strength observed for mix 95(50M50S)5C may have resulted from likely excess of material coated with asphalt, since it can lead to losses related to reduced friction between particles, to low adherence between asphalt coating and cement, or, yet from propagation of flaws in asphalt coating itself. Besides, it was possible observing hard time making specimens with 50% milled homogeneous and regular, due to excess of granular material.

Studies by Kasu et al. (2020), Ghanizadeh et al. (2018) and Fedrigo (2015) only showed axial compression drop with RAP content increase. It is worth highlighting that the aforementioned authors used materials with rougher granulation to make mixes with milled; therefore, it is expected to have divergence in results.

However, Maciel et al. (2018) mixed RAP and cement to moderately plastic silty soil and found compression gains due to increased RAP content – although gains were lower than the herein recorded ones.

With respect to additive addition, it accounted for benefits to all mixes, since no specimen resisted immersion in water when they did not have cement in them. Soil plasticity data, even the herein assessed RAP contents, were not enough to contribute with a granular portion capable of ensuring higher resistance to the 5% Portland cement aliquot. Assumingly, higher strength rates can be reached from the addition of higher additive rates.

As for indirect tensile strength, there was strength gain in mix 95(30M70S)5C in comparison to mix 95(20M80S)5C, which was followed by drop in strength in mix 95(50M50S)5C. The same behavior was observed for unconfined compressive strength. Once again, it is worth pointing out the hard time making specimens regular, mainly that of mix 95(50M50S)5C, which was worsened by the reduced dimensions of specimens used in test.

Baldovino et al. (2020) cite studies, according to which, the addition of other alternative materials, such as fibers, to the soil-cement mix led to association between tensile and compression strength. Thus, the presence of a ductile material, such as asphalt-coating RAP aggregates, likely increased tension distribution capacity in specimens, and it contributed to strength-to-traction gain.

Dokovic et al. (2019) cite that mixes whose tensile are higher than 0.4 MPa represent satisfactory stabilization. Accordingly, the performance recorded for the mixes was good, because the observed tensile strength corresponded to unconfined compressive rates ranging from 38% to 41%.

According to Ingles & Metcalf (1972), tensile strength is close to 10% of the compressive strength. Studies presented by Dokovic et al. (2019), Oliveira (2018), Fedrigo (2015), Trichês et al. (2013) also recorded associations higher than those indicated by Ingles & Metcalf (1972) when they analyzed tensile and compression tests of mixes added with RAP and cement.

Durability test led to mass losses equal to 4.68%, 4.20% and 2.20%, in mixes 95(20M80S)5C, 95(30M70S)5C and 95(50M50S)5C, respectively. Given the recorded low mass losses, it is possible assuming that RAP reduced mass loss in the mixes. It may be explained by the fact that granular material addition, such as RAP, to a clayey base brought along improvements that made cements agglutinating action more efficient.

Low values were also observed by Kasu et al. (2020) and Avirneni et al. (2016). Vargas (1978) and Catton (1962) cite that mass loss in A-7 soil stabilized with cement must not be higher than 7%. Ingles & Metcalf (1972) inform soil-cement mass loss requirement equal to 7% for the sub-base, to 10% for bases for light traffic roads and to 14% for intense traffic roads.

Hydraulic characterization of soil-RAP and soil-RAP-cement mixes

Permeability test showed hydraulic conductivity at magnitude of 10^{-7} cm/s in pure soil and in mixes with 20% and 30% RAP. As for the 50% mix, conductivity recorded 10^{-6} cm/s. This difference in magnitude is associated with the addition of higher RAP rates, since it makes water passage through the small interconnected channels easier. Permeability values close to those of pure soil (100S) in mixes 20M80S and 30M70S are justified by the prevailing amount of soil in the mix.

When cement was added to the mixes, their permeability at RAP rates of 20% and 30% recorded conductivity at magnitude 10^{-8} cm/s, and this value was lower than that in cement-free mixes. Mixes with 50% content, in their turn, did not show variation in magnitude (10^{-6} cm/s) in comparison to the cement-added mixes. This finding meets statements by Ingles & Metcalf (1972). Impermeability in different mixes and in pure soil was taken into consideration, even with changes in hydraulic conductivity magnitude.

It is likely to have chemical-nature factors, given that the herein used CP V-ARI cement has composition and fineness features different from those of common cement, which reduce permeability. Therefore, it is necessary carrying out specifics tests to assess this hypothesis. Mollamahmutoglu & Avci (2018) studied the effects of highly plastic clayey mix with superfine cement and found reduced permeability due to increased cement content.

Assessing the feasibility of using mixes in pavement layers

The recorded results allowed assessing the technical feasibility of using mixes based on standards DNIT: 139-ES: Paving – granulometrically stabilized sub-base; 141-ES: Paving – granulometrically stabilized base; 140-ES: Paving

– sub-base of soil improved with cement; 142-ES: Paving – base of soil improved with cement; and 143-ES: Paving – Soil-cement base.

Table 6 presents a checklist that shows the requirements in the aforementioned standards to apply the empirical method for pavement dimensioning to find out whether the mixes fulfil, or not, such requirements.

Table 6 - Checklist for the requirements of the DNIT standard.

Standard	Requirements	Service					
		without cement			with 5% cement		
		20M80S	30M70S	50M50S	95(20M80S)	95(30M70S)	95(50M50S)
DNIT 139/2010 – ES	IG = 0	No	No	No	-	-	-
	% retained #10 consisting of hard particles, free of soft fragments, organic materials or prejudicial substances	Yes	Yes	Yes	-	-	-
	CBR ≥ 20%	No	No	Yes	-	-	-
	Expansion ≤ 1%	No	No	Yes	-	-	-
DNIT 141/2010 – ES	Granulometry falls within one of the indicated ranges	No	No	No	-	-	-
	LL ≤ 25% e PI ≤ 6%	No	No	No	-	-	-
	% passing on #200 ≤ % passing na #40	No	No	No	-	-	-
	CBR ≥ 80% ou CBR ≥ 60%	No	No	No	-	-	-
	Expansion ≤ 0,5%	No	No	Yes	-	-	-
	Abrasion ≤ 55%	Yes	Yes	Yes	-	-	-
DNIT 140/2022 – ES	% retained #10 consisting of hard particles, free of soft fragments, organic materials or prejudicial substances	-	-	-	Yes	Yes	Yes
	CBR ≥ 30%	-	-	-	Yes	Yes	Yes
	Expansion ≤ 1%	-	-	-	Yes	Yes	Yes
	LL ≤ 25% e PI ≤ 6%				No	No	No
DNIT 142/2022 – ES	% retained #10 consisting of hard particles, free of soft fragments, organic materials or prejudicial substances	-	-	-	Yes	Yes	Yes
	CBR ≥ 80%	-	-	-	Yes	Yes	Yes
	Expansion ≤ 0,5%	-	-	-	No	No	Yes
	LL ≤ 25% e PI ≤ 6%	-	-	-	No	No	No
DNIT 143/2022 – ES	Soil granulometry falls within the indicated range	-	-	-	No	No	No
	UCS ≥ 2,1 MPa	-	-	-	No	No	No

Although RAP and cement additions have improved soil and mixes properties, they were capable of making the materials able to be used as pavement base and sub-base layers. The greatest challenge was presented by soil features, rather than by RAP.

Soil appeared too fine and highly plastic, and these features were not changed enough to meet the requirements for granulometrically stabilized layer of soil improved with either cement or soil-cement base.

Figure 3 depicts the granulometric curve of soil and mixes, with and without cement, at limit F of DNIT 141-ES standard, which corresponds to one of the granulometric composition limits demanded for granulometrically stabilized bases for light traffic roads.

As already shown in table 6, none of the cement-free mixes matched the aforementioned limit.

Accordingly, figure 4 presents the granulometric curve of soil and mixes, with and without cement, in the granulometric limit set by DNIT 143-ES standard. Once again, none of the cement-free mixes matched the limit.

However, although mixes 95(30M70S)5C and 95(50M50S)5C regard cement-free mixes, it was observed that they matched limit F of DNIT 141-ES standard and that all soil-RAP-cement mixes

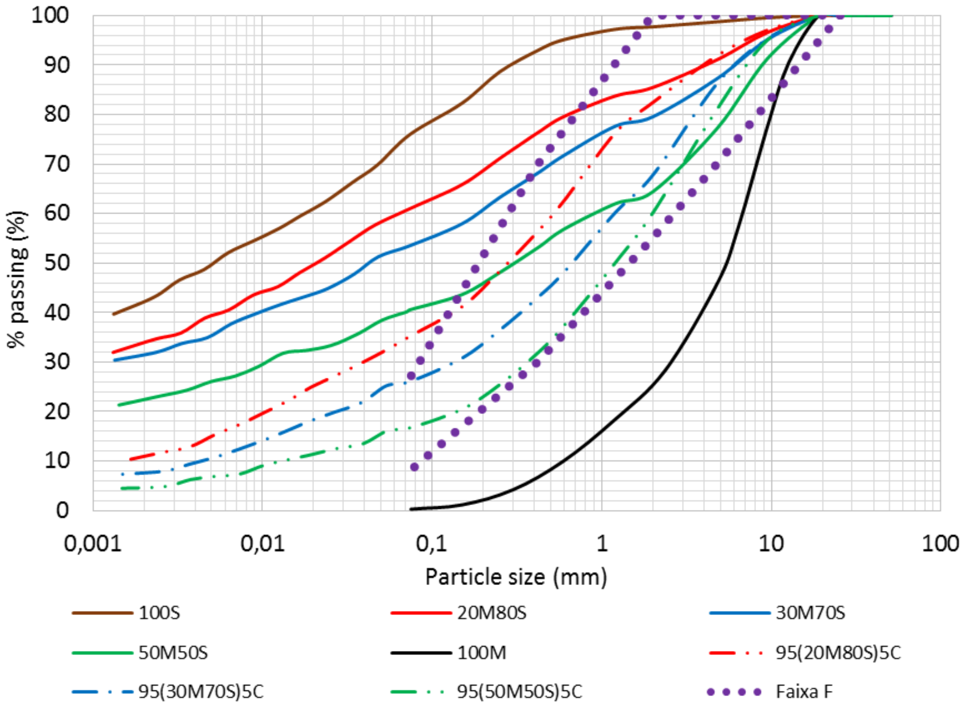

Figure 3 - Grain size distribution of the soil, mixes and RAP inserted in the limits of granulometric range F of the DNIT 141-ES standard.

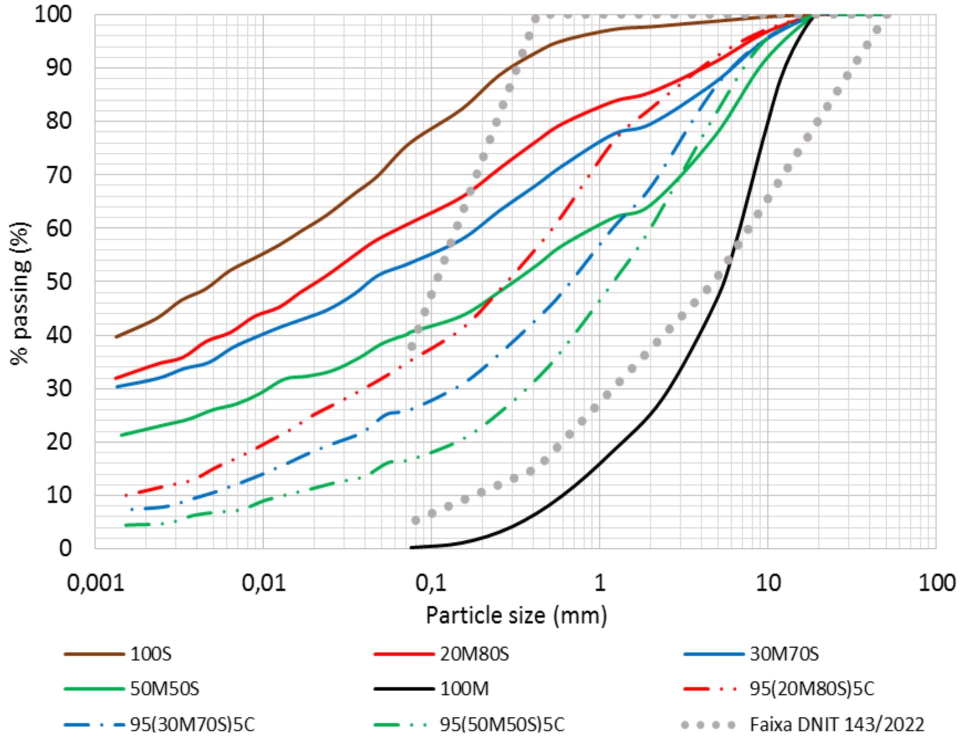

Figure 4 - Grain size distribution for the soil, mixes and RAP inserted in the limits of granulometric range of the DNIT 143-ES standard.

matched the granulometric limit of DNIT 143-ES standard.

This finding led to the enquiry about the possibility of facing soil-RAP-cement mixes as new granular material, given that 5% cement is seen as low content to change a highly plastic fine soil.

Economic feasibility had to be assessed, because it would be necessary using more additive to solve the plasticity issue and, in case of demands for cement improved base and of soil-cement base, it would be necessary to make a new cement addition.

However, according to requirements in DNIT 141-ES standard, mixes 95(30M70S)5C and 95(50M50S)5C could be used as base for light traffic road if they are taken as new granular material and if their plasticity is controlled.

CONCLUSIONS

Based on results analysis and discussion, it is possible concluding that:

a) RAP addition to mixes with soil made them more granular and, consequently, it reduced their plasticity, without changing soil classification. It also increased maximum dry density and reduced optimum moisture content in them. There was increase in CBR and expansion reduction;

b) CP V-ARI cement addition made the mixes even more granular and moderately plastic. It changed ASSHTO classification and significantly stressed the CBR increase;

c) the highest unconfined compressive strength and indirect tensile strength in soil-RAP-cement mixtures was achieved for the mixture containing 30% RAP. However, it was lower than requirements in the soil-cement standard. Nevertheless, the tensile strength recorded for the mixes was satisfactory;

d) cement-added mixes presented good durability. Increased RAP content reduced mass loss in the mixes;

e) increase of RAP content can increase permeability. On the other hand, coefficient of permeability can have its magnitude reduced due to cement addition;

f) although RAP and Portland cement addition did not match the conditions imposed by DNIT standards for use in pavements base and sub-base layers, these additions improved the mixes properties;

g) in respect to soil-RAP-cement mixes, in particular, it is possible stating that they got closer to mixes with cement improved soil than soil-cement mixes, because they improved their susceptibility to water and reduced their expansions, but they did not get stiffness equivalent to that of soil-cement mixes.

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