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Recycling of Portuguese granite quarry fines in geotechnical works: hydraulic and mechanical characterization

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ABSTRACT The fines of two Portuguese granite quarries, located in the Northern region, have been object of a research program aiming its recycling in the construction of transport infrastructures and geotechnical works. In the first phase of this program, a vast number of laboratorial tests were carried out to determine the geoenvironmental and geotechnical properties of these materials. In a second phase, the materials will be used to construct a trial embankment road section. In this paper, the results obtained in the hydraulic and mechanical laboratory tests are presented and discussed. It is concluded that the studied materials show technical viability to be used, in particular, in the construction of embankment transport infrastructures.

INTRODUCTION

The extractive and transformation industry in Portugal produces several dozen million tons of aggregates and ornamental rocks per year (t/y) for consumption in the construction industry. This activity originates annually a high amount of quarry fines, for which there are no technically and economically viable applications able to mitigate, either the costs related to their stockage and management, or their negative influences on the environment.

Nowadays, the waste prevention and management legislation and policies privilege the prevention, reuse and recycling of the quarry fines, and of the waste in general, instead of its elimination in landfill, being that the advantages that result from the implementation of these procedures are both environmental and economical, namely: a) the extension of the lifetime of the landfills; b) the preservation of the non-renewable natural resources; c) the reduction of the emission of CO_2 to the atmosphere; and d) the possibility of constructing the public works with lower costs.

The application in transport infrastructures and geotechnical works is one of many possibilities of recycling of these wastes in the construction industry, with important advantages, which derive from the fact these works consume, normally, great volumes of material and avoid rather expensive treatments of the raw materials, contrarily to other industrial applications.

In this context, an agreement on cooperation was established between the National Laboratory of Civil Engineering (LNEC) and Mota-Engil Company (ME Group), which explores granite quarries in the Northern region of Portugal and pretends to identify solutions for the valorisation of fines that result from the production of aggregates and sands. This research program, in which the Faculty of Sciences of the University of Lisbon (FCUL) also participates, aims to evaluate the adequacy of these materials for the construction of transport infrastructures and other geotechnical works, namely in clay liners and final covers of landfills, in the containment of contaminated areas and in embankments.

The first phase of the experimental program refers to an exhaustive geoenvironmental and geotechnical laboratorial study of the fines of two granite quarries selected by ME Group, which comprehended chemical (classical and environmental), mineralogical, physical, hydraulic and mechanical characterization tests.

In a second phase, a trial embankment road section will be performed to calibrate the laboratory results and to evaluate the performance of quarry fines in the construction of embankment transport infrastructures.

The results obtained in the first characterization phase of these materials concerning the hydraulic and mechanical (deformability and shear strength) laboratory tests are presented and analysed in this paper.

MATERIALS AND METHODS

Granite Quarry Fines

The granite quarry fines are generated during the process of production of inerts (crushing, screening and washing of aggregates and sands) in the ME Group Industrial Centres (quarries). This Company explores six granite quarries in the Northern region of the country (Fig. 1), which produce a total of 63 000 t/y of fines. The joint production of the two selected quarries, Moinho de Vento Quarry, in Portela, Famalicão (FAM), and Bouça do Menino Quarry, in Cervães, Barcelos (CRV), is nearly 25 000 t/y of fines.

In both quarries the explored rock is the calc-alkaline two-mica granite (monzogranite or monzonitic granite), predominantly biotitic, of hercynian age. In FAM, the extracted rocks belong to the "Airão, Aves and Roriz Granites" and present medium grain with a porphyritic tendency, while in CRV the granites belong to the variety designed as "Non-porphyritic granite, with coarse grain or coarse to medium grain".

Since the processing methods of the fines is different in both quarries, it was necessary to adopt different sampling procedures in each of them. In FAM, the cake, which designates the quarry fines after being pressed and dehydrated in a press-filter, was directly sampled with a shovel of a wheel loader. In CRV a wooden and open structure was constructed and interiorly lined with geotextile to prevent material losses during the direct collection of the quarry sludges from a reservoir tank. The samples collected in the quarries, each one with approximately 4 t, were adequately conditioned in plastic containers and transported to laboratory. According to the defined criteria, the samples were initially air-dried and, after, desegregated with hammers lined with rubber. After being desegregated, the material was sieved, homogenised and conditioned in bags.

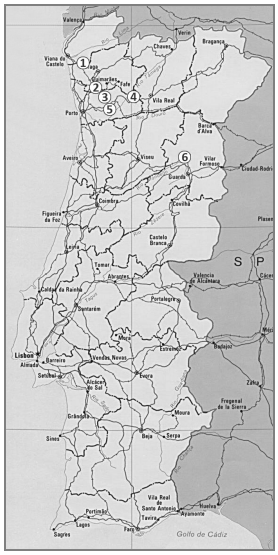


Fig. 1 Location of the granite quarries of ME Group, with inert washing facilities and production of fines

The laboratorial characterization revealed that the quarry fines present: a) high natural moisture content, w, (FAM: 34.6%; CRV: 25.2%); b) specific gravity of solid particles, G_s, reflecting the mineralogical composition and similar to the majority of natural soils (FAM: 2.66; CRV: 2.73); c) non plastic characteristics, in the case of CRV, and liquid limit, w_L, of 39 and plasticity index, I_P, of 13, in the case of FAM; and d) fine-grained size (FAM: 18% sand, 67% silt and 15% clay; CRV: 49% sand, 46% silt and 5% clay). Table 1 presents the compaction parameters obtained in both samples.

TABLE 1 Compaction parameters of the quarry fines

Compaction parameters		Quarry	
		FAM	CRV
Standard Proctor (SP)	γ_{dmax} (kN/m^3)	15.4	13.3
	OMC_{SP} (%)	19.9	17.9
Modified Proctor (MP)	γ_{dmax} (kN/m^3)	17.3	17.2
	OMC_{MP} (%)	15.0	13.6

γ_{dmax} = Maximum dry density; *OMC* = Optimum moisture content.

Considering the Unified Soil Classification System (USCS) of the American Society for Testing and Materials (ASTM D 2487-00), the fines of both quarries are classified as ML: inorganic sandy silts or with sand. The application of the classification for roadway purposes of the American Association of State Highway and Transportation Officials (AASHTO Classification System) show that the FAM fines belong to group A-6 of clayey soils and the CRV fines to group A-4 of silty soils.

The evaluation of the degree of environmental hazardness of the quarry fines revealed that these materials are inert waste, hence with low pollutant potential. Therefore, it is not expected that the construction of transport infrastructures and geotechnical works with these materials can contribute to the degradation of the quality of subsoil and water resources.

The fines from both quarries present a similar mineralogical composition, with quartz, feldspar and mica as predominant minerals. The X-ray diffractograms of the clayey fraction, however, reveal a rather high proportion of smectite in FAM and a reduced proportion in CRV.

Permeability Tests

The hydraulic performance of the quarry fines was evaluated based on the hydraulic conductivity, *k*, determined in permeability tests, using a rigid-wall permeameter (101.4 mm diameter, 50.0 mm height).

The ASTM D 5856-95 (2002) Standard and the methodologies proposed by Roque (2001) were adopted in the realization of the tests. Two sets of specimens were prepared, each one with four distinct moisture contents: a) 2% dry of *OMC* ($OMC_{-2\%}$); b) *OMC*; c) 2% wet of *OMC* ($OMC_{+2\%}$); and d) 4% wet of *OMC* ($OMC_{+4\%}$). One of the sets was compacted with standard Proctor equivalent effort (SP) and another with modified Proctor equivalent effort (MP), totalizing 16 specimens.

The permeability tests were carried out with demineralised water and downward percolation, to better simulate the real infiltration conditions that occur in the majority of geotechnical works in which these materials can be applied. A constant head was applied in the permeability tests, with four different levels, always beginning in the level with a lower head. The FAM fines, that present a lower *k* than the CRV fines, were subject to a maximum head of 2.00 m (hydraulic gradient, $i = 40$), while in CRV the maximum head was 1.00 m ($i = 20$).

Consolidation Tests

The compressibility study of the quarry fines involved the conduction of one-dimensional consolidation tests in an oedometer. In the initial phase of the tests the necessary procedures were adopted to evaluate the one-dimensional swell or settlement potential of the materials, in order to anticipate the sensibility to water and its volumetric behaviour in public works. The respective test procedures were adapted from ASTM D 2435-04 and ASTM D 4546-03 standards.

The tests were conducted with specimens prepared with $OMC_{SP-2\%}$, OMC_{SP}, $OMC_{MP-2\%}$ and OMC_{MP}. Two specimens were prepared for each moisture content and each Proctor equivalent effort, corresponding to a total of eight by quarry, to which a vertical effective stress, σ_v, of approximately 25 and 50 kPa was initially applied.

The loading plan of the specimens included two phases. Initially, with the aim of evaluating the volumetric behaviour of the fines, each specimen was submitted to a σ_v of approximately 25 or 50 kPa and to inundation. Only after the evaluation of the one-dimensional expansive or collapse potential, did the consolidation tests begin. In this second phase of

loading, the maximum vertical effective stress reached 399.1 kPa. During the test, a discharge-recharge cycle took place, to assess the swell and recompression characteristics of the materials.

Triaxial compression shear tests

The mechanical strength of the quarry fines was determined by the realization of triaxial compression shear tests, consolidated drained. The tests were conducted according to an internal LNEC procedure, adapted from the standard BS 1377: Part 8:1990, of the British Standards Institution, in two main stages: a) saturation (applying back pressure) and consolidation; and b) specimens compression (shearing to failure). The tests ended when the imposed axial strain was around 20%.

The experimental program included tests over specimens prepared with $OMC_{SP-2\%}$, OMC_{SP} $OMC_{MP-2\%}$ and OMC_{MP}. Four specimens were prepared for each moisture content and each Proctor equivalent effort, in a total of 16 by quarry, to which were applied, respectively, confining effective stresses of 25, 50, 100 and 200 kPa. The execution of these tests aimed, beyond the determination of the intrinsic characteristics of the shear strength, the evaluation of the eventual influence of the moisture content and Proctor equivalent effort in the mechanical strength of the fines.

RESULTS

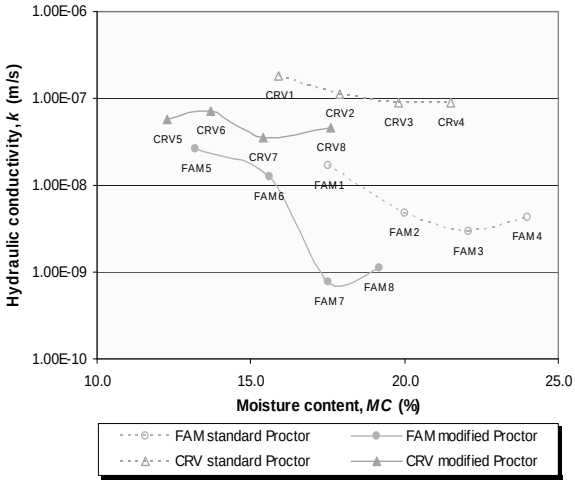
Hydraulic Conductivity

Fig. 2 presents, for all the specimens of FAM and CRV, the mean value of k, determined from the values of k after the flow rate stabilization, and the variation of k in function of the value of the moisture content of the tested standard Proctor and modified Proctor specimens.

Deformability

The one-dimensional swell or settlement potential evaluation tests showed that the quarry fines do not reveal significant volumetric variations when subject to inundation, reason for which it is not relevant to present the obtained results in this paper. The maximum swell, lower than 0.4%, was observed in two specimens and the collapse, with a maximum value of 0.7%, in the other 14 specimens.

The results obtained in the consolidation phase of the oedometer test are resumed in Table 2, where the compression index (C_c) and the swell index (C_r) are indicated for the 16 specimens.



Specimen hydraulic conductivity k x 10^{-9} (m/s)[(a)]			
standard Proctor			
FAM1 ($OMC_{SP-2\%}$)	= 17.0	CRV1 ($OMC_{SP-2\%}$)	= 180.0
FAM2 (OMC_{SP})	= 4.8	CRV2 (OMC_{SP})	= 110.0
FAM3 ($OMC_{SP+2\%}$)	= 2.9	CRV3 ($OMC_{SP+2\%}$)	= 89.0
FAM4 ($OMC_{SP+4\%}$)	= 4.3	CRV4 ($OMC_{SP+4\%}$)	= 90.0
modified Proctor			
FAM5 ($OMC_{MP-2\%}$)	= 26.0	CRV5 ($OMC_{MP-2\%}$)	= 57.0
FAM6 (OMC_{MP})	= 12.0	CRV6 (OMC_{MP})	= 72.0
FAM7 ($OMC_{MP+2\%}$)	= 0.8	CRV7 ($OMC_{MP+2\%}$)	= 35.0
FAM8 ($OMC_{MP+4\%}$)	= 1.1	CRV8 ($OMC_{MP+4\%}$)	= 47.0

[(a)] Test temperature, T = 20 ºC.

Fig. 2 Variation of the hydraulic conductivity value in function of the moisture content value of the FAM and CRV standard Proctor and modified Proctor specimens.

TABLE 2 Compression and swell indexes of the FAM and CRV standard Proctor and modified Proctor specimens

Index	Specimen							
	FAM1 ($OMC_{SP-2\%}$)		**FAM2 (OMC_{SP})**		**FAM3 ($OMC_{MP-2\%}$)**		**FAM4 (OMC_{MP})**	
	FAM1a	**FAM1b**	**FAM2a**	**FAM2b**	**FAM3a**	**FAM3b**	**FAM4a**	**FAM4b**
C_c	0.0395	0.0365	0.0402	0.0335	0.0333	0.0232	0.0277	0.0246
C_r	0.0131	0.0136	0.0226	0.0145	0.0121	0.0116	0.0138	0.0121
	Specimen							
	CRV1 ($OMC_{SP-2\%}$)		**CRV2 (OMC_{SP})**		**CRV3 ($OMC_{MP-2\%}$)**		**CRV4 (OMC_{MP})**	
	CRV1a	**CRV1b**	**CRV2a**	**CRV2b**	**CRV3a**	**CRV3b**	**CRV4a**	**CRV4b**
C_c	0.0315	0.0195	0.0249	0.0302	0.0179	0.0231	0.0192	0.0139
C_r	0.0007	0.0049	0.0066	0.0048	0.0056	0.0046	0.0043	0.0069

"a" and "b" in FAM and CRV indicate that the vertical stress applied to the specimen during the inundation phase was 25 kPa and 50 kPa (approximate values), respectively.

Shear Strength

The values obtained, in the triaxial compression shear tests, for internal friction angle by the peak failure criteria, in effective stresses, φ', were the following: 31.9º, in FAM1 ($OMC_{SP-2\%}$), 32.2º, in FAM2 (OMC_{SP}), 38.3º, in CRV1 ($OMC_{SP-2\%}$), and 34.2º, in CRV2 (OMC_{SP}). These values result from the test of series of three specimens. The specimens of FAM1, FAM2 and CRV1 were subject to the confining effective stresses, σ_3', of 25, 50 and 100 kPa, while the specimens of CRV2 were subject to a σ_3' of 50, 100 and 200 kPa. Since the remaining tests are in development, it is not possible to present their results.

DISCUSSION

The hydraulic characterization shows that the studied quarry fines present very low k values, with FAM being the less permeable.

The values of k in the SP specimens of the FAM fines were around 4.0×10^{-9} m/s, with the exception of the specimen FAM1, $OMC_{SP-2\%}$, in which the obtained value was around 1.7×10^{-8} m/s. The same uniformity of values is not observed in the MP specimens for different compaction moisture contents, but the behaviour is identical, that is, the value of k reduces from $OMC_{MP-2\%}$ to $OMC_{MP+2\%}$ and rises from $OMC_{MP+2\%}$ to $OMC_{MP+4\%}$. As a matter of fact, for both Proctor equivalent efforts, the value of k reduces with the increase of the compaction moisture content, but the lower values were obtained in the specimens $OMC_{SP+2\%}$ and $OMC_{MP+2\%}$.

Similar behaviour was observed in the CRV specimens, although the reduction of k given an increase in MC is less significant than in FAM. Similarly to what was observed in FAM, there is also no reduction in the value of k in the CRV specimens compacted with MC higher to $OMC_{SP+2\%}$ and $OMC_{MP+2\%}$. Respecting the k values obtained in the specimens belonging to each of the Proctor equivalent efforts, uniformity is observed, with the SP specimens presenting values of k around 1.0×10^{-7} m/s and the MP specimens values around 5.0×10^{-8} m/s.

In general, considering the fines of both quarries, the values of k from the MP specimens were always lower than the k values from the SP specimens, independently of the compaction MC. Considering the lowest values of k in the MP and SP specimens of the two quarries fines, obtained in the specimens $OMC_{MP+2\%}$ (FAM7 and CRV7) and $OMC_{SP+2\%}$ (FAM3 and CRV3), respectively, it is concluded that, with the MP equivalent energy, the value of k decreases around 4 times in FAM and 2.5 times in CRV, compared with the SP equivalent energy.

Considering the obtained values of k and the values depicted in the current Portuguese legis-

lation (Decree-Law n.º 183/2009, August 10th), it is observed that the FAM fines are adequate for the construction of the clay liner of inert landfills. The same applies to the CRV fines when compacted with the MP method and with *MC* higher than *OMC* when compacted with the SP energy. Considering the case of the non-hazardous and hazardous landfills, only the FAM fines with $OMC_{MP+2\%}$ reveal adequate for the construction of the liner system. Concerning the construction of the landfill final cover, the possibility to apply these materials in its construction is admissible, given that the legislation mentioned above does not contain any minimum requirements for the value of *k*.

Concerning the deformability parameters obtained, the values of C_c (0.0139 to 0.0402) and C_r (0.0007 to 0.0226) indexes are rather low, for it is possible to admit the recycling of these materials in the construction, for example, of embankments of transport infrastructures. Compared to FAM fines, the CRV fines present lower C_c and C_r indexes, especially in what concerns C_r.

It should be noted that, in general, the values of C_c are higher in the SP specimens, either in FAM or CRV. Concerning C_r, it is observable that for the FAM fines, the values are always bigger in the SP specimens than in the MP specimens, while for the CRV fines no relation is observed between C_r and the Proctor equivalent effort.

The values obtained in the triaxial compression shear tests for internal friction angle, in effective stress, vary between 31.9º and 38.3º, showing that the shear strength of these materials is reasonable. These values are similar to those referenced in the bibliography for sand materials.

CONCLUSIONS

This research program pretends to contribute to the recycling of waste, in general, and of quarry fines, in particular, through its use in transport infrastructures and geotechnical works, in substitution of the non-renewable natural materials traditionally applied.

The hydraulic characterization of these materials revealed that, despite presenting a very low *k*, lower than 2.6×10^{-8} m/s, in FAM fines, and than 1.8×10^{-7} m/s, in CRV fines, only in the FAM fines with $OMC_{MP+2\%,}$ the value of *k* satisfies the minimum requirements ($k \leq 1{,}0 \times 10^{-9}$ m/s) demanded by the current Portuguese legislation for its use in the construction of the clay liner of hazardous and non-hazardous landfills. In the case of inert landfills, since the value of *k* required by the legislation is lower or equal to 1.0×10^{-7} m/s, the obtained values of *k* for FAM fines show its viability for its application in the studied moisture contents and Proctor equivalent effort. The same applies for the CRV fines compacted with MP equivalent effort and compacted with *MC* higher to *OMC* with SP equivalent effort. Concerning the construction of the landfill final cover, it is admissible, considering the low value of *k* obtained with the two quarry fines, the application of these materials in its construction, since the current legislation does not demand any minimum requirements for the value of *k*.

On the other hand, the mechanical characterization of the quarry fines showed a low compressibility (C_c between 0.0139 and 0.0402) and reasonable shear strength (internal friction angle, in effective stress, φ', between 31.9º and 38.3º), which reveals its suitability for the construction of embankments of transport infrastructures and of geotechnical works.

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REFERENCES

Roque, A. J. (2001). Transfert advectif et diffusif de polluants inorganiques dans les barrières d'étanchéité minérales présentes dans les Centres de Stockage de Déchets. Application aux sols fins portugais. Thèse de Doctorat Génie Civil – Sols, INSA de Lyon, 697 p.