Civil Engineering
Engengharia Civil

Analysis of the Resilient Modulus and California Bearing Ratio in mixtures containing slate waste and clayey soil

http://dx.doi.org/10.1590/0370-44672021740028

Raphael Lucio Reis dos Santos[1,4]
https://orcid.org/0000-0002-6644-200X
Conrado de Souza Rodrigues[2,5]
https://orcid.org/0000-0002-7306-8845
Vinícius Antônio Florentino Camargo[3,6]
https://orcid.org/0000-0002-2296-7525
Armando Belato Pereira[1,7]
https://orcid.org/0000-0002-5229-5483
João Marcos Guimarães Rabelo[1,8]
https://orcid.org/0000-0001-8638-4348

[1]Centro Federal de Educação Tecnológica de Minas Gerais - CEFET-MG, Varginha - Minas Gerais - Brasil.

[2]Centro Federal de Educação Tecnológica de Minas Gerais - CEFET-MG, Belo Horizonte - Minas Gerais - Brasil.

[3]Departamento de Edificações e Estradas de Rodagem de Minas Gerais - DER-MG, Belo Horizonte - Minas Gerais - Brasil.

E-mails : [4]raphael.santos@cefetmg.br, [5]crodrigues@civil.cefetmg.br, [6]viniciusflorentinocamargo@gmail.com, [7]armandobelato@cefetmg.br, [8]joaomarcos@cefetmg.br

Abstract

The use of slate waste can help to reduce the impacts caused to the environment due to the decrease of the appropriate disposal areas and the disordered consumption of raw material. This article presents an analysis of the Resilient Modulus (RM) and the California Bearing Ratio (CBR) of this waste in mixtures with clayey soil. To analyze variations in RM and CBR due to the increase in the slate waste content, tests were carried out on reference mixtures (REF) and mixtures containing slate waste (SLT). The tests were carried out for mixtures of granular material (gneiss for REF and slate waste for SLT) and clay soil, containing different levels of granular materials (50%, 60%, 70%, 80% and 90%) It was observed that the values of Resilient Modulus and California Bearing Ratio of the SLT mixtures increased 62.8% and 127.0% with the addition of the slate waste between the SLT 50/50 and SLT 90/10 mixtures, respectively. This behavior was similar to that presented by the REF mixtures, which increased 125.0% in RM and 60.1% in CBR for the same addition of granular material. The results obtained indicate that the mixtures containing slate waste presented RM and CBR similar to those of conventional materials (such as the REF mixtures) used in layers of sub-base and the base of pavements. Finally, it was concluded that the relationship between RM and CBR is non-linear for both mixtures (REF and SLT) in function of granular material addition.

Keywords: California Bearing Ratio, geotechnical tests, resilient modulus, pavement, slate waste.

1. Introduction

Almost all human and industrial activities produce waste and its increasing accumulation is the cause of serious environmental and economic issues in the world (Cardoso, 2016). Disfani *et al.* (2011) indicated that the reuse of waste reduces the demand for scarce virgin natural resources, as well as reduces the amount of waste deposited.

The reuse of recycled granular materials (RGM) presents significantly lower carbon footprints compared to traditional quarried materials, which will consequently lead to a more sustainable environment (Arulrajah *et al.*, 2013). RGM can be used as alternatives materials for civil works (Del carpio, 2006; Aatheesan *et al.*, 2010; Arulrajah *et al.*, 2013). Therefore, the usage of RGM (including slate waste) is considered a viable and sustainable solution to minimize the waste while reducing the demand for scarce virgin quarried materials.

Brazil is the second largest producer and exporter of slate in the world (Spain is the first), with 90% of the national production coming from the State of Minas Gerais (Rodrigues, 2015). According to Chiodi and Chiodi (2014), the production of slate in the State is about 0.6 million tons per year. The extraction of slate for use as a construction material generates large quantities of waste (about 30% in mass) that are disposed on nearby extraction sites, with the consequent technical, economic, environmental, and social problems (Mansur *et al.*, 2006).

Several researchers have compared the RM of MGR with that of conventional natural aggregates. The studies by Leite *et al.* (2011) and Molin *et al.* (2004) indicated that the RM is similar for recycled and natural materials. Other authors have indicated that the addition of MGR in mixtures for application as pavement layers increases the RM value (Arm, 2003; Kim *et al.*, 2007). Although some studies have been carried out to evaluate the resilient modulus in MGR for paving applications, few have been carried out to examine RM and CBR due to the percentage increase of waste in mixtures.

In this context, due to the large volume of waste from slate cutting available in Minas Gerais, the environmental responsibility and the possibility of application in pavement, this article aims to analyse the resilient modulus and California Bearing Ratio of mixtures containing slate waste to verify their properties in comparison with conventional mixtures of paving materials.

2. Resilient modulus

According to Brito (2006), resilient modulus was introduced by Francis Hveem in 1955, to better represent the Elasticity Module (EM) of the materials under cyclic loading. Both the RM and the EM have the same concept, both being represented by the ratio between the tension and the deformation. The motivation for the differentiation of these, were the discrepancies between the order of magnitude of displacements of the materials used in paving with respect to the elastic materials commonly used in engineering.

Literature provides several equations that have been used to model the RM of soils and granular materials, but several authors (Medina and Motta, 2005; Klinsky, 2008, Solanki *et al.*, 2010) reports that Equation 1, based on the composite model and presents in Standard Method of Test for Determining the Resilient Modulus of Soil and Aggregate Materials (AASTHO, 2003), produces good determination of the RM, independent of the granulometry of the evaluated material.

$$RM = K_1 \times \sigma_3^{K_2} \times \sigma_d^{K_3} \quad (1)$$

Where: RM = Resilient Modulus;
σ_3 = Containment tension;
σ_d = Deviation tension; K_1, K_2 e K_3 = Experimental coefficients.

The researched literature indicates RM values for granular materials in the range of 100 MPa and 500 MPa, as also reported in studies by Bennert *et al.* (2000). Table 1 presents the mean RM values in surveys for different types of materials (included RGM) applied to the pavement.

Table 1 - Resilient modulus values for granular materials in the researched literature.

Authors	Granular materials	Compaction energy	RM (MPa)
Nunes *et al.* (1996)	Slate waste	Modified	272
Bennert *et al.* (2000)	Recycled concrete aggregate	Normal	378
Nataatmadja and Tan (2001)	Recycled concrete aggregate	Modified	337
Neto (2004)	Mixture of gravel (50%) + sandy soil (50%)	Modified	207
	Mixture of gravel (70%) + clay soil (30%)	Modified	236
Fernandes (2004)	Recycled aggregates of construction and demolition waste (CDW)	Intermediate	242
		Modified	276
Leite (2007)	Recycled aggregates of construction and demolition waste (CDW)	Intermediate	270
		Modified	320

All studies indicated in Table 1, obtained resilient modulus within the range indicated for conventional materials by Thorn and Brown (1989): limestone (330 - 540 MPa), granite (300 MPa), sandstone (290 MPa), sand and gravel mixture (140 - 470 MPa) and sand (110 - 150 MPa). Although, Nunes *et al.* (1996) concluded that the slate waste studied posse adequate resilient properties, but not high when compared with primary aggregates.

3. Methodology

In this research, two different mixtures containing granular material and clayey soil were evaluated. The first mixture, used as reference (REF), containing gneiss stabilized granulometrically with clayey soil (conventional material used in paving). And the second, denominated SLT, a mixture of slate waste with clayey soil (same material used in REF).

The REF and SLT materials were mixed in the proportions of 50%, 60%, 70%, 80% and 90% (in mass), of granular material in the mixtures for the geotechnical characterization. The representation of the mixtures is summarized in Table 2.

Table 2 - Content of the REF and SLT.

Mixtures	% of aggregate	% of soil	Representation
Gneiss + Clayey soil	50	50	REF 50/50
	60	40	REF 60/40
	70	30	REF 70/30
	80	20	REF 80/20
	90	10	REF 90/10
Slate waste + Clayey soil	50	50	SLT 50/50
	60	40	SLT 60/40
	70	30	SLT 70/30
	80	20	SLT 80/20
	90	10	SLT 90/10

The CBR tests were performed based on the DNIT-ME 172/2016 standard and used 5 specimens for each mixture (REF and SLT). To obtain the compaction curve, and consequent determination of the optimum moisture content and maximum dry bulk density, modified compaction energy was used. The others geotechnical properties (granulometry and Atterberg limits) considered the mean of 3 specimens per content. Figure 1 shows the submerged specimens to determine the expansion and CBR later.

Figure 1 - Submerged specimens to determine the expansion and CBR later.

The RM tests were performed in the Dynamic Test Laboratory and were performed according to DNIT-ME 134/2018. A quantitative of 3 specimens per proportion (18 in total) were cast molded at their optimum moisture content (information collected through the compaction curve). The specimens were compacted to 100% modified maximum dry density. The test was initiated by placing the specimens in the triaxial chamber, where the initial conditioning phase was performed, as required by the standard, through the application of a sequence of repetitive loads, in order to eliminate the large plastic deformations that occur at the beginning the application of loads. After the stage of conditioning of the test specimens, in which the large plastic deformations were eliminated, 6 cycles with 3 phases each of load were applied for each state of stresses in the loading phase (totaling 18 phases). At each stage of load application, the resilient deformations were recorded for the stress state, obtained through the average of the last five load peaks. The load application was done through a timer, which had intervals whose duration was 0.1 second and frequency equal to 1.0 Hertz. The axial deformations of the test specimens were measured by a Linear Variable Differential Transducer (LVDT), which transformed the axial deformations during electric potential loading. The values were recorded in a data acquisition system managed by the SICTRI software. The computational resource records the deformations generated by the load and calculates the Resilient Modulus for each stress state. Figure 2 shows the equipment used in the RM tests.

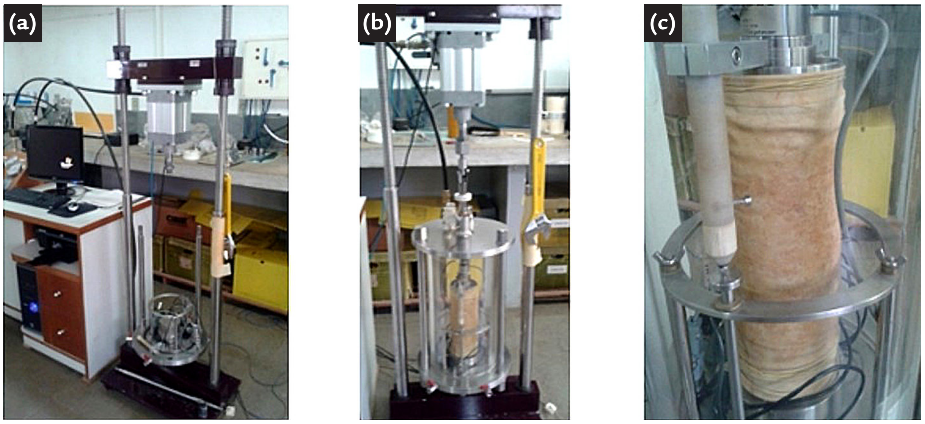

Figure 2 - (a) Triaxial equipment, (b) Triaxial test in Progress, (c) Detail of specimen.

4. Results and analysis

Materials characterization tests were carried out using the previously described methodologies. The geotechnical properties of mixtures REF and SLT obtained from the laboratory tests are presented in Table 3.

Table 3 - Geotechnical properties of mixtures.

Mixture	Liquid limit (%)	Plasticity index (%)	Maximum dry density (g/cm^3)	Optimum moisture content (%)	Expansion (%)	CBR (%)
REF 50/50	46.3	18.5	2.000	9.6	0.10	45.9
REF 60/40	44.5	16.4	2.050	7.9	0.04	70.5
REF 70/30	42.5	14.9	2.100	7.2	0.04	75.6
REF 80/20	41.6	14.6	2.200	5.5	0.02	82.3
REF 90/10	38.3	12.3	2.250	5.1	0.01	103.1
SLT 50/50	26.1	8.1	2.020	9.9	0.06	41.5
SLT 60/40	25.9	8.5	2.125	8.2	0.04	67.9
SLT 70/30	23.1	7.4	2.188	6.6	0.08	72.5
SLT 80/20	21.5	5.8	2.250	5.1	0.04	79.0
SLT 90/10	20.7	4.1	2.260	4.6	0.02	94.0

There was a reduction in the values of the Atterberg limits according to the percentage increase in stone (gneiss and slate waste) material in the mixtures. It should also be noted that this property presents a better performance in SLT mixtures in relation to REF, considering that the Brazilian standard (DNIT-141/2010) establishes the limits of 25% and 6%, respectively for the liquid limit and plasticity index, for the use of material as a base layer in asphalt pavements.

The optimum moisture content was obtained through the compaction curves of the mixtures, illustrated in Figure 3 and Figure 4, and ranged from 5.1% to 9.6% for the REF mixtures and from 4.6% to 9.9% for the SLT mixtures.

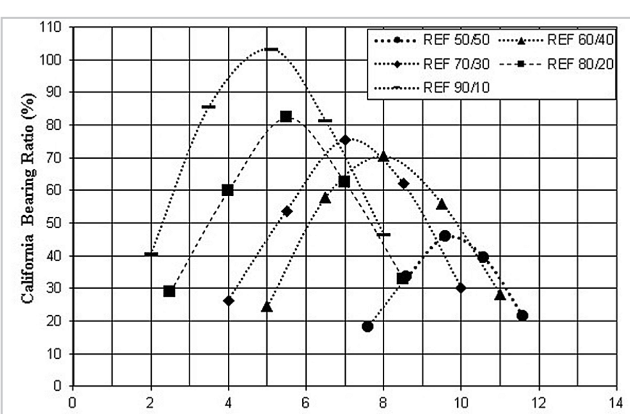

Figure 3 - Compaction curves for REF mixtures.

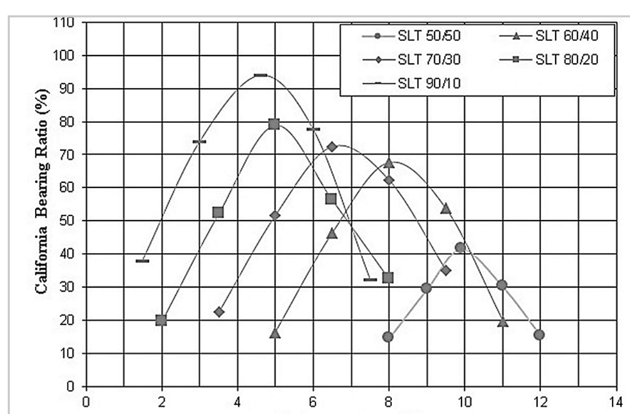

Figure 4 - Compaction curves for SLT mixtures.

Research by Moreira *et al*. (2008) and Mendes *et al*. (2016) indicated a reduction in the optimum moisture content with the increase of granular material in the mixtures, a parameter also observed in this study. An inverse relationship occurs with the maximum dry specific mass, which presented values between 2.000 g/cm³ and 2.250 g/cm³ for REF and between 2.020 g/cm³ and 2.260 g/cm³ for SLT, that is, the values increased with the percentage of granular material inclusion. In these properties, the SLT mixtures presented a behavior similar to that of REF.

It is observed in the compaction curves, that small variations in moisture in relation to the optimum moisture content cause a great reduction in the CBR of both mixtures (REF and SLT). The mixtures with natural aggregate (gneiss) showed higher CBR than those with slate waste, when comparing the same content of granular material in the mixtures (example: 103.1% for REF 90/10 and 94.0% for SLT 90/10), also verified by Poon and Chan (2006). Hossain and Mol (2011) related that the inclusion of stone material in mixtures increases CBR, something also observed in this research in REF mixtures (125% with a variation between 50% and 90% of gneiss in mixtures) and SLT (127% with an increase from 50% to 90% of slate waste in the mixtures).

The RM results obtained through the composite model, presented, for different stresses (σ_3 and σ_d) applied in the tests, values between 109 and 433 MPa for the REF mixtures and between 98 and 411 MPa for the SLT mixtures; indicating similar values for natural and recycled aggregate, as reported in Molin *et al*. (2004) and Leite *et al*. (2011). These values, when compared with the results found in literature and presented in Table 1, are within the range reported in the researches.

The range of RM values for all stresses (σ_3 and σ_d), the average values of RM, as well as the values of the coefficients obtained from the composite model, can be seen in Table 4.

Table 4 - Results of the Resilient Modulus tests of the mixtures.

Mixtures	CP	Composite model $RM = K_1 \times \sigma_3^{K_2} \times \sigma_d^{K_3}$				RM range (MPa) for all stresses	RM (MPa)	Mean RM (MPa)
		K1	K2	K3	R2			
REF 50/50	1	304.5	0.1690	-0.0029	0.994	149 - 209	183	168
	2	539.7	0.3698	0.0171	0.996	115 - 198	159	
	3	643.5	0.3844	0.0529	0.985	109 - 203	161	
REF 60/40	1	335.4	0.1317	0.1172	0.982	136 - 246	180	182
	2	320.2	0.1369	0.0876	0.981	136 - 244	180	
	3	323.9	0.0256	0.2245	0.978	120 - 252	185	
REF 70/30	1	358.2	0.1706	0.0812	0.983	142 - 267	186	186
	2	374.4	0.1706	0.0964	0.980	149 - 268	189	
	3	432.5	0.1916	0.1481	0.978	116 - 258	184	
REF 80/20	1	524.9	0.0187	0.2498	0.954	173 - 311	226	260
	2	514.6	0.0404	0.2121	0.958	198 - 433	291	
	3	468.6	0.0703	0.1715	0.986	181 - 348	265	
REF 90/10	1	379.2	0.2117	-0.0770	0.978	206 - 326	249	269
	2	1049.0	0.3932	0.0364	0.942	215 - 422	276	
	3	867.2	0.3677	-0.0157	0.912	223 - 401	283	
SLT 50/50	1	187.5	0.0606	-0.0243	0.983	141 - 193	167	156
	2	600.7	0.4029	0.0209	0.987	113 - 200	155	
	3	502.0	0.3556	0.0436	0.983	98 - 189	145	
SLT 60/40	1	348.0	0.0574	0.1919	0.974	113 - 249	195	171
	2	430.1	0.2857	0.0594	0.990	121 - 243	171	
	3	206.7	-0.0662	0.2456	0.978	117 - 215	146	
SLT 70/30	1	424.8	0.1840	0.1624	0.979	108 - 238	179	183
	2	508.6	0.2105	0.1871	0.980	116 - 279	190	
	3	384.1	0.1137	0.2017	0.985	111 - 249	180	
SLT 80/20	1	562.7	0.1367	0.1461	0.989	209 - 411	279	241
	2	408.3	0.1242	0.1052	0.984	162 - 294	229	
	3	367.0	0.0155	0.2279	0.976	131 - 283	214	
SLT 90/10	1	1087.7	0.3575	0.0920	0.973	198 - 389	276	254
	2	970.0	0.3071	0.1471	0.928	187 - 403	253	
	3	641.0	0.5290	-0.2058	0.935	98 - 309	233	

The mixtures (REF and SLT) showed a non-linear behavior for RM, as reported by Neves and Correia (2006) for granular materials. The analysis of the RM values for different stresses (σ_3 and σ_d) applied in the tests and the average RM values indicates that there is an increase in the stiffness of the mixtures with the addition of stone material, confirming the studies by Arm (2003) and Kim *et al.* (2007).

The average RM values of the SLT mixtures (156 MPa, 171 MPa, 183 MPa, 241 MPa and 254 MPa for SLT 50/50, SLT 60/40, SLT 70/30, SLT 80/20 and SLT 90/10, respectively) indicated an increase of 62.8% in RM with the addition of an additional 40% slate waste in mixtures. However, the RM values were lower than the research carried out by Nunes *et al.* (1996), which obtained an average RM of 272 MPa for slate waste.

The average RM values of the REF mixes were 168 MPa, 182 MPa, 186 MPa, 260 MPa and 269 MPa for REF 50/50, REF 60/40, REF 70/30, REF 80/20 and REF 90/10, respectively, indicating an increase of 60.1% in the resilient modulus with the addition of more than 40% of gneiss in the mixtures. Therefore, the behavior of the REF and SLT mixtures were similar in relation to the resilient modulus.

From the results of the presented resilient modulus and California Bearing Ratio tests, it was possible to verify the relationship between them. Linear regression was performed between the mean RM and the CBR of the mixtures (REF and SLT), as shown in Figure 5.

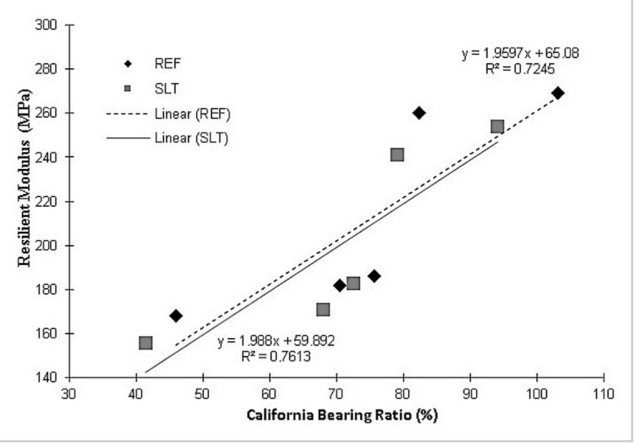

Figure 5 - Linear regression between RM and CBR of the mixtures.

It is possible to verify that both mixtures have a non-linear relationship between RM and CBR, although it is possible to verify a growth trend of RM and CBR with the increase in the stone material content. The coefficient of determination (R^2) of the linear regression was 0.72 and 0.76 for the REF and SLT mixtures, respectively, showing again similar behavior between the slate waste and gneiss (conventional aggregate).

5. Conclusions

In this research, it was concluded that the values of Resilient Modulus and California Bearing Ratio of the SLT mixtures behave similarly to those of the REF mixtures. While there was an increase of 62.8% in RM and 127.0% in CBR caused by the addition of 40% (in mass) slate waste in the mixtures, an increase of 60.1% and 125.0% in REF mixes was observed for the same conditions. Although an increase in the RM and CBR values was observed for both mixtures with an increase in the stony material content, it was not possible to verify linearity between these two properties.

The knowledge of the RM and CBR values of the materials is extremely important, since in Brazil these parameters are used in the new National Pavement Design Method (MeDiNa) and in the empirical design method DNER (1981), respectively. The DNER method has fulfilled its purpose in the road design sector for years, however, it is obsolete due to the growth in traffic, the increase in requests and the load capacity of commercial vehicles. Although MeDiNa does not use only the results of RM, it can be said that the similar behavior of this parameter in mixtures REF and SLT is indicative of the possible replacement of conventional materials by waste as paving materials.

In addition, this research also contributes to the development of a mechanistic database by providing parameter values of the RM composite model for five mixtures with different proportions of stone material (slate and gneiss residue), enabling the development of correlations between the material's conventional and residues for application in pavement layers. Thus, it is expected that from the results presented in this research, slate waste can have their use expanded in substitution to conventional materials in paving.

Acknowledgments

The authors would like to thank the Centro Federal de Educação Tecnológica de Minas Gerais (CEFET-MG) and the Departamento de Edificações e Estradas de Rodagem de Minas Gerais (DER-MG) for supporting this research.

References

AATHEESAN, T.; ARULRAJAH, A.; BO, M.; VUONG, B.; WILSON, J. Crushed brick blends with crushed rock for pavement systems. ***Proceedings of the Institution of Civil Engineers***: Waste and Resource Management, London, v. 163, n.1, p. 29-35, 2010.

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS. ***AASHTO T 307***: Standard method of test for determining the resilient modulus of soils and aggregate materials. Washington, DC: AASHTO, 2003.

ARM, M. ***Mechanical properties of residues as unbound road materials***. 2003. 125 f. Thesis (Doctoral in Engineering) - Department of Land and Water Resources Engineering, KTH Royal Institute of Technology, Stockholm, Sweden, 2003.

ARULRAJAH, A.; PIRATHEEPAN, J.; DISFANI, M.; BO, M. Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. ***Journal of Materials in Civil Engineering***, v. 25, n. 8, p. 1077-1088, 2013.

BENNERT, T.; PAPP JR, W. J.; MAHER, A.; GUCUNSKI, N. Utilization of construction and demolition debris under traffic-type loading in base and subbase applications. ***Transportation Research Record***, v. 1714, n. 1, p. 33-39, 2000.

BEZERRA NETO, R. S. ***Análise comparativa de pavimentos dimensionados através dos métodos empírico do DNER e mecanístico e proposta de um catálogo simplificado de pavimentos para a região de Campo Grande (MS)***. 2004. 169 f. Dissertação (Mestrado em Engenharia de Transportes) - Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2004.

BRITO, L. A. T. ***Avaliação e análise paramétrica do ensaio de compressão diametral sob cargas repetidas em misturas asfálticas***. 2006. 180 f. Dissertação (Mestrado em Engenharia Civil) – Escola de Engenharia, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2006.

CARDOSO, R.; SILVA, R. V.; DE BRITO, J.; DHIR, R. Use of recycled aggregates from construction and demolition waste in geotechnical applications: a literature review. ***Waste Management***, v. 49, n. 1, p. 131-145, 2016.

CHIODI FILHO, C.; CHIODI, D. K. ***Plano de ação para sustentabilidade do setor de rochas ornamentais***: ardósia em Papagaios. Belo Horizonte: FEAM, 2014. v. 1, p. 1-50.

DEL CARPIO, J. A. V. ***Estudo da influência da adição da cinza de casca de arroz nas propriedades do CCR (Concreto Compactado com Rolo) para seu uso em pavimentos compostos***. 2009. 138 f. Dissertação (Mestrado em Engenharia Civil) - Universidade Federal de Santa Catarina, Florianópolis, 2009.

DEPARTAMENTO NACIONAL DE ESTRADAS DE RODAGEM. ***Método de Projeto de Pavimentos Flexíveis***. Rio de Janeiro: DNER, 1981.

DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES. ***Norma DNIT 134/2018-ME***: Pavimentação - Solos - Determinação do módulo de resiliência. Rio de Janeiro: DNIT, 2018.

DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES. ***Norma DNIT 141/2010-ES***: Pavimentação - Base estabilizada granulometricamente - Especificação de serviço. Rio de Janeiro: DNIT, 2010.

DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES. ***Norma DNIT 172/2016-ME***: Solos - Determinação do Índice de Suporte Califórnia utilizando amostras não trabalhadas. Rio de Janeiro: DNIT, 2016.

DISFANI, M. M.; ARULRAJAH, A.; BO, M.; HANKOUR, R. Recycled crushed glass in road work applications. ***Waste Management***, v. 31, n. 11, p. 2341-2351, 2011.

FERNANDES, C. G. ***Caracterização mecanística de agregados reciclados de resíduos de construção e demolição dos municípios do Rio de Janeiro e de Belo Horizonte para uso em pavimentação***. 2004. 109 f. Dissertação (Mestrado em Engenharia Civil) - Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2004.

HOSSAIN, K. M. A.; MOL, L. Some engineering properties of stabilized clayey soils incorporating natural pozzolans and industrial wastes. ***Construction and Building Materials***, v. 25, n. 8, p. 3495-3501, 2011.

KIM, W.; LABUZ, J.; DAI, S. Resilient modulus of base course containing recycled asphalt pavement. ***Transportation Research Record***, v. 2005, n. 1, p. 27-35, 2007.

KLINSKY, L. M. G. ***Proposta de reaproveitamento de areia de fundição em sub-bases e bases de pavimentos flexíveis, através de sua incorporação a solos argilosos***. 2008. 215 f. Dissertação (Mestrado em Engenharia Civil) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Paulo, 2008.

LEITE, F. C. ***Comportamento mecânico de agregado reciclado de resíduo sólido da construção civil em camadas de base e sub-base de pavimentos***. 2007. 216 f. Dissertação (Mestrado em Engenharia de Transportes) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2007.

LEITE, F.; MOTTA, R.; VASCONCELOS, K.; BERNUCCI, L. Laboratory evaluation of recycled construction and demolition waste for pavements. ***Construction and Building Materials***, v. 25, n. 6, p. 2972-2979, 2011.

MANSUR, A. A. P.; PERES, A. E. C.; PALHARES, L.; MANSUR, H. S. Study of pore size distribution of slate ceramic pieces produced by slip casting of waste powders. ***Minerals Engineering***, v. 19, n. 5, p. 525-527, 2006.

MEDINA, J.; MOTA, L. ***Mecânica dos Pavimentos***. 3. ed. Rio de Janeiro: Editora Interciência, 2005.

MENDES, T. M.; MORALES, G.; REIS, P. J. Use of basaltic waste as red ceramic raw material. ***Cerâmica***, v. 62,

n. 362, p. 157-162, 2016.

MOLIN, C.; LARSSON, K.; ARVIDSSON, H. Quality of reused crushed concrete strength, contamination and crushing technique. *In*: INTERNATIONAL RILEM CONFERENCE ON THE USE OF RECYCLED MATERIALS IN BUILDINGS AND STRUCTURES, 1., 2004, Barcelona, Spain. ***Proceedings*** [...]. Barcelona, Spain: RILEM Publications, 2004. p. 150-155.

MOREIRA, J. M. S.; MANHÃES, J. P. V. T.; HOLANDA, J. N. F. Processing of red ceramic using ornamental rock powder waste. ***Journal of Materials Processing Technology***, v. 196, n. 1-3, p. 88-93, 2008.

NATAATMADJA, A.; TAN, Y. L. Resilient response of recycled concrete road aggregates. ***Journal of Transportation Engineering***, v. 127, n. 5, p. 450-453, 2001.

NEVES, J.; CORREIA, A. G. Consideração da não-linearidade do comportamento dos solos na modelação numérica de pavimentos rodoviários. *In*: CONGRESSO NACIONAL DE GEOTECNIA, 10., 2006, Lisboa, Portugal. ***Anais*** [...]. Lisboa, Portugal: Sociedade Portuguesa de Geotecnia, 2006. v. 2. p. 473-482.

NUNES, M. C. M.; BRIDGES, M. G.; DAWSON, A. R. Assessment of secondary materials for pavement construction: technical and environmental aspects. ***Waste Management***, v. 16, n. 1-3, p. 87-96, 1996.

POON, C. S.; CHAN, D. Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. ***Construction and Building Materials***, v. 20, n. 8, p. 578-585, 2006.

RODRIGUES, R. K. Propostas de aproveitamento de resíduos de ardósia da cidade de Pompéu, Minas Gerais. ***Revista Intercâmbio***, v. 6, n. 1, p. 86-95, 2015.

SOLANKI, P.; ZAMAN, M.; DEAN, J. Resilient modulus of clay subgrades stabilized with lime, class C fly ash, and cement kiln dust for pavement design. ***Transportation Research Record***, v. 2186, n. 1, p. 101-110, 2010.

THORN, N. H.; BROWN, S. F. The mechanical properties of unbound aggregates from various sources. *In*: JONES, R. H.; DAWSON, A. R. (ed.). ***Unbound aggregates in roads***. Oxford: Butterworth-Heinemann, 1989. cap. 17, p. 130-142.

Received: 26 April 2021 - Accepted: 4 June 2021.

CC BY All content of the journal, except where identified, is licensed under a Creative Commons attribution-type BY.