Laboratory study of manganese mining overburden mixed with lime as a paving subbase layer

Rosa, Giovanna de Freitas[1,2], Motta, Rosângela dos Santos[1], and Boscov, Maria Eugênia Gimenez[1]

[1]University of São Paulo, Brazil
[2]Knight Piésold, Canada

Abstract. This paper presents the results of a laboratory investigation comprising geotechnical characterization, CBR, and resilient modulus tests carried out on a manganese overburden, in the natural state and mixed with 3% and 4% lime, to evaluate the suitability of the materials for road construction. The test results were used to calculate the allowable stresses for a typical Brazilian flexible asphaltic pavement for low volume roads. Allowable stresses considering a subbase built with lime-amended manganese overburden were compared to the stresses calculated for a lateritic clayey-sand subbase to evaluate the efficacy of the manganese overburden and its mixture with lime. The allowable stresses were converted in N (number of equivalent single axle loads - ESAL). The results of the investigation indicated that the manganese sterile with 3% lime addition and 7 days of curing time achieved slightly higher N values than the typical lateritic subbase road for the same cross-section: N increased from 10^{13} to 10^{14} using the alternative material. This is a promising reuse alternative to introduce manganese in the circular economy and to preserve natural soils from exploitation.

Keywords: Manganese overburden, Low-volume traffic roads, Resilient modulus.

1 Introduction

Manganese (Mn) is the fourth most used metal in the world (INTERNATIONAL MANGANESE INSTITUTE, 2020), with manifold applications such as metallic alloys (mainly with pig iron for steel alloys, but also copper, zinc, tin, and lead alloys), batteries, and chemical compounds (mainly for animal feed fertilizers). Brazil is the world's fourth largest producer of manganese, after Ukraine, South Africa, and Australia (LIMA & NEVES, 2016), generating annually over 300 million tons of tailings and overburden as by-products of manganese mining.

Sustainability is the present watchword for engineering activities; therefore, by-products should be inserted in the circular economy. A promising alternative for manganese mining overburden is the application as construction material for the widely used flexible asphaltic road pavements; in which case, additives may be necessary to meet technical requirements.

Soil-lime mixtures are commonly used in pavement layers, and there is an extensive literature on this subject (BALBO, 2007), as well as standards and chapters in paving guides of organizations such as AASHTO, US Corp of Engineers, and Austroads.

This paper presents a preliminary assessment of the suitability of manganese overburden improved with lime as a construction material for the sub-base of asphaltic flexible pavements, based on CBR and resilient modulus tests, and on stress analysis of a pavement cross-section for low-volume roads obtained by numerical modeling. This paper also aims to indicate a beneficial destination for a material typically stockpiled or discarded in tailings facilities, with the additional advantage of preserving natural soils generally used in pavements' infrastructure.

2 Materials and Methodology

2.1 Materials

The overburden, a residue of the mining activity, consists of the material removed until the targeted ore vein is intersected. Ore is then mined and processed to become the final product, and the waste generated by the beneficiation process is called tailings. Brazilian studies show that manganese overburden has a high fines content and is predominantly comprised of silt (CARVALHO *et al*., 2021, VIANA *et al*., 2012).

The investigated material was collected from an overburden pile (Cajengá Mine – Granha Ligas – Minas Gerais – Brazil) following the Theory of Sampling principles, developed by Pierre Gy (Gy, 1998). Before the laboratory tests, the material was air-dried in the shade to the hygroscopic water content.

High-calcium hydrated lime (CH-II) was utilized for the mixtures. Lime contents of 3% and 4% (by dry mass) were added to the manganese overburden, as usually employed in Brazilian pavement projects and in accordance with the guidelines of ASTM D5102 standard.

2.2 Methodology

The geotechnical characterization of the manganese overburden comprised particle size analysis, Atterberg limits, and compaction test, conforming to ASTM D6913, ASTM D2487, ASTM D4318, and ASTM D698 standards, respectively. CBR and expansion ratio tests (ASTM D1883) were performed on specimens of natural overburden and mixtures, compacted at the respective optimum water content of standard Proctor effort, to evaluate the effect of lime addition on expansion.

Resilient modulus tests (AASHTO T307 and Austroads AGPT-T-053) were carried out with as-compacted overburden, as-compacted mixtures, and mixtures after curing times of 7 days, 14 days, and 90 days.

The performance of the materials was then evaluated by applying parameters obtained from these tests to numerical modeling. A flexible (asphaltic) pavement cross-section, typical of low-traffic volume highways in Brazil, was analyzed, consisting of 0.05m of hot mixed asphalt (HMA) coating, 0.15m of well graded crushed stone, 0.15m of subbase of lateritic clayey sand and subgrade of silty soil. This typical cross-section was the basis for comparison with a similar cross-section where the subbase of lateritic clayey sand was replaced by each material evaluated in this paper (overburden and overburden-lime mixtures).

AEMC (Multiple Layer Elastic Analysis) software was used to obtain the maximum allowable vertical stress in the pavement layers, which was then used to calculate the parameter N (number of equivalent single axle loads – ESAL) using the Shell of Amsterdam expression (1), proposed by Heukelom & Klomp in 1962. The improvement in the mechanical-structural performance was related to the increase in the allowable number N.

$$\sigma_{v,adm} = c \times \frac{MR}{1 + 0.7 \times logN} \quad (1)$$

where $\sigma_{v,adm}$ is the maximum allowable vertical stress, *c* is a constant ranging between 0.006 and 0.008, *MR* is the resilient modulus, and *N* is the number of equivalent single axle loads.

Values of MR and Poisson ratio of the materials used in the cross-section for the structural analysis were obtained from the internal library of the MeDiNa software (National Pavement Design Method - new Brazilian flexible pavement methodology and software for mechanistic-empirical asphaltic pavement design). For the overburden improved with 3% lime, the Poisson ratio was adopted as 0.3, according to studies of Poulos *et al*. (SANTOS, 2023).

3 Results and Discussions

3.1 Geotechnical Characterization

The obtained particle size distribution of the investigated manganese overburden (Fig. 1) is consistent with the values reported in the literature (CARVALHO *et al*., 2021; VIANA *et al*., 2012). It can be observed that the overburden has a high fines content, with approximately 90% passing the #200 sieve, which indicates that the material is composed mostly of silt and clay fractions. The specific gravity is 3.287, higher than usual values for natural soils.

The liquid and plastic limits are 55% and 47%, respectively. According to the Unified Soil Classification System (USCS), the overburden is classified as ML.

Fig. 2 illustrates the compaction curves obtained for the overburden and the mixtures. According to extensive literature, lime addition causes an increase in the optimum moisture content and a decrease in the maximum dry density (BOSCOV, 1990; OJURI et al., 2017). Similar behavior was observed by Bastos et al. (2016) for the mixture of iron ore tailings with lime, compacted at reduced modified energy. In the case of the manganese overburden, the addition of lime resulted in an increase in the optimum moisture content and the maximum dry density. Ongoing mineralogical tests may explain this difference of behavior.

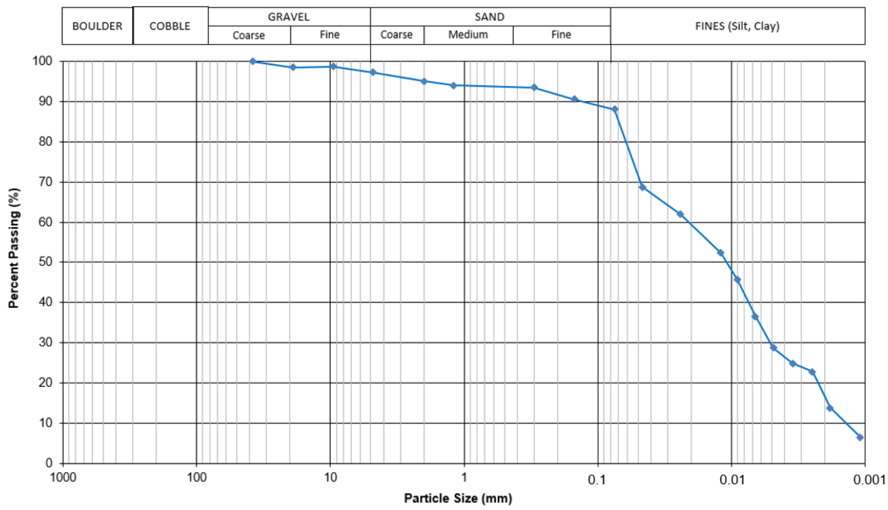

Fig. 1. Particle size distribution curve – manganese overburden.

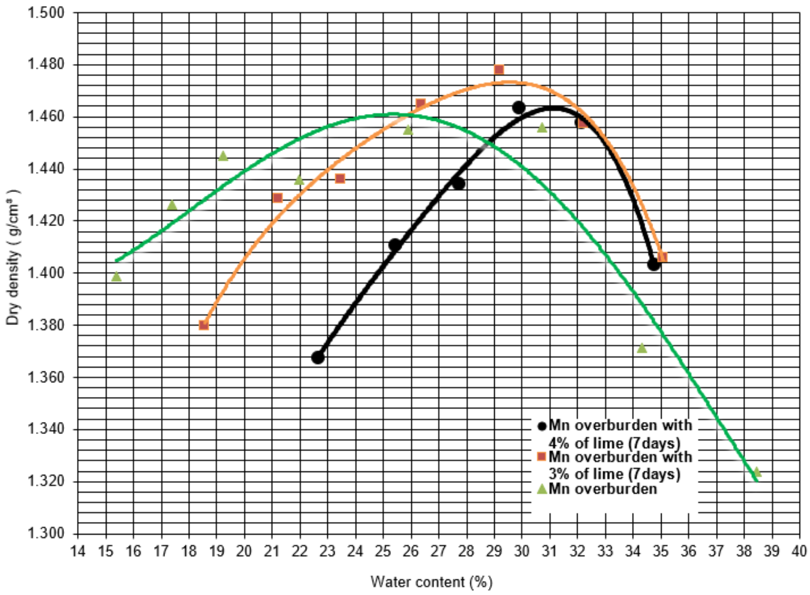

Fig. 2. Compaction curves – manganese overburden and manganese overburden-lime mixtures.

The CBR and expansion rate test results are shown in Table 1. With lime addition, the material becomes less expansive and the CBR value increases considerably.

Table 1. Results of compaction, CBR, and expansion tests.

	Mn overburden	Mn overburden + 3% lime (7 days)	Mn overburden + 4% lime (7 days)
Compaction energy	Standard	Standard	Standard
Maximum dry density (g/cm^3)	1.461	1.473	1.465
Optimum moisture (%)	25.1	29.2	31.2
CBR (%)	4	23	25
Expansion ratio (%)	3.29	0.59	0.48

In 1985, Aranovich proposed the composite model, which applies to fine soils in Brazil (MEDINA & MOTTA, 2015). This model was used in this paper and correlates the resilient modulus to the confining and deviator stress, with regression coefficients obtained through dynamic triaxial laboratory tests.

Fig. 3., Fig. 4, and Table 2 present results of the resilient modulus tests with different confining and deviator stresses carried out on as-compacted overburden and on mixtures at different curing. The confining stress value of 0.1 MPa was used to define the resilient modulus since it is approximately the stress experienced by the base and subbase layers, and k_1, k_2, and k_3 are the regression coefficients of Aranovich's model.

Table 2. Summary of results of the resilient modulus tests – confining stress σ_3 = 0.1 MPa and deviator stress σ_d = 0.1 MPa.

	k_1	k_2	k_3	MR (MPa)
Mn overburden	78	0.2278	-0.2148	76
Mn overburden + 3% lime - 7 days	75	0.1168	-0.3146	118
Mn overburden + 3% lime - 14 days	75	0.1168	-0.3146	118
Mn overburden + 3% lime - 90 days	153	0.2328	-0.4071	229
Mn overburden + 4% lime - 7 days	118	0.1145	-0.3161	188
Mn overburden + 4% lime - 14 days	119	0.0694	-0.2879	198
Mn overburden + 4% lime - 90 days	313	0.0426	-0.1280	381

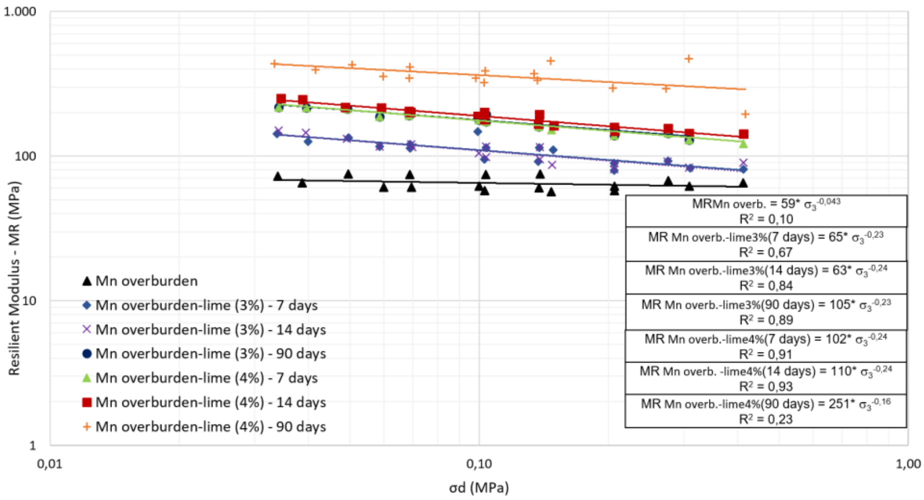

Fig. 3. Resilient modulus as a function of the deviator stress (σ_d).

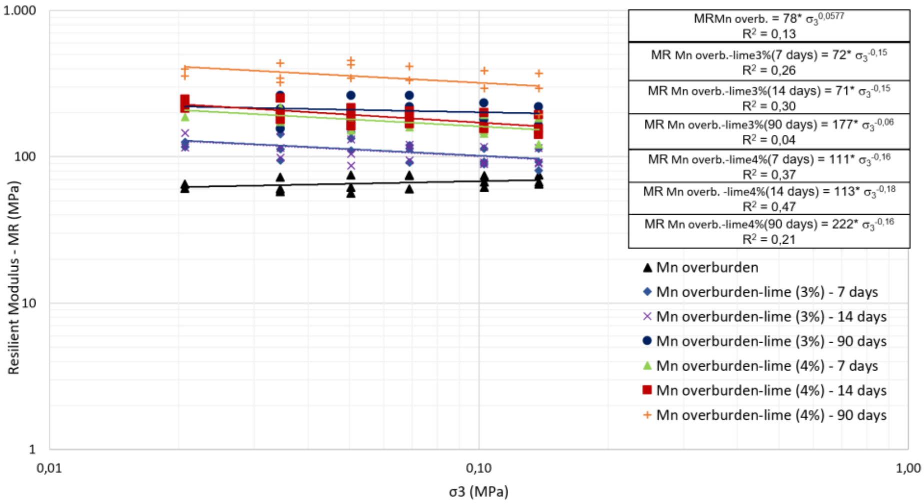

Fig. 4. Resilient modulus as a function of the confining stress (σ_3).

3.2 Suitability of the mixture in the paving cross-section

The results in Table 2 indicate that the overburden alone is not adequate as sub-base material; however, its behavior when improved with lime should be further investigated. The overburden-lime mixture at 3% with a curing time of 7 days was selected to compare to the typical lateritic road design since it yielded the lowest MR value: for longer curing times and higher lime content, performance will certainly be better. Fig. 5 illustrates the cross-sections analyzed, the characteristics of the materials used (MR and Poisson ratio ν), and the vertical stress values (σ_z) calculated through stress analysis by the AEMC software, with the pavement undergoing the standard road axle load used in Brazil (8,200 kg).

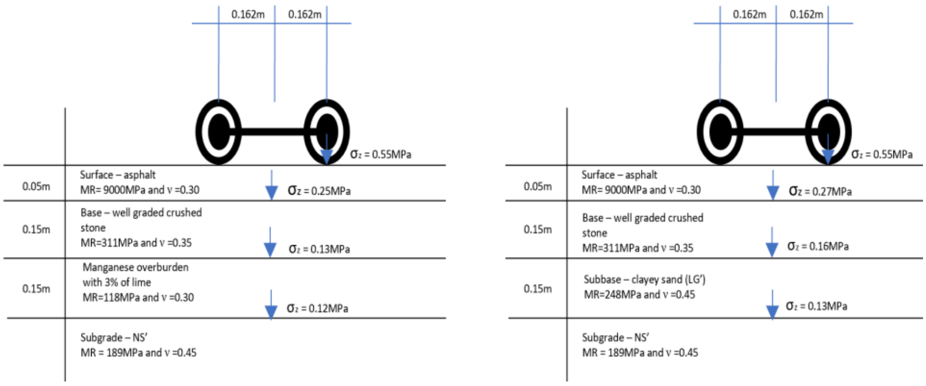

Fig. 5. Pavement cross-section with a lateritic clayey sand subbase (used in Brazil) and with a subbase composed of manganese overburden improved with 3% lime.

For the overburden improved with 3% lime, the vertical stress reaching the subgrade (0.12 MPa) was practically the same as for the lateritic clayey sand (0.13 MPa).

Using equation (1) with constant c equal to 0.007, the value of the allowable number of equivalent axial loads for the cross-section with lateritic clayey sand subbase is $N \leq 1x10^{13}$. When the same procedure was performed for the cross-section with the overburden improved with 3% lime, N increased to $N \leq 2x10^{14}$.

The findings outlined in this study regarding the utilization of manganese mining overburden as a paving layer are consistent with the results reported by Carvalho et al. (2021). With a different approach, Carvalho et al. (2021) incorporated well-graded crushed stone at a ratio of 39.5% instead of blending the overburden with lime, and this composition was deemed suitable for application as the base layer in asphalt pavements.

4 Conclusions

This paper presents geotechnical and mechanical characteristics (MR) of the manganese overburden and the overburden improved with lime at 3% and 4% contents for use in asphaltic pavements. The resilient modulus was observed to considerably increase with the presence of lime, while the expansion ratio decreased.

Results indicate that, from a technical perspective, manganese overburden improved with lime is a viable alternative as sub-base of asphaltic pavements. The inclusion of the lime-mixed overburden in the paving structure results in a decrease in the value of the subgrade vertical stress and a corresponding increase in the allowable value of N (ESAL).

It should be noted that stress analyses of the road cross-section used the lowest resilient modulus value obtained for the overburden-lime mixtures. Therefore, it can be inferred that increases in the curing time and lime content can lead to a higher resilient modulus and consequently better performance than the analyzed mixture (3% lime and 7 days of curing).

From an environmental point of view, the use of manganese overburden mixed with lime in asphaltic pavements represents a good solution for its destination and, therefore, for the mitigation of the negative environmental impacts currently caused by overburden piles. Moreover, the reuse of manganese could potentially lower project costs and limit the exploitation of natural soils for road construction.

The laboratory investigation should include different compaction energies and the effect of relative compaction and moisture deviations on the mechanical behavior of the investigated materials. Permanent deformation analyses were not included within the scope of this study and should be carried out in the future to verify the long-term performance of the mixtures. Also, the impacts of waste variability should be assessed.

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References

1. Internacional Manganese Institute – IMnI Annual Review – 2020, https://www.manganese.org/wp-content/uploads/2021/04/2020-Annual-Review-ENG.pdf, last accessed in 2023/02/13.
2. Lima, Thiers Muniz., Neves, Carlos Augusto Ramos (Coordenadores): Sumário Mineral 2015. Departamento Nacional de Produção Mineral (DNPM). Vol 35, 130-140 (2016).
3. Balbo, José Tadeu.: Pavimentação asfáltica. Oficina de Textos (2007).
4. Carvalho, Glauber Miranda de., Viana, Hélio Marcos Fernandes., Rodrigues, Rubem Xerxes Trindade., Rocha, João Paulo Freire., Rodrigues, Gilson Junior.: Laboratory road performance of Licínio de Almeida – BA manganese mining waste, when mixed with brita 1. Revista Eletrônica de Gestão E Tecnologias Ambientais 9(1), 99-116 (2021).
5. Viana, Nívea Cristina da Silva., Reis, Érica Linhares., Faria, Geraldo Lucio de., Araújo, Fernando Gabriel da Silva.: Mineralogical characterization of silico-carbonate manganese ore litotypes from morro da mina mine. In: 67º ABM International Congress, pp. 243-250, Rio de Janeiro (2012).
6. Gy, Pierre. Sampling for analytical purposes. Wiley, 1998.
7. Santos, Victoria Vazzoler Rodrigues dos.: Caracterização experimental de parâmetros-chave de rejeitos de mineração compactados em aterros – Master's dissertation. University of Porto (2023).
8. Boscov, Maria Eugênia Gimenez.: Estudo comparativo do comportamento de um solo saprolítico e de um solo laterítico estabilizados com cal – Master's dissertation. University of São Paulo (1990).

9. Ojuri, Oluwapelumi O., Adavi, A. A., Oluwatuyi, Opeyemi E.: Geotechnical and environmental evaluation of lime–cement stabilized soil–mine tailing mixtures for highway construction. Transportation Geotechnics (10), 1-12 (2017).
10. Bastos, Lucas Augusto de Castro., Silva, Gabriela Cordeiro., Mendes, Júlia Castro., Peixoto, Ricardo André Fiorotti.: Using Iron Ore Taillings from Tailling Dams as Road Material. Journal of Materials in Civil Engineering 28(10), 04016102 (2016).
11. Medina, Jacques de., Motta, Laura Maria Goretti da.: Mecânica dos Pavimentos. 3rd edn. SIBI/UFRJ, Rio de Janeiro (2015).