Evaluation of Bolivian Lateritic Gravels as Pavement Base Material Using Engineering Specifications Established in other Tropical Regions

Durval Párraga Morales
Research Fellow, Universidad Privada Boliviana (UPB), Cochabamba, Bolivia, durvalx9@gmail.com

Juan Carlos Rojas Vidovic
Professor, Universidad San Francisco Xavier de Chuquisaca (USFX), Sucre, Bolivia, geotecnia@gmail.com

RESUMO: O desenvolvimento da infraestrutura rodoviária na Amazônia boliviana apresenta desafios técnicos significativos, principalmente devido à escassez de agregados naturais ou pedras britadas disponíveis para fins de construção. Em vez disso, materiais granulares naturalmente ocorrentes, como cascalhos lateríticos, são abundantes nesta região, oferecendo uma alternativa atrativa para uso como geomateriais nas camadas estruturais de pavimentos. Assim, o presente estudo avaliou a adequação dos cascalhos lateríticos para uso como material de base por meio de sua avaliação utilizando especificações locais bolivianas, bem como duas especificações internacionais desenvolvidas em países tropicais, como Brasil e Austrália. Para esse fim, o estudo avaliou 24 amostras de cascalhos lateríticos coletadas de várias localidades distribuídas pela região amazônica boliviana. A avaliação envolveu um extenso programa laboratorial que integrou testes mecânicos e geotécnicos, bem como análises químicas e mineralógicas. Os resultados da avaliação destacam que a especificação local atual da Administradora Boliviana de Carreteras (ABC) é restritiva. Além disso, as especificações do Brasil e da Austrália demonstram maiores relaxamentos nos requisitos de parâmetros geotécnicos e mecânicos. Finalmente, os resultados deste estudo apoiam fortemente e recomendam o desenvolvimento de especificações locais para a seleção de cascalhos lateríticos para sua aplicação como material de base para pavimentos.

PALAVRAS-CHAVE: Cascalho laterítico, pavimento, Solos tropicais, Geotecnia, camada de base.

ABSTRACT: The development of road infrastructure in the Bolivian Amazon presents significant technical challenges, mainly due to the scarcity of natural aggregates or crushed stones available for construction purposes. Instead, naturally occurring granular materials like lateritic gravels are abundant in this region, offering an attractive alternative for use as geomaterials in the structural layers of pavements. Thus, this study assessed the suitability of lateritic gravels for use as base course material through its evaluation using local Bolivian specifications, as well as two international specifications developed in tropical countries such as Brazil and Australia. For this purpose, the study evaluated 24 samples of lateritic gravels collected from various locations distributed across the Bolivian Amazon region. The evaluation involved an extensive laboratory program that integrated mechanical and geotechnical tests, as well as chemical and mineralogical analysis. The evaluation results highlight that the current local specification of Bolivian Highway Administration (Administradora Boliviana de Carreteras, ABC) is restrictive. Moreover, the specifications from Brazil and Australia show more relaxed requirements for geotechnical and mechanical parameters. Finally, the results of this study strongly support and recommend the development of local specifications for selecting lateritic gravels for their application as base course material for pavements.

KEYWORDS: Lateritic gravels, pavement, tropical soils, geotechnical, base course.

1 INTRODUCTION

The study of lateritic materials in developing countries with tropical climates contributes to the understanding of their engineering behavior for potential use as construction geomaterials, particularly for in low cost pavements. In addition, the severe climatic conditions in humid tropical and sub-tropical zones of the world, such as the Bolivian Amazon, accelerate the intense weathering of materials, resulting in a lack of traditionally used natural or crushed granular stone for construction purposes. This leads to the adoption of more costly and environmental impacting alternatives, such as transporting natural gravels from hundreds of kilometers away for rural unpaved road infrastructure that meets traditional specifications. As a result, implementing cost-effective pavement solutions becomes unfeasible. Moreover, severe tropical climatic conditions contribute to the formation of lateritic soils with residual origins. These soils exhibit unique geotechnical, chemical, and mineralogical properties that differ from sedimentary soils formed in temperate climates with moderate weathering, which are typically studied in traditional soil mechanics literature (Gidigasu 1976; Blight and Leong 2012). Furthermore, the application of strict specifications developed in regions with temperate climates for the selection of lateritic gravels has resulted in their rejection as construction geomaterials, instead classifying them as marginal soils for construction purposes. However, this does not reflect the good performance observed in the field when tropical gravels are used as surface material to maintain rural unpaved roads in the northeastern Amazon region of Bolivia. In this context, this study evaluates the geotechnical, mechanical, chemical, and mineralogical characteristics of lateritic gravels from the Bolivian Amazon region for their potential use as construction material in pavement base courses. The results of this study are expected to be utilized by road authorities to develop and implement technical specifications for assessing lateritic gravels as geomaterials in road construction.

2 MATERIAL AND METHODS

2.1 Materials

For the experimental program, 24-sampling locations were selected along a 600 km rural road section in northeast part of the Beni department, located in the Amazon region of Bolivia. These locations encompass various topographical features, vegetation types, and drainage conditions. Figure 1 displays the characteristic natural sources of lateritic gravels evaluated for this study. Prior to conducting the laboratory tests, the collected soil samples were air-dried following the recommendations from previous studies on laboratory analysis of lateritic soils (Sunil and Krishnappa 2012).

Figure 1. Representative natural source of lateritic gravels.

2.2 Experimental program

2.2.1 Methods for laboratory test

The geotechnical and mechanical tests were conducted according to the following standards: unit weight of solids [D854 (ASTM 2014)], Atterberg limits [D4318 (ASTM 2017a)], grain size distribution [D6913 (ASTM 2017b)], Modified Proctor tests [ASTM D1557 (ASTM 2012)], California Bearing Ratio (CBR) and expansion tests [ASTM D1883 (ASTM 2016)], and resistance-to-abrasion [ASTM C131 (ASTM 2020)]. In addition, soil classification was carried out following the Unified Soil Classification System (ASTM, 2011) and the AASHTO classification system (AASHTO, 1991). The chemical analysis to determine the SiO_2, Al_2O_3, and Fe_2O_3 content was carried out using Atomic Absorption Spectroscopy (AAS). Morphological and microstructural characterization was performed using Scanning Electron Microscopy (SEM) using a Tescan Vega3 XM SEM equipment. Moreover, mineralogical identification was carried out through X-ray diffraction (XRD) using a Siemens (BRUKER AXS) D-5000 X-ray diffractometer (θ-2θ) equipped with a Cu anode (λ = 1.5406 Å), operating at 40 kV and 25 mA for the primary beam and a curved graphite monochromator for the secondary beam.

2.2.2 Base course materials specifications

This study evaluated three technical specifications for assessing soils used as unbound base course materials. The first specification is the local standard set by the Bolivian Highway Administration (Administradora Boliviana de Carreteras – ABC, 2011). It's worth mentioning that the requirement ranges in this specification have been taken from regions in North America that have a significantly different climate. In addition to the local specification, two international specifications were taken into account: the Department of Infrastructure and Transportation of Brazil (DNIT, 2007), and the State Road Authority of Western Australia (MRWA, 2002). These international standards were developed based on extensive experience and field research specifically focused on road construction using lateritic gravels.

The evaluation focused on conventional geotechnical and mechanical parameters, which are generally considered to be the most relevant for assessing the performance of road pavement materials. Table 1 shows a comparison of parameters specified by ABC, contrasting them with the corresponding range parameters in the DNIT and MRWA specifications.

Table 1. Requirement for an unbound base course.

Description	ABC 2011	DNIT 2007	MRWA 2002
Specification class	Type A	Type A	Lt16
Materials types	Natural aggregates or crushed stones	Lateritic gravels	Lateritic gravels
Conventional parameters			
4-day soaked CBR, (%)	≥ 80	≥ 80	≥ 80
Swell, (%)	≤ 0.5	≤ 0.5	—
Liquid limit, LL (%)	≤ 25	≤ 40	≤ 35
Plasticity index, PI (%)	≤ 6	≤ 15	≤ 16
Los Angeles abrasion, LA (%)	≤ 40	≤ 65	≤ 50
Chemical parameters			
SiO_2/R_2O_3, S/R	—	≤ 2	—
$Al_2O_3 + Fe_2O_3$, (%)	—	—	≥ 20*
Other specified parameters	Fractured faces, Particle shape, sand equivalent.	Sand equivalent	Dust ratio, Linear Shrinkage, Dryback

Note: (*) minimum limit for crushed lateritic.

The main difference between the local Bolivian specifications and the international specifications is the introduction of chemical parameters for the selection of lateritic gravels for use in pavement bases. For example, the Brazilian specification (DNIT, 2007) incorporates chemical parameters such as the silica/sesquioxides molecular ratio (S/R), as shown Equation (1).

$$S/R = (SiO_2/60) / [(Al_2O_3/102) + (Fe_2O_3/160)] \tag{1}$$

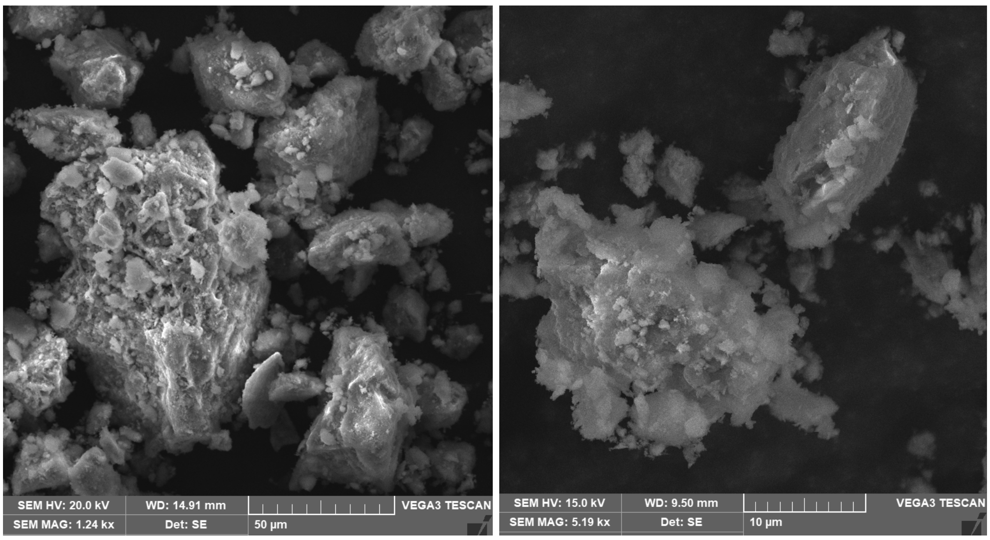
According to Winterkorn and Chandransenkharan (1951), the degree of laterization in lateritic materials can be assessed based on the silica/sesquioxide molecular ratio using the following criteria: non-laterized soils have an S/R ratio greater than 2. In contrast, in lateritic or laterized soils, the S/R ratio ranges between 1.33 and 2.0. Mature or highly laterized lateritic materials have an S/R ratio lower than 1.33.

Furthermore, based on their experience in road construction using lateritic gravels in Australia, Cocks and Hamory (1998) established the sesquioxides content as a chemical criterion for selecting lateritic gravels as pavement base courses, setting a minimum limit of 10% for the sesquioxides content ($Al_2O_3 + Fe_2O_3 \geq 10\%$). In addition, the most recent specification from the Western Australia Main Roads Department (MRWA, 2002) specifies a minimum limit of 20% ($Al_2O_3 + Fe_2O_3 \geq 20\%$) for the selection of crushed lateritic used in pavements.

3 RESULTS AND DISCUSSION

3.1 Mineralogical and chemical analysis

The qualitative X-ray diffraction (XRD) analysis conducted on the fine fraction of lateritic gravels samples have identified Clay and Non clay minerals. These include predominant clay minerals such as kaolinite [$Al_2Si_2O_5(OH)_4$] in abundant proportion and illite [$(K, H_3O)Al_2Si_3AlO_{10}(OH)_2$] in smaller proportions. Furthermore, non-clay minerals like gibbsite [$Al(OH)_3$], which are highly abundant, and a small presence of quartz (SiO_2) were observed. Additionally, the analysis revealed the absence of swelling clays such as smectite and montmorillonite. The mineralogical composition observed in all samples is consistent with previous findings reported for lateritic soils from other regions worldwide. Moreover, SEM micrographs in Figs. 2(a) at 1.24kx magnification reveals that sand and fines fraction of lateritic gravels primarily consist of irregularly shaped grains, mainly subangular in form. Furthermore, SEM micrograph in Fig. 3(b) at 5.19kx magnification reveals a porous and microaggregate structure in the particles, mainly composed of agglomerations of kaolinite minerals and quartz grains due to intense tropical weathering. Similar characteristics have been documented in geotechnical studies of lateritic soils from other tropical regions worldwide (Camapum de Carvalho et al. 2015). The chemical analysis focused on identifying iron oxide (Fe_2O_3), aluminum oxide (Al_2O_3), and silicon oxide (SiO_2), which are of particular interest for calculating the chemical parameters proposed by DNIT and MRWA for the classification and selection of lateritic soils for their application as geomaterials in construction. Results of AAS test from all samples of lateritic gravels indicate that the percentage of oxides varies from 1.8 to 24.5 % of Fe_2O_3, 6.5 to 26.7 % of Al_2O_3, and 40.4 to 78.3 % of SiO_2.



(a) (b)

Figure 2. Microstructure of fine fracction of lateritic gravels: (a) SEM at 1.24 kx magnification, and (b) SEM at 5.19 kx magnification.

3.2 Geotechnical and mechanical characteristics

Table 2 shows the statistical summary of the results from geotechnical and mechanical characterization conducted on the 24 samples of lateritic gravels. The granulometric analysis reveals that Bolivian lateritic gravels are primarily composed of a granular fraction containing lateritic concretions within a fine soil matrix (clays and silt). The composition of the granulometric fractions of all tested samples varies from 23.3 to 88.2% of gravels (concretions), 2.2 to 57.7% of sands, and 6.6 to 33.8% of fines. The specific gravity values range from 2.6 to 3.3. From dry unit weight − moisture content relationship, the maximum dry unit weight (γ_d) values vary between 17.6 kN/m³ and 21.9 kN/m³, while the optimum moisture content (w_{opt}) values varies between 9.3% and 16.3%. Furthermore, the soaked CBR values range from 49% to 204% at 100% compaction in the modified Proctor test. Also, the swelling potential was minimal for a water immersion period of 96 hours. The presence of kaolinite and the absence of smectite group minerals are consistent with low swelling, along with the presence of iron and aluminum in the lateritic gravels. The plasticity index ranges from 6% to 23%, and the Los Angeles abrasion values of the concretions range from 22% to 49%.Thus, the lateritic gravels are classified according to the AASHTO classification into class A-2-4, A-2-6, and A-2-7. Similarly, in the Unified Soil Classification System, they are categorized as GC, GM, GW-GC, and SC-SM.

Table 2. Statistical summary results of geotechnical and mechanical tests.

Designation	Standard methods	Laboratory results		
		Minimum	Maximum	Average
Gravel, (%)	ASTM D422 (ASTM 2007)	23.3	88.2	59.0
Sand, (%)		2.2	57.7	19.5
Fines, (%)		6.9	33.8	22
Atterberg limits				
Liquid limit, LL (%)	ASTM D4318 (ASTM 2017)	21.6	48.3	39.6
Plastic limit, PL (%)		15.7	30.2	23.2
Plasticity index, PI (%)		6.0	23.0	14.5
Resistance to abrasion				
Los Angeles abrasion, LA (%)		22.0	49.0	35.5
Specific gravity of grains	ASTM D854 (ASTM 2014)	2.6	3.3	2.9
Maximum dry unit weight, (kN/m^3)	ASTM D1557	17.6	21.9	19.8
Optimum moisture content, (%)	(ASTM 2012)	9.3	16.3	12.8
Soaked CBR at 100%, (%)	ASTM D1883	49	204	126.5
Swell, (%)	(ASTM 2016)	0.00	0.07	0.01

3.3 Evaluation for potential application in pavement base course

Figs. 3 (a-d) presents the laboratory results of all the samples tested for the liquid limit, plastic index, soaked CBR, and resistance to abrasion, along with the respective specification limits established by ABC, DNIT, and MRWA.Thus, Figure 3 (a) shows that in the liquid limit (LL%) analysis of all samples, only one sample meets the ABC specification (LL < 25%), while eleven samples fall within the DNIT (LL < 40%) and MRWA (LL < 35%) specifications. In Figure 4 (b), the plastic index (PI%) data show that one sample complies with the ABC specification (PI < 6%), whereas five samples satisfy the DNIT specification (PI < 15%) and seven samples satisfy the MRWA specification (PI < 16%). With respect to resistance to abrasion, Figure 4 (c) shows that 21 samples meet the limit proposed by ABC (LA < 40%), while all 24 samples meet the specification limits proposed by both DNIT (LA < 65%) and MRWA (LA < 50%). Finally, 20 samples exceed the maximum recommended value (CBR - soaked > 80%) for soils to be used as base materials as established by the three specifications under analysis. Therefore, based on conventional parameters, seven samples meet the requirements for use in base material.

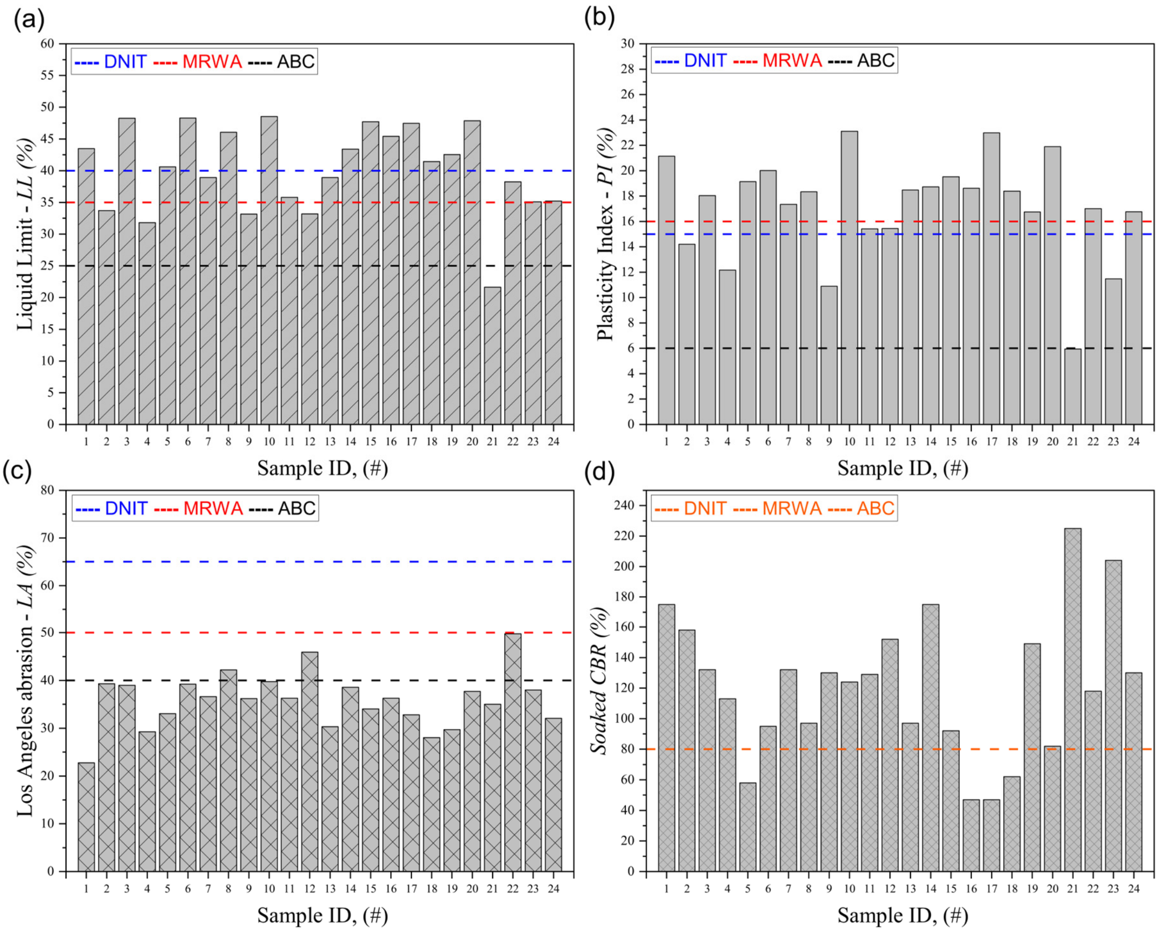


Figure 3. Limits for conventional parameters for base course: (a) Liquid limit, (b) Plasticity index (c) Los Angeles abrasion, and (d) Soaked CBR.

Furthermore, Figures 4 (a, b, and c) shows the grain size distribution curves of Bolivian lateritic gravels compared to the envelope specifications of ABC, DNIT and MRWA, respectively. The continuous black curves in the figures represent the upper and lower bounds of the envelope specifications. The analysis of grain size distribution curves for all samples show that they do not meet the strict grading requirements specified by ABC. Moreover, 18 samples fall within the specified grading envelope of DNIT, while 8 samples meet the envelope specifications of MRWA.

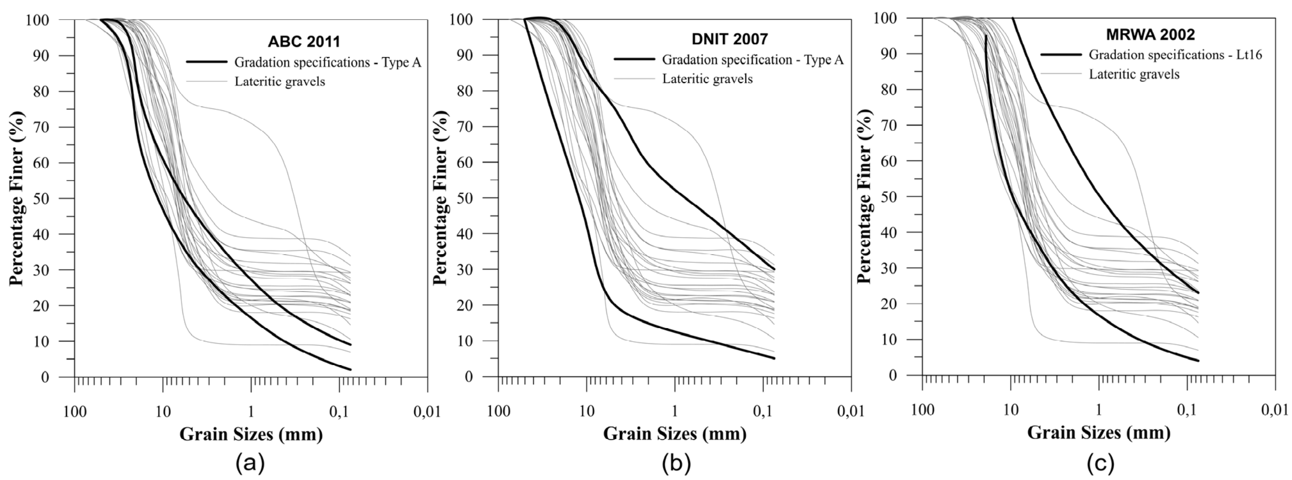


Figure 4. Grain size distribution curves of all samples with base course grading envelopes.

Figure 5 presents the results of chemical parameters proposed by DNIT and MRWA specifications for the selection of lateritic gravels for pavement base courses. Based on the graphical assessment of results, all samples are outside the criteria limits of the silica/sesquioxide molecular ratio (S/R ≤ 2) set by DNIT. Conversely, 20 samples comply with the sesquioxide content as proposed by MRWA (Al2O3 + Fe2O3 ≥ 20).

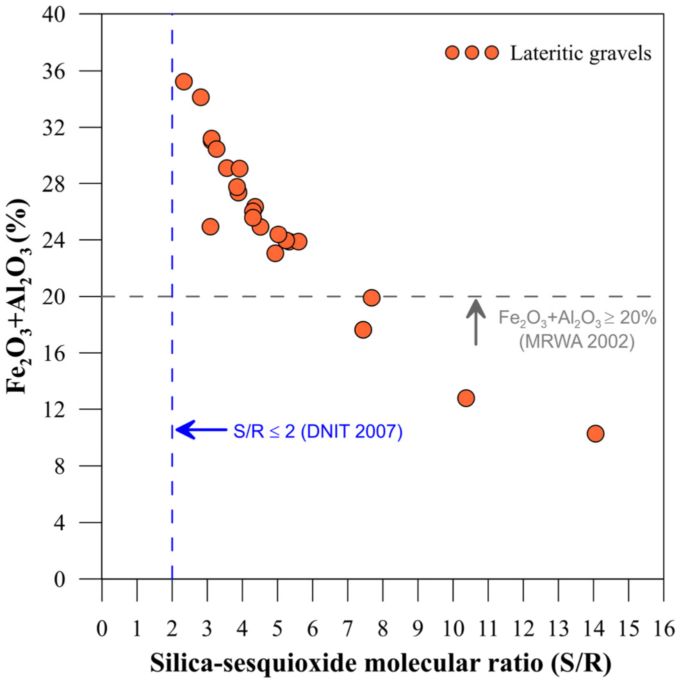


Figure 5. Results and chemical selection criteria for lateritic gravels for use in base course.

Previous studies conducted in other tropical regions of the world show that some lateritic soils do not meet the S/R ratio criterion. Additionally, there is reported difficulty in comparing the values of S/R ratio due to a wide range of values found in the literature. This is mainly attributed to the particle size fraction of the tested soils, the use of modified (normalized and unnormalized molecular masses) S/R formulas, and the testing method used for determining the chemical components (Netterberg, 2014).

4 CONCLUSIONS

Based on the assessment of three road specifications for material selection in pavement base courses, which are based on geotechnical, mechanical, and chemical requirements, conducted on the 24 samples of Bolivian lateritic gravels, the following conclusions can be drawn.

The evaluation results highlight that the current local specification of ABC is restrictive when applied to the selection of naturally occurring lateritic gravels for use as base layer material. This is due to strict ranges for geotechnical and geomechanical parameters, as well as the lack of consideration for chemical parameters-based selection criteria. Moreover, the specifications from Brazil (DNIT, 2007) and Australia (MRWA, 2002) demonstrate greater relaxations in terms of granulometric grading, liquid limit, plasticity index, and resistance to abrasion, allowing some samples of lateritic gravel to meet these limits. Additionally, the majority of the samples exhibit CBR resistance and expansion values that significantly meet the limits established by the specifications. Thus, the results suggest that some samples showcases suitable geotechnical and geomechanical characteristics for their use in the base layer of roads.
On the other hand, the evaluation of chemical parameters shows that the limits proposed by MRWA appear to be more appropriate for the lateritic gravels of Bolivia. However, the study's findings strongly advocate for highway infrastructure authorities to make informed decisions regarding the development of local specifications. These specifications should be based on, or adapted from, standards from other tropical regions that have proven effective in practice fo the application of lateritic materials, such as Brazilian and Australian specifications. Finally, the results show the potential use of naturally occurring lateritic gravels as an

alternative both technically and economically due to their good engineering characteristics, as well as their abundance in the Bolivian Amazon.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the Research Unit at the Center for Civil and Environmental Engineering Research (CIICA) of the Universidad Privada Boliviana (UPB) for their support during the conduct of this research.

REFERENCES

ABC (Administradora Boliviana de Carreteras). (2011). *Manual de diseño de conservación vial*. Bolivia: Grupo APIA XXI.

ABC (Administradora Boliviana de Carreteras). (2011). Manual de diseño de conservación vial. Bolivia: Grupo APIA XXI.

ASTM. (2011). *Standard practice for classification of soils for engineering purposes (Unified Soil Classification System)*. ASTM D2487-11. West Conshohocken, PA: ASTM.

ASTM. (2012*). Standard test methods for laboratory compaction characteristics of soil using modified effort (2,700 kN-m/m3)*. ASTM D1557. West Conshohocken, PA: ASTM.

ASTM. (2014). *Standard test methods for specific gravity of soil solids by water pycnometer.* ASTM D854. West Conshohocken, PA: ASTM.

ASTM. (2016). *Standard test method for California bearing ratio (CBR) of laboratory-compacted soils*. ASTM D1883. West Conshohocken, PA: ASTM.

ASTM. (2017a). *Standard test methods for liquid limit, plastic limit, and plasticity index of soils.* ASTM D4318. West Conshohocken, PA: ASTM.

ASTM. (2017b). *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis* . ASTM D6913. West Conshohocken, PA: ASTM.

ASTM. (2020). *"Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine."* ASTM C131, West Conshohocken, PA.

Blight, G. E., & Leong, E. C. (Eds.). (2012). Mechanics of residual soils. CRC Press.

Cocks, G. C., & Hamory, G. (1988). Road construction using lateritic gravel in Western Australia. In International Conference on Geomechanics in Tropical Soils, 2nd, 1988, Singapore (Vol. 1).

de Carvalho, J. C., de Rezende, L. R., Cardoso, F. B. D. F., de FL Lucena, L. C., Guimarães, R. C., & Valencia, Y. G. (2015). Tropical soils for highway construction: Peculiarities and considerations. Transportation Geotechnics, 5, 3-19.

Departemento Nacional de Infraestrutura de Transportes (DNIT). *Pavimentacao –Base estabilizada granulometricamente com utilizacao de solo lateritico – Especificacao de servico*; 2007. Norma DNIT–098/2007–ES.

Gidigasu, M. D. (1976). Laterite Soil Engineering. Pedogenesis and Engineering Principles.

Main Roads Department Western Australia (2002). Selection and use of naturally occurring materials as nace an dubbase. Perth: Main Roads Western Australia.

Netterberg, F. (2014). Review of specifications for the use of laterite in road pavements. Contract: AFCAP/GEN/124). Crown agents, AFCAP and UKaid.

Sunil, B. M., & Krishnappa, H. (2012). Effect of drying on the index properties of lateritic soils. Geotechnical and Geological Engineering, 30, 869-879.

Winterkorn H, Chandransenkharan EC. Laterite soils and their stabilization. HRB. Bull; 1951. No. 44.