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Aplicação da Metodologia MCT para Determinação da Erodibilidade de Solos em Taludes de Corte Rodoviários na Região do Quadrilátero Ferrífero
Application of MCT Methodology to Determine Soil Erodibility in Road Cutting Slopes in Quadrilátero Ferrífero Region

Bruno de Oliveira Costa Couto[1] & Romero César Gomes[2]

[1]Instituto Federal Goiano, Campus Rio Verde, Avenida Sul Goiana, km 01, S/N, Zona Rural, CEP: 75.901-970, Rio Verde, GO, Brasil.
[2]Universidade Federal de Ouro Preto, Núcleo de Geotecnia da Escola de Minas,
Campus Universitário Morro do Cruzeiro, S/N, CEP: 35.400-000, Ouro preto, MG, Brasil.
E-mails: bruno.couto@ifgoiano.edu.br; romero@em.ufop.br
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Resumo

A erodibilidade é definida como a suscetibilidade do solo aos processos erosivos. Apesar de diversos estudos desenvolvidos na área agronômica, ainda existem lacunas no que se refere a taludes de corte rodoviários, principalmente pelas diferentes condições estruturais do solo. O presente trabalho aborda a erodibilidade de taludes de corte rodoviários localizados na região do Quadrilátero Ferrífero - MG, com presença de horizontes de comportamentos antagônicos em relação à erosão. A avaliação da erodibilidade foi feita por meio de ensaios de caracterização geotécnica, metodologia Miniatura Compactada para Solos Tropicais (MCT), infiltrabilidade e perda de massa por imersão modificada. Os resultados da metodologia MCT demonstram comportamento nitidamente diferente entre solos resistentes e erodíveis, confirmando que condições lateríticas aumentam a resistência do solo frente à erosão hídrica. O critério de erodibilidade MCT verificou que solos erodíveis são mais instáveis quando em contato com a água, mostrando melhor desempenho quando comparado à metodologia MCT convencional. Portanto, solos mais intemperizados ou em condição lateríticas, são mais resistentes aos processos erosivos, enquanto que solos menos evoluídos, com horizontes C, são propensos à erosão, necessitando de medidas de controle que evitem sua exposição direta as intempéries.
Palavras-chave: Erodibilidade; Metodologia MCT; Taludes de Corte; Quadrilátero Ferrífero.

Abstract

Erodibility is defined as soil susceptibility to erosive processes. Although several studies have been developed in agronomic area, there are still gaps regarding road slopes, mainly due to the different soil structure conditions. This present work addresses the erodibility in road cut slopes located in the Quadrilátero Ferrífero – MG, with presence of horizons of antagonistic behavior in relation to erosion. The erodibility evaluation was made by geotechnical characterization, Compacted Miniature for Tropical Soils methodology (MCT), infiltrability and modified immersion mass loss tests. The results of MCT methodology demonstrate distinctly behavior between resistant and erodible soils, confirming that lateritic conditions increase soil resistance against water erosion. The MCT erodibility criterion checked that erodible soils are more unstable when in contact with water, showing better performance when compared to conventional MCT test. Therefore, more weathered or lateritic soils are more resistant to erosive processes, while less evolved soils, such as C horizons, are prone to erosion, requiring control measures to prevent their direct exposure to weathering.**Keywords:** Erodibility; MCT Methodology; Cutting Slopes; Quadrilátero Ferrífero.

1 Introdução

Soil erosion is one of the most important problems in the world which demands much attention. This process affects both urban and rural regions, originating a number of problems, among which loss of fertile soils, reduction of available water for human supply, and decrease in agricultural productivity (Denardin, 1990; Bastos, 1999; Tefera & Sterk, 2010; Liu et al., 2019).

Water erosion estimation can become complex due to the interference of several variables, such as: climate, topography, use and management (Wischmeier *et al*., 1971; Morgan, 2005; Moreira & Polivanov, 2019). However, soils under the same environmental conditions have different erosion rates, indicating that the soil itself, through its intrinsic properties, contributes to erosive process, a condition that is analyzed under the specific concept of “erodibility” (Wang *et al*., 2013; Havaee *et al*., 2015).

Soil erodibility is studied by different areas, such as agronomy, geology, pedology and geotechnics, being more focused by agronomic researchers, because of the extensive arable areas around the world. The geotechnical area has been presenting an increase in number of works and methodological proposals, mainly due to impacts on urban areas resulting from anthropic intervention. Among these interferences, we highlight the cut slopes located on highway and vicinal roads margins, which has a lack of adequate vegetation cover, resulting in soil losses, which leads to sediments accumulation on roads or even slope rupture. According to Soares *et al.* (2018), when slopes are excavated without proper road construction techniques, there may be progressive intensification of the surface erosive process, generating deeper features because of the exposure of less stable horizons.

Considering erodibility study in cut slopes, it is difficult to measure the soil potential by direct methods, mainly because these slopes have tortuous geometry and high gradient that make it difficult to install field plots. Therefore, the indirect approach by intrinsic soil properties, determined by laboratory or field test, is more suitable for this condition.

The indirect approach is centered in some soil properties as grain sizes distribution, plasticity, selected chemical properties, bulk density and organic matter, (Wischmeier *et al*., 1971; Denardin, 1990; Silva *et al.,* 2000; Lima *et al.,* 2007; Havaee *et al*., 2015; Moreira & Polivanov, 2019). However, most of the existing methodologies are based on temperate climate soils, with little application to tropical soils, especially in the Brazilian oxisols. Some authors claim that intrinsic soil properties, in isolate way, are not sufficient to evaluate erodible potential of tropical soils, because the changes caused by pedogenetic evolution process are not considered, which leads to the formation of highly stable aggregates, that resist against water action (Silva *et al*., 2015; Oliveira *et al*., 2018; Silva *et al*.; 2019).

In order to overcome this limitation, the MCT methodology is promising in estimating the erodibility of tropical soils. This method was specially developed to verify the geotechnical behavior in tropical regions, with hot and humid climate, and incorporating a potential system to evaluate the erodibility of Brazilian soils, since it associates geology and pedology in the prediction of soil behavior against erosion. The resulting classification from MCT test divides tropical soils in two groups: lateritic and non-lateritic behavior. Lateritic behavior occurs in tropical soils with accumulation of iron and aluminum oxides, resulting in great aggregate stability, high bearing capacity and low expansion, characteristics of erosion resistant soils. (Nogami & Villibor, 1995; Paes, 2017).

In this context, the present article is part of soil erodibility indirectly approach in road cut slopes, through the association of physical and geotechnical properties, evaluated together with MCT methodology. In order to minimize the interference of environmental variables, the specific sampling pattern was adopted, where slopes with presence of two typically different horizons in relation to erosion were chosen.

2 Materials and Methods

2.1 Study Area Characterization

The slopes investigated in this study are situated in Quadrilátero Ferrífero region, which is one of the most important world’s mineral provinces (Ribeiro *et al*., 2014). This area presents great domain of less evolved soils with high influence of original material. Therefore, erosive processes are predominant over pedogenesis, conditioned by both the relief and the resistance of most part of regional rocks to weathering (Carvalho Filho *et al*., 2010).

In this way, it is necessary to study soil erosion adopting similar geomorphological and climatic conditions, making it possible to establish correlations on the erodibility from same environmental and spatial reference. Thus, the present article studies the soil erodibility of Quadrilátero Ferrifero's slopes, composed of two horizons which present distinct behavior against erosive processes: one shows resistance, while the other, susceptibility to erosion (Figure 1).

From this condition, ten slopes were chosen, designated by the initials of the region in which they are located, and the pedological classification was made based on Brazilian Soil Classification System (Santos *et al*., 2006), as shown in Table 1. In order to simplify the reference of each sample, a criterion was adopted for their nomenclature, where the erosion resistant horizons were called upper horizons (using letter "U") and the erodible horizons were entitled lower horizons (using letter "L"), according to Figure 1.

Slope	Location	Pedological Classification	Horizons Sampled	Identification Adopted
ITA	Itabira - MG	Latossolo Vermelho Distrófico típico (oxisol)	Bw	ITA – U
			C	ITA – L
VAR	Vargem Alegre - MG	Latossolo Vermelho Distrófico típico (oxisol)	Bw	VAR – U
			C	VAR – L
OBR	MG -443 Road Ouro Branco - MG	Latossolo Vermelho Acriférrico típico (oxisol)	Bw	OBR – U
			C	OBR – L
MRN	Mariana - MG	Neossolo Regolítico Distrófico típico (leptosol)	A	MRN – U
			C	MRN – L
ALG	Entrance Alegria Mine Mariana - MG	Neossolo Regolítico Distrófico típico (leptosol)	A	ALG – U
			C	ALG – L
PTO	Ouro Preto - MG	Latossolo Vermelho Distrófico típico (oxisol)	Bw	PTO – U
			C	PTO – L
ATP	Antônio Pereira Ouro Preto - MG	Latossolo Vermelho Acriférrico típico (oxisol)	Bw	ATP – U
			C	ATP – L
LVN	Lavras Novas, Ouro Preto - MG	Cambissolo Háplico Tb Distrófico típico (Inceptsol)	Bi	LVN – U
			C	LVN – L
AMF	Maria Firmino Ave Ouro Branco - MG	Latossolo Vermelho Eutrófico típico (oxisol)	Bw	AMF – U
			C	AMF – L
CNG	Congonhas Ave Ouro Branco - MG	Latossolo Vermelho Distrófico cambissólico (oxisol)	Bw	CNG – U
			C	CNG – L

Table 1 Soils samples Description. Legend: Bw = Latossolic B horizon; Bi = Incipient B horizon.

2.2 Test Methods

To characterize the different horizons, disturbed and undisturbed samples were collect according to established by NBR 9604 procedure – Well opening and ground inspection trench, with disturbed and undisturbed samples (ABNT, 2016a). The following geotechnical characterization tests were performed: NBR 6457 – Soil samples: preparation

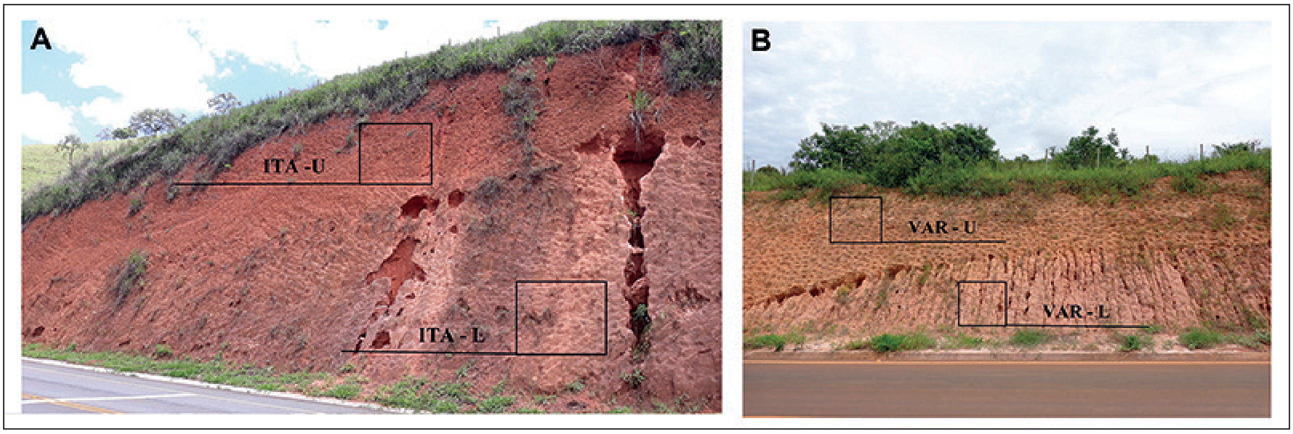

Figure 1 Examples of slopes approached at Quadrilátero Ferrífero, with details of soils sampled: (A) Itabira (ITA), with the upper (ITA – U) and lower (ITA – L) samples; (B) Vargem Alegre (VAR), with the upper (VAR – U) and lower (VAR – L) samples.

for compaction and Characterization tests (ABNT, 2016b); NBR 7181 – Soil: particle size analyses (ABNT, 2016c); NBR 6458 – Gravel grains retained in the sieve 4.8 mm: specific mass, apparent specific mass and water absorption determination (ABNT, 2016d); NBR 6459 – Soil: Liquid limit determination (ABNT, 2016e); NBR 7180 – Soil: Plasticity limit determination (ABNT, 2016f).

To evaluate soil lateritic behavior, the MCT methodology was used and the samples were submitted to compaction mini-MCV (Moisture Condition Value) and mass loss immersion, according to procedures established on DNER-ME 258 – Soil: miniature equipment compaction (DNER, 1994a) – and DNER-ME 256 – Soil: miniature equipment compaction – immersion mass loss determination (DNER 1994b).

2.3 MCT Erodibility Criterion

Using MCT Methodology, it is possible to evaluate the soil erodibility potential. In accordance with Nogami & Villibor (1979), this estimation is based on two parameters: the modified soil loss by immersion (Pi) and the sorption coefficient (s). For these authors, soils are considered erodible when Pi. s^{-1} ratio is greater than 52 (Pi. $s^{-1} > 52$). Pejon (1992), studying the erodibility trough geotechnical mapping of the Piracicaba chart, used this criterion and suggested adopting the ratio Pi. s^{-1} greater than 40 as an erosion limit (Pi. $s^{-1} > 40$).

The modified mass loss immersion test was determined from undisturbed samples collected from beveled PVC rings (50 mm in diameter and 50 mm in height) which were subsequently immersed in water to determine the disintegration potential. The Pi coefficient was determined by the ratio between dry mass of detached soil and its initial dry mass. In this method, soils samples were tested in two conditions: natural moisture and air dried (for 72 hours, at least).

The sorption coefficient was determined by the infiltrability test, which aims to identify the capillary rise rate in soil samples. For this method, undisturbed samples are also collected on beveled PVC rings (50 mm in diameter and 25 mm in height), which are placed on a porous stone, connected to a graduated burette. The sample's base coincides with the level of capillary tube, so, only through capillary process is that water enters the soil. Using graduated ruler and timer, the distances traveled at time intervals, in quadratic order, are recorded (1, 2, 4, 9, 16, 25, 49, *etc.*) until the time that soil samples proved to be fully saturated, which happens when water flow in burette ceases.

With the distance traveled in the burette (in cm) and the square root of the necessary time for it ($min^{1/2}$), is possible to define a curve (distance traveled x $time^{1/2}$). This curve has a typically bilateral behavior, with strong initial rectilinear section, followed by horizontal stabilization. The sorption coefficient is calculated by the inclination of initial rectilinear stretch. Similar to Pi determination, we used two conditions to determine the sorption coefficient: natural moisture and air dried (for 72 hours, at least).

3 Results and Discussion

Physical characterization is considered primordial in the investigation of geotechnical problems, because can influence other soil properties. The particle size distribution shows that the upper horizons (U) have higher clay percentage (Table 2). As a consequence, soil particles have more cohesion, increasing resistance to water erosion, similar results as found by Knapen *et al.* (2007); Havaee *et al.* (2015) and Cassol *et al.* (2018).

On the other hand, the erodible horizons (L) presented higher silt and fine sand percentage, materials with low binder property and which have dispersive properties when immersed in water (Wischmeier *et al.*, 1971; Morgan, 2005; Ampontuah *et al.*, 2006). These results proved the influence of soil particles on susceptibility to erosive processes, in a similar response founded by Soares *et al.* (2018) studying erodibility in cut slopes in Bom Jardim municipality – RJ, Brazil.

Considering the Atterberg limits, erodible soils presented low values or even a lack of plasticity (NP < PI < 16), according to Table 2. In contrast, resistant soils show higher PI values, relating plasticity to resistance against erosion. It is important to emphasize that plasticity behavior of soils is related to other properties, such as fine particle content and mineralogy. These two parameters are associated with the amount of water which a particular soil can absorb and with its dispersive characteristics. However, Atterberg limits (LL, PL and PI) cannot be used as absolute parameter to identify erodible soils, but many researchers claim that the high values are associated to resistance to dispersion (Igwe & Ejiofor, 2005; Nandi & Luffman, 2012).

Samples	Particle Size Distribution						γ_s (KN/m³)	Atterberg Limits		
	G (%)	CS (%)	MS (%)	FS (%)	S (%)	C (%)		LL (%)	PL (%)	PI (%)
ITA – U	0,2	1,4	4,8	17,1	26,8	49,7	27,06	68	30	38
ITA – L	8,1	4,4	8,6	23,9	47,6	7,4	26,26	39	33	6
VAR – U	1,1	0,7	4,7	11,5	26,2	55,8	26,41	61	31	30
VAR – L	0,4	1,1	5,0	25,8	60,7	7,0	25,07	40	31	9
OBR – U	0,4	4,3	3,3	57,0	25,5	9,5	27,82	50	34	16
OBR – L	0,6	1,2	3,4	3,4	83,8	7,6	27,07	57	50	7
MRN – U	1,2	2,8	2,5	14,7	56,3	21,5	28,72	51	34	17
MRN – L	0,1	3,4	17,5	27,4	44,8	6,8	27,22	28	NP	0
ALG – U	14,4	6,8	7,2	8,5	36,3	26,8	27,24	37	22	15
ALG – L	0,1	4,3	18,6	28,9	42,5	5,6	26,40	28	22	6
PTO – U	4,2	4,9	6,9	18,6	20,2	45,2	28,21	51	31	20
PTO – L	9,5	6,1	11,4	25,4	27,1	20,5	27,34	34	22	12
ATP – U	1,2	5,2	11,0	57,7	12,6	12,3	29,97	30	21	12
ATP – L	7,1	2,8	7,4	39,7	33,0	10,0	31,31	28	17	11
LVN – U	1,5	8,6	18,9	30,5	20,7	19,8	26,76	53	19	34
LVN – L	1,0	10,7	21,8	31,7	26,3	8,5	26,36	0	NP	0
AMF – U	3,1	4,9	7,5	20,7	22,8	41,0	26,60	59	34	25
AMF – L	2,6	12,7	25,6	10,2	13,3	35,6	27,04	55	39	16
CNG – U	0,7	3,6	10,9	44,8	18,5	21,5	27,82	57	33	24
CNG – L	3,5	4,7	10,8	27,7	37,8	15,5	26,02	49	36	13

Table 2 Physical characterization. Legend: G = gravel; CS = coarse sand; MS = medium sand; FS = fine sand; S = silt; C = clay; γ_s = specific weight of soil grains; LL = liquid limit; PL = plasticity limit; PI = plasticity index; NP = non-plastic.

The MCT Methodology was developed to verify geotechnical soil behavior in tropical regions (Nogami & Villibor, 1979; Nogami & Villibor, 1995), incorporating a potential system to evaluate the erodibility of Brazilian soils, since it associates geology and pedology in the prediction of soil behavior against erosion. Table 3 presents the classification parameters and resultant class according to MCT methodology, considering the coefficients d', c', soil loss by immersion (Pi) and specific erodibility (e').

Samples	d'	c'	Pi (%)	e'	Classification
ITA – U	77,73	2,18	17,1	0,78	LG'
ITA – L	38,04	0,50	318,1	1,62	NA
VAR – U	51,69	1,81	30,1	0,86	LG'
VAR – L	20,89	1,11	286,1	1,56	NS'
OBR – U	44,15	0,18	123,5	1,25	LA
OBR – L	43,21	0,95	179,5	1,35	NA'
MRN – U	28,93	0,76	240,0	1,46	NA'
MRN – L	22,06	0,58	300,7	1,61	NA'
ALG – U	35,93	1,06	85,3	1,12	LA'
ALG – L	4,55	0,65	259,6	1,91	NS'
PTO – U	20,36	2,04	20,0	1,06	LG'
PTO – L	19,64	0,70	150,4	1,36	NA'
ATP – U	129,05	2,17	5,0	0,59	LG'
ATP – L	53,33	1,19	27,0	0,86	LA'
LVN – U	33,01	1,01	82,0	1,13	LA'
LVN – L	16,25	0,38	278,0	1,59	NA
AMF – U	23,13	2,08	37,3	1,07	LG'
AMF – L	14,62	1,16	87,3	1,31	NA'
CNG – U	19,64	2,07	40,1	1,12	LG'
CNG – L	3,55	0,90	254,9	2,01	NS'

Table 3 MCT classification parameters. Legend: Pi = soil loss by immersion; e' = specific erodibility; LG' = clayey lateritic; NA' = sandy non-lateritic; NS' = silty non-lateritic; NA = non-lateritic sand; LA = lateritic sand; LA' = sandy lateritic.

The d' coefficient presented great variation, and the highest values in the resistant horizons (U), mainly due to higher clay contents and their specific mineralogical characteristics, such as kaolinite and iron and aluminum oxides content. According to Nogami & Villibor (1995), clayey soil with lateritic behavior have d' coefficient greater than 20. The same observation can be made for the c' coefficient, which also presents higher values in resistant horizons (U). This results are consequence of a combined effect between particle size distribution and cohesion imposed by the mini-MCV compaction test, where the fine particles are rearranging, due to the compaction energy, resulting in greater aggregation and stability.

The MCT classification was different according to erosion behavior observed. The resistant soils (U) presents lateritic characteristics (LG', LA' and LA). In addition, these combined properties increase the cohesive forces and aggregate stability against water erosion. Similar results were founded in the research developed by Pejon (1992) and Silva *et al.* (2019), where lateritic condition explained the resistance against erosion.

Contrarily, erodible soils present non-lateritic behavior (NS', NA' and NA), consequence of higher silt and fine sand percentage, which are considered low cohesion materials. These soils are less evolved and present expansive and partially weathered materials, which contribute to elevate specific erodibility (e') and soil loss by immersion (Pi).

The sample MRN-U was classified as NA', which does not represent the erosion resistance condition observed in the field. It is a consequence from destruction of original soil structure in MCT procedures for mini-MCV compaction test, since it is necessary to disaggregate and separate the passing fraction in sieve n° 200 (0,075 mm). In this procedure, the silt fraction is released, and the mini-MCV compaction process fails providing the previously existing aggregation, resulting in high immersion mass loss.

An ambiguous situation was observed in LA' group, with the framing of resistant soils (LVN - U and ALG - U) as erodible soil (ATP – L). The LVN - U and ALG - U samples are considered poorly evolved soils, *i.e.*, that do not have weathering level that shows an advanced lateritic condition. Considering ATP-L sample, even being an erodible horizon, it exhibits lateritic characteristics caused by property changes during the MCT test. As Nogami & Villibor (1995) claim, under natural conditions, soils of this class have low bearing capacity and can be collapsible when immersed in water. However, when properly compacted, they acquire high bearing capacity, cohesion and low expandability when subjected to water action.

The MCT erodibility criterion was used to evaluate the original soil structure when it comes in contact with water, especially in modified immersion mass loss (Figure 2 and Figure 3). In this context, the mass losses were quite different between the two types of horizons. Resistant soils have low mass loss, which present a maximum value of 15 %. In contrast, erodible horizons exhibited high mass losses, reaching 80 %, due to presence of micaceous minerals and low cohesion, characteristics also identified in the conventional MCT test.

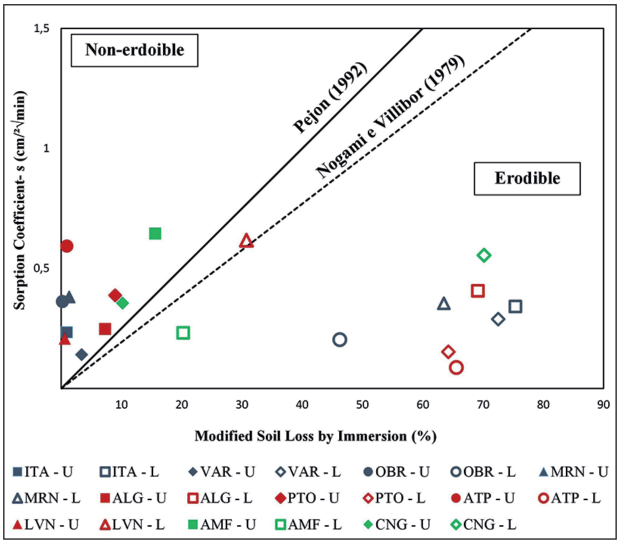

Figure 2 MCT erodibility criterion (natural moisture condition)

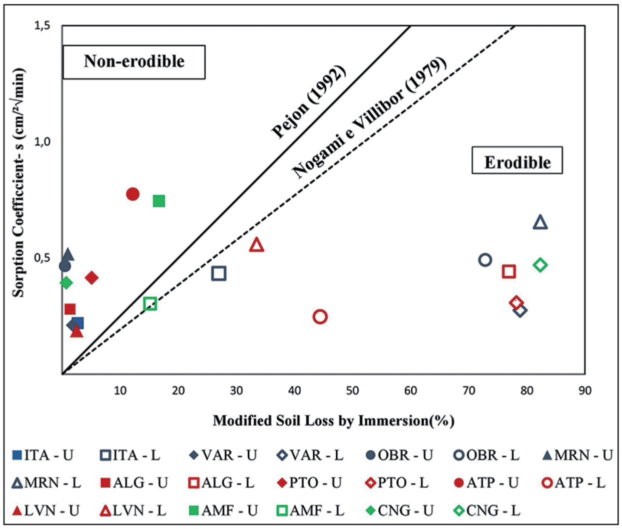

Figure 3 MCT erodibility criterion (72-hour air dried condition).

Erosion resistant soils presented $0,627 < Pi.s^{-1} < 29,476$, while erodible horizons $49,757 < Pi.s^{-1} < 754,023$, proving efficiency in distinguishing soil behavior against erosion. The two criteria used clearly separate resistant from erodible soils, focusing in Pejon (1992), which was able to distinguish all the studied samples. These observations are similar to other results found in literature such as Bastos (1999), Menezes & Pejon (2010) and Paes (2017).

The erodible horizons tend to increase mass loss in air-dry condition, associating the soil drying effect to the increase of soil susceptibility to erosion. Therefore, the lower moisture content in the beginning of rain can provide a greater material loss. Similar observations were found by Menezes & Pejon (2010) in soils of São Carlos and São Pedro municipalities in São Paulo State.

By using undisturbed samples, preserving original structure and aggregation, the erodibility criterion showed a corresponding behavior observed in field for MRN-U, LVN-U, ALG - U and ATP – L samples. Condition that was not clear in MCT conventional test. Therefore, we can conclude that MCT erodibility criterion (Pi.s^{-1}) overcomes an existing limitation in the MCT methodology, considering the erodibility theme.

4 Conclusions

The results confirm that soils with higher weathering degree have less susceptibility to water erosion, as observed in B horizons samples (upper horizons - U). In contrast, C horizons (lower horizons – L) are more susceptible to erosion due to their low cohesion and high percentage of silt and fine sand, which makes particle dragging easier.

The lateritic characteristics influence the susceptibility to erosive processes, where resistant soils present lateritic behavior, due to the advanced pedogenetic evolution process, while erodible soils, lacking such property, present instability when subjected to water action.

The MCT methodology shows promising application in distinguishing potentially erodible soils, mainly by the immersion mass loss test. However, it has limitation in some cases due to the destruction of original soil structure in samples preparation, as observed for the MRN–U and ATP–L samples. In this context, the MCT erodibility criterion was fundamental to distinguish soil behavior in relation to erosion, and it can be used to investigate erodibility potential of soils in road slopes.

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