UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE GEOCIÊNCIAS

Interpretação de SWRC de rejeito de ferro itabirítico com foco na avaliação da saturação de pilhas de rejeitos filtrados

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Dissertação apresentada ao Programa de Pós-Graduação em Recursos Minerais e Hidrogeologia para obtenção do título de Mestre.

Área de concentração: Hidrogeologia e Meio Ambiente.

Orientador: Prof. Dr. Fernando Antonio Medeiros Marinho

SÃO PAULO

2022

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Nadai, Felipe Moschem de
Interpretação de SWRC de rejeito de ferro itabirítico com foco na avaliação da saturação de pilhas de rejeitos filtrados / Felipe Moschem de Nadai; orientador Fernando Antônio Medeiros Marinho. -- São Paulo, 2022.
62 p.

Dissertação (Mestrado - Programa de Pós-Graduação em Recursos Minerais e Hidrogeologia) -- Instituto de Geociências, Universidade de São Paulo, 2022.

1. Rejeitos de mineração. 2. Mecânica dos solos não saturados. 3. Geotecnia. 4. Curva de retenção de água no solo. 5. Empilhamento de rejeito filtrado. I. Marinho, Fernando Antônio Medeiros, orient. II. Título.

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Dissertação de Mestrado

Nº 885

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SÃO PAULO

2022

AGRADECIMENTOS

Agradeço à Universidade de São Paulo e ao sistema de universidades públicas vigente no Brasil pela possibilidade de desenvolver um mestrado de forma gratuita. Sem a gratuidade da USP, a realização de projetos de pesquisa como esse seria menos acessível à comunidade acadêmica e profissional.

Agradeço ao Prof. Dr. Fernando Marinho pela orientação na pesquisa bibliográfica e no desenvolvimento dos artigos científicos presentes nessa dissertação. Sem a sua orientação e seu conhecimento, a realização desse projeto de pesquisa teria sido muito mais difícil.

Agradeço ao Eng. Dr. João Paulo Silva, primeiro por ter me dado o incentivo inicial a fazer o mestrado na época em que eu trabalhava na Geoconsultoria, e também pela colaboração na elaboração dos artigos científicos apresentados neste documento. Sem seu incentivo inicial, eu não teria tido iniciativa de buscar fazer essa pesquisa.

Agradeço à Geoconsultoria pela minha iniciação na atividade profissional em geotecnia. A oportunidade de atuar profissionalmente me colocou em contato com o tema desta pesquisa e me incentivou a estudar cada vez mais sobre geotecnia.

Agradeço à Bentley Systems pela oportunidade de trabalhar com software para geotecnia, o que me coloca em aprendizado contínuo sobre essa ciência. Além disso, sem a disponibilidade do PLAXIS LE para a modelagem computacional nessa pesquisa, esse projeto teria sido muito mais trabalhoso.

Agradeço à Vale S.A. e ao Instituto de Pesquisa Tecnológica pela realização dos ensaios de laboratório usados nesta pesquisa. O acesso aos resultados desses ensaios foi fundamental para a elaboração dos artigos científicos frutos desse projeto.

Agradeço aos professores Dr. Ricardo Hirata, Dra. Alexandra Suhogusoff e Dr. Luiz Carlos Ferrari, além de novamente ao Prof. Dr. Fernando Marinho, pelo aprendizado obtido nas disciplinas cursadas durante o curso de mestrado. Esse aprendizado foi fundamental no direcionamento da minha pesquisa.

Agradeço à minha esposa Luiza e meus pais, Natalicio e Goreti, pelo incentivo, paciência e suporte durante a realização deste projeto de pesquisa.

RESUMO

O aumento da utilização de deposição de rejeitos por meio de empilhamento de material não saturado tem levado a necessidade de maiores estudos relacionados com o comportamento da água nestes materiais após a sua disposição. Os eventuais problemas advindos desta deposição estão não somente relacionados com o processo de compactação, mas também com a capacidade de retenção de água destes materais. Misturar rejeito de deslamagem com materiais mais grossos, como rejeito flotado, tem ganhado popularidade como forma de superar os problemas no empilhamento seco de materiais de granulação fina. O problema está associado a ocorrência de elevado grau de saturação, particularmente na base das pilhas, devido à capacidade de retenção de água. Entretanto, há pouca informação a respeito do desempenho hidráulico não-saturado dessas misturas de rejeito. Ensaios de caracterização geotécnica básica, ensaios de compactação, ensaios edométricos e ensaios para determinação das curvas de retenção de água de rejeitos de minério de ferro itabirítico de deslamagem, flotado e suas misturas foram analisados. As curvas de retenção de água do solo (SWRC) obtidas experimentalmente e as suas respectivas funções condutividade hidráulica não saturadas, obtidas usando o método Fredlund and Xing (1994), foram analisadas em condição de equilíbrio ao longo da profundidade de 100 metros de um depósito de rejeito filtrado hipotético. Esse trabalho apresenta o efeito da subida de água por capilaridade nas misturas de rejeito obtido por meio da interpretação das curvas de retenção de água. Observou-se que rejeito de deslamagem puro mantém grau de saturação acima de 80% ao longo de dezenas de metros acima do nível freático, devido à capilaridade; por outro lado, no rejeito flotado puro e nas misturas a espessura da pilha com saturação acima de 80% é de menos de 1 m. Além disso, estudos numéricos de percolação não saturada mostraram que o efeito de chuva e evapotranspiração representativas do Quadrilátero Ferrífero não altera as conclusões obtidas pela interpretação da SWRC com relação a ascenção capilar, mas indica o efeito do clima na zona ativa.

Palavras-chave: rejeitos de mineração; solos não saturados; geotecnia; curva de retenção de água; empilhamento seco; grau de saturação.

ABSTRACT

The increase in the adoption of dry stacking of unsaturated material to dispose tailings is demanding further studies related to the behavior of water in this materials after the disposition. The problems arising from unsaturated deposition are not only related to the compaction process, but also with the water retention capacity of these materials. Blending desliming tailings with coarser materials, such as flotation tailings, has been gaining popularity as a way to overcome the problems in dry stacking fine grained materials. The problem is associated with the occurence of high saturation degree, particularly at the bottom of the piles, due to the water retetion capacity. However, there is little information about the hydraulic performance of these tailings blends. Basic geotechnical characterization tests, compaction tests and tests to determine water retention of itabirite iron ore desliming tailings, flotation tailings and their blends were analyzed. The experimentally obtained Soil Water Retention Curves (SWRC) and their respective unsaturated hydraulic conductivity function, obtained through the Fredlund and Xing method (1994), were analyzed in equilibrium condition along the 100 meters depth of a filtered tailings deposit. This work presents the effect of the rise of water by capillarity in tailings blends obtained through the interpretation of the water retention curves. It was observed that pure desliming tailings maintain a degree of saturation above 80% along tens of meters above the phreatic level, due to capillarity; on the other hand, in the pure flotation tailings and in the blends the thickness with saturation degree above 80% is less than 1 meter. Furthermore, numerical studies of unsaturated percolation showed that the effect of rain and evapotranspiration representative of the Quadrilátero Ferrífero does not change the conclusions obtained by the SWRC interpretation regarding capillary rise, but indicates the effect of climate in the active zone.

Keywords: tailings; unsaturated soils; geotechnics; soil water retention curve; dry stacking; saturation degree.

Sumário

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1. ORGANIZAÇÃO DO TEXTO

O presente documento apresenta no Capítulo 2 uma introdução ao tema da dissertação: desempenho hidráulico não saturado de rejeito de minério de ferro itabirítico. Primeiro, é feito uma contextualização do tema, de forma a mostrar sua relevância; depois são apresentados os conceitos teóricos usados no trabalho. No Capítulo 3 é apresentado o primeiro artigo científico produzido, no qual são apresentados ensaios de caracterização geotécnica de rejeitos de ferro itabiríticos de deslamagem, de flotação, e suas misturas, além de uma análise por meio da interpretação da Curva de Retenção de Água (SWRC, Soil Water Retention Curve) da saturação interna de pilha de rejeito devido a capilaridade. No Capítulo 4 é apresentado o segundo artigo científico produzido, no qual são apresentadas análises de percolação de pilhas não saturadas de rejeito de ferro itabirítico de deslamagem, de flotação e suas misturas, sob a influência de chuva e evapotranspiração representativa da região do Quadrilátero Ferrífero. No Capítulo 5 são apresentadas as conclusões que podem ser tomadas dos artigos científicos produzidos, e as conclusões finais sobre desempenho hidráulico de pilhas de rejeito não saturadas de minério de ferro itabirítico. No Capítulo 6 são feitas sugestões para a continuação de pesquisa neste tema. No Capítulo 7 são apresentadas as referências deste documento. E no Capítulo 8 são apresentadas o comprovante de submissão do primeiro artigo científico.

2. INTRODUÇÃO

A mineração provém boa parte dos recursos materiais utilizados nas atividades humanas, por isso é fundamental para as sociedades humanas desde o início da civilização. Esta necessidade por recursos minerais não deve se reduzir no curto prazo e os rejeitos dos processos de mineração devem ser adequadamente dispostos de modo a evitar problemas socioambientais. Segundo Brown et al. (2019) o minério de ferro correspondeu a 94% dos 3,2 bilhões de toneladas de minério metálico produzidas no mundo em 2019, o que mostra a importância desse minério. Nesse processo, são gerados 1,4 bilhão de toneladas de rejeito de minério de ferro por ano no mundo

(Carmignano et. al., 2021). No Brasil, produziu-se 396 milhões de toneladas de minério de ferro beneficiado em 2019, segundo o Anuário Mineral Brasileiro (2020). Em 2014, foi gerado 275 milhões de toneladas de rejeito de ferro no Brasil (Lima, 2019). Especificamente na região geográfica do Quadrilátero Ferrífero, no estado de Minas Gerais, foram produzidas 203 milhões de toneladas de minério de ferro em 2020 (Carmignano et. al., 2021). No Quadrilatero Ferrífero, a origem do ferro são rochas itabiríticas. O método de concentração do minério de ferro a partir de rocha itabirítica mais utilizado é a flotação catiônica reversa, na qual o minério sedimenta e o rejeito é retirado por flotação. Antes da flotação, o minério bruto passa por um processo de deslamagem. Desse modo, são gerados dois rejeitos distintos, rejeito lama e rejeito flotado, que apresentam características geotécnicas distintas (Ferreira, 2015). O rejeito lama costuma apresentar granulometria de menor diâmetro, argilo-siltoso, enquanto que o rejeito flotado apresentar maior diâmetro de grãos, areno-siltoso.

Para o descarte do rejeito, a solução mais adotada é o lançamento hidráulico em barragens (IBRAM, 2016). Entretanto, com a ruptura catastrófica de barragens de rejeito nos últimos anos, como as ocorridas nos municípios de Mariana (2015) e Brumadinho (2019), ambas no Quadrilátero Ferrífero, reguladores e opinião pública local vem demandando a substituição da disposição de rejeitos em barragens por alternativas de menor risco de colapso (Leonida, 2020). Nesse contexto, o empilhamento à seco de rejeito de ferro filtrado vem se despontando como uma solução viável do ponto de vista técnico e econômico, ganhando cada vez mais popularidade nos últimos anos (Davies, 2011), apesar do maior custo operacional devido a não bombeabilidade do rejeito filtrado. A Figura 1 apresenta a variação parâmetros físicos, como o grau de saturação, de acordo com o desaguamento do rejeito. Nota-se que os rejeitos filtrados são sempre não saturados e não bombeáveis. Também não ocorre segregação entre sólidos e água livre.

A não bombeabilidade do rejeito filtrado exige que seja carregado por caminhão ou esteira transportadora, depositado e compactado mecanicamente. Por outro lado, além de ser uma alternativa mais segura, o empilhamento de rejeito filtrado permite a reciclagem da água usada no beneficiamento mineral e requer uma menor área (Davies et al, 2010, and Gomes, 2016). Essas vantagens fizeram com que a adoção da técnica de empilhamento de rejeito filtrado ganhe popularidade nas últimas décadas, como mostrado na Figura 2, especialmente em localidades com escassez de água (climas áridos) e indisponibilidade de terreno por restrições ambientais. Outras vantagens do empilhamento de rejeito filtrado é que não é necessário se preocupar com água livre ou com a necessidade de construção de barreira capilar para redução da contaminação freática (Crystal, 2018, and Garino, 2012). Desse modo, a tendência é que empilhamento filtrado passe a ser cada vez mais adotado para a disposição de rejeitos de minério, não somente em regiões de clima árido, mas também em regiões úmidas como o sul da China (Li, 2016) e o Quadrilátero Ferrífero (Zorzal, 2016, and Gomes, 2016).

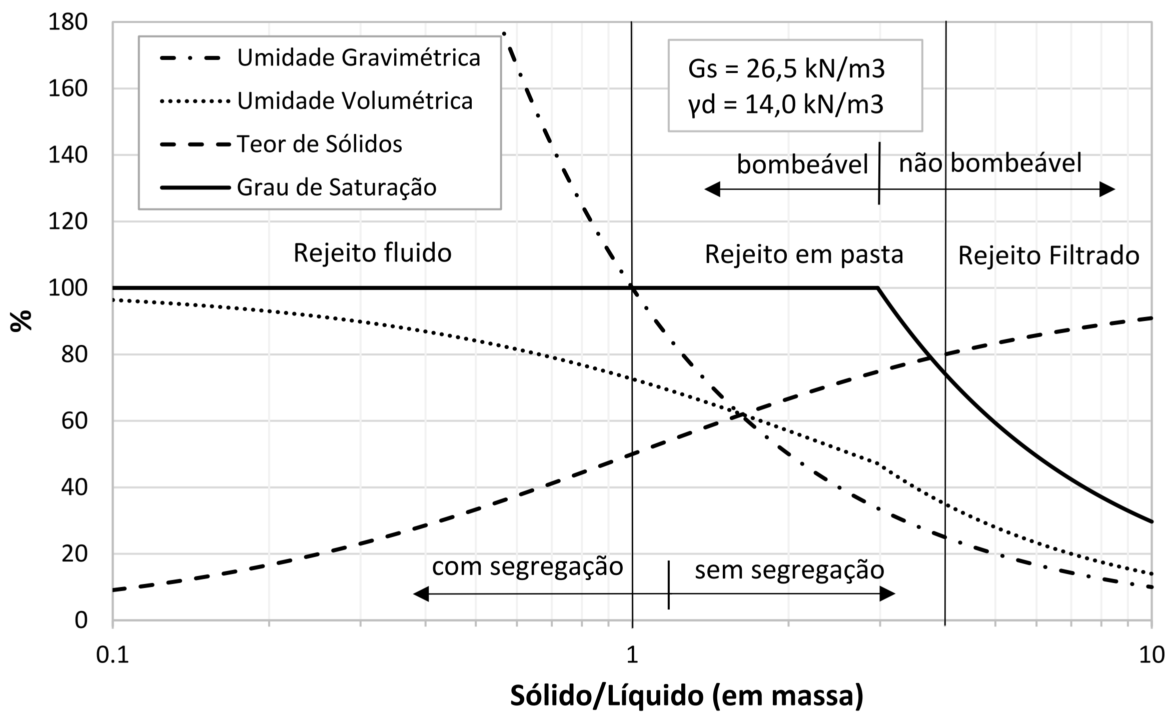

Figura 1 - Parâmetros físicos ao longo do desaguamento de rejeito (adaptado de Garino, 2012)

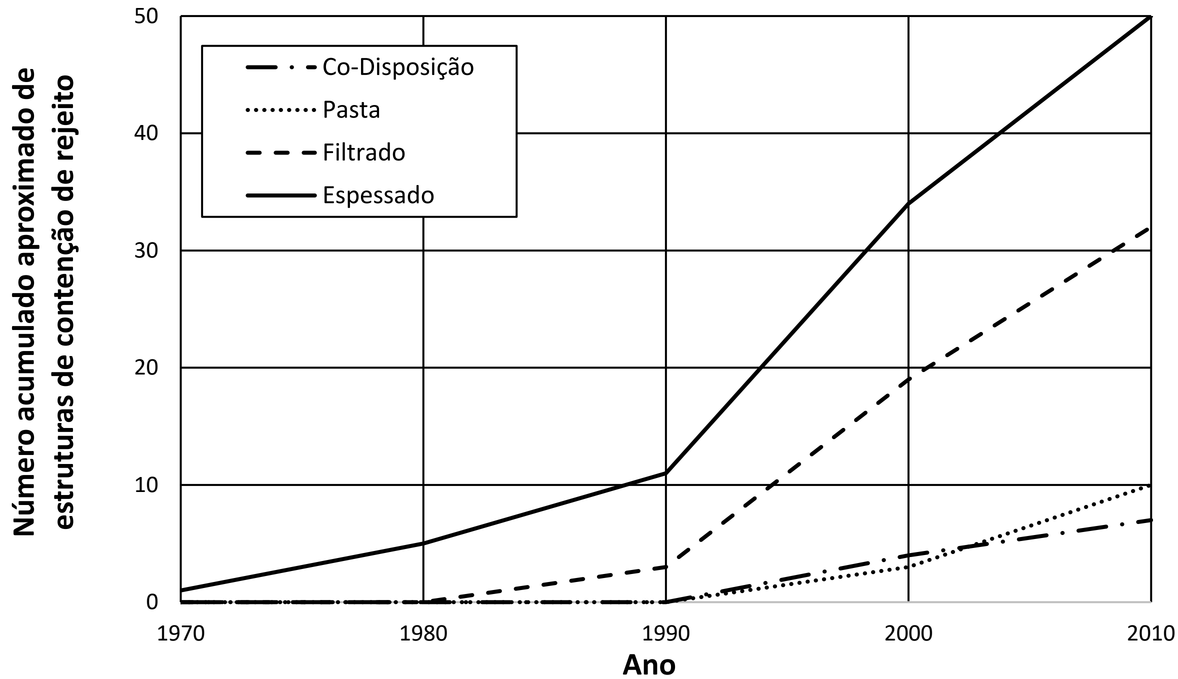

Figura 2 - Adoção de diferentes técnicas de disposição de rejeito desaguado no mundo, entre 1970 e 2010 (adaptado de Davies, 2011)

Pilhas não saturadas de rejeito, apesar de apresentarem um menor risco de ruptura em comparação com barragens, ainda apresentam uma dose de risco de ruptura por cisalhamento ou liquefação, pois não eliminam totalmente o risco de ressaturação, especialmente em regiões chuvosas (Zhang, 2017, and Li, 2016). Um dos principais fatores para mitigar o risco de ruptura das pilhas é a manutenção de um baixo grau de saturação interna ao longo de toda vida-útil (Crystal, 2018). A preocupação com a grau de saturação interno de pilhas é tal que a pluviometria local se constitui em um critério de mesma importância que topografia, disponibilidade de terreno, granulometria e mineralogia do rejeito na escolha da tipologia de disposição de rejeito. Inclusive, é comum recomendações técnicas para que se evite a adoção de disposição de rejeito filtrado em áreas de pluviometria alta (Caldwell, 2015). No que se refere à granulometria, rejeitos finos geralmente não são adequados a filtragem e disposição a seco (Ulrich, 2019).

Nesse contexto, os rejeitos lama de minério de ferro itabirítico impõem um desafio: sua granulometria fina retém umidade, com grau de saturação comumente acima de 80%, chegando a valores próximos de 100% nas proximidades do nível freático. Esse alto grau de saturação inviabiliza o empilhamento não saturado de rejeito lama puro, devido a problemas de traficabilidade e maior risco de ruptura por cisalhamento ou liquefação.

A prática de misturar rejeito lama com material de granulometria mais grossa, como rejeito de flotação gerado no mesmo processo de concentração mineral, tem o objetivo de diminuir a retenção de umidade por parte da mistura resultante. Entretanto, enquanto há muita informação a respeito de disposição de rejeito hidráulico ou em pasta, ainda falta informação pública e estudos geotécnicos a respeito da efetividade de empilhamento de rejeito filtrado (Davies, 2011). Por exemplo, é preciso entender o desenvolvimento de poropressões no interior da pilha, para garantir que excesso de poropressões se dissipe rapidamente (Caldwell, 2015, and Crystal, 2018). É preciso entender também o efeito no grau de saturação causado pela mistura de material fino com material granular, visto que essa prática melhora o desempenho hidráulico não saturado (Caldwell, 2015) e também oferece ganho de resistência mecânica (Garino, 2012).

Devido à natureza não saturada do empilhamento a seco, parâmetros geotécnicos como a Curva de Retenção de Água do Solo (SWRC) e a função de condutividade hidráulica não saturada são de particular importância (e.g. Davies, 2011). Por exemplo, no empilhamento não saturado de rejeitos filtrados, as camadas depositadas interagem umas com as outras: inicialmente, a camada de baixo ajuda na secagem da camada recém depositada; posteriormente, a camada de baixo retorna umidade para a camada de cima (Daliri, 2016). Assim, o desempenho não saturado do rejeito filtrado pode ter um efeito positivo no comportamento mecânico da pilha. No entanto, estes processos de equilíbrio de umidade e sucção também dependem da interação com o meio ambiente e devem ser cuidadosamente estudados.

Diferente de outras técnicas de disposição de rejeitos, nas quais não há compactação mecânica, no empilhamento a seco de rejeito filtrado também são de interesse parâmetros como umidade ótima de compactação, densidade máxima seca e parâmetros de deformabilidade, pois é preciso garantir uma adequada compactação mecânica na deposição. Geralmente a umidade ótima de compactação corresponde a um grau de saturação entre 60% e 80% (Davies, 2011). O desempenho hidráulico não saturado dos rejeitos, seja rejeito puro, seja mistura, afeta até mesmo a escolha do equipamento de filtragem a ser adotado: filtros prensa são capazes de operar com uma variedade maior de materiais, enquanto que filtros a vácuo são melhores para operações de larga escala (Davies, 2011).

Outro aspecto importante a ser levado em conta da escolha da disposição de rejeito por empilhamento a seco é a tonelagem, ou seja, a taxa de geração de rejeitos. Anos atrás a técnica do rejeito filtrado estava restrita a tonelagens menores que 20 mil toneladas por dia, mas atualmente a evolução dos equipamentos de filtragem faz viável tonelagem maior que 30 mil toneladas por dia (Leonida, 2020). As recentes pilhas de rejeito filtrado com quase 100 mil toneladas por dia deixam claro que não faz mais sentido a exclusão automática dessa técnica em casos de alta tonelagem (Crystal, 2018), como é o caso das minas de ferro itabirítico do Quadrilátero Ferrífero.

O escopo dessa dissertação é estudar, sob a luz do estado-da-arte da ciência do fluxo da mecânica dos solos não saturados, o comportamento da água em materiais a serem depositados sob a técnica de empilhamento a seco de rejeito filtrado. Os materiais a serem estudados são misturas de rejeito lama e rejeito flotado de minério de ferro itabirítico, e suas misturas com até 30% de rejeito lama em massa. É estudado também o efeito da pluviometria sobre a pilha não saturada de rejeito filtrado, visto que as intensas estações chuvosas do Quadrilátero Ferrífero (mais de 1200 mm em seis meses) podem aumentar o grau de saturação no interior da pilha em comparação com a situação de equilíbrio com fluxo nulo. Esse estudo é feito por meio de uma análise de um elemento da pilha posicionado no centro do maciço, funcionando assim como um lisímetro.

Os estudos foram consolidados no formato de dois artigos: “SWRC interpretation of iron ore tailings blends focusing on saturation assessment of filtered tailings piles” e “Unsaturated seepage analysis of blends of itabirite slime and flotation tailings under rainfall influence”. O primeiro deles foi submetido à Geotechnical Engineering (ICE Proceedings).

2.1. Literatura sobre percolação não saturada

A modelagem numérica de fluxo não saturado de água em meios porosos, como o solo, se baseia na equação de Richards, que expressa a lei de Darcy associada ao principío de conservação de massa:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial \psi}{\partial z} + 1\right)\right] \quad [1]$$

Na equação 1, K é a condutividade hidráulica não saturada, ψ é sucção matricial, "z" é a cota vertical, θ é a umidade volumétrica e "t" é o tempo (Richards, 1931).

Uma das variáveis da equação de Richards é condutividade hidráulica não saturada, que é função da umidade volumétrica. A umidade volumétrica, por sua vez, é alterada pelo fenômeno de armazenamento de água no meio poroso, ou seja, a massa de água de entrada e de saída em um volume elementar podem ser diferentes num instante do tempo. Esse fenômeno ocorre devido ao preenchimento e esvaziamento dos poros (Fredlund et. al., 1993).

O armazenamento de água é a variação umidade volumétrica do solo em função da sucção matricial gerada pela distribuição de poros de um solo (Fredlund et. al., 1993). Em outras palavras, o armazenamento de água é o coeficiente linear de uma função que correlaciona umidade volumétrica com a sucção. Essa função é chamada de Curva de Retenção de Água (SWRC, Soil Water Retention Curve), e seu formato típico é apresentado nas Figura 3. Com a definição da SWRC é possível modelar o armazenamento de água nos poros e, assim, respeitar a conservação de massa no cálculo de percolação não saturada usando a equação de Richards.

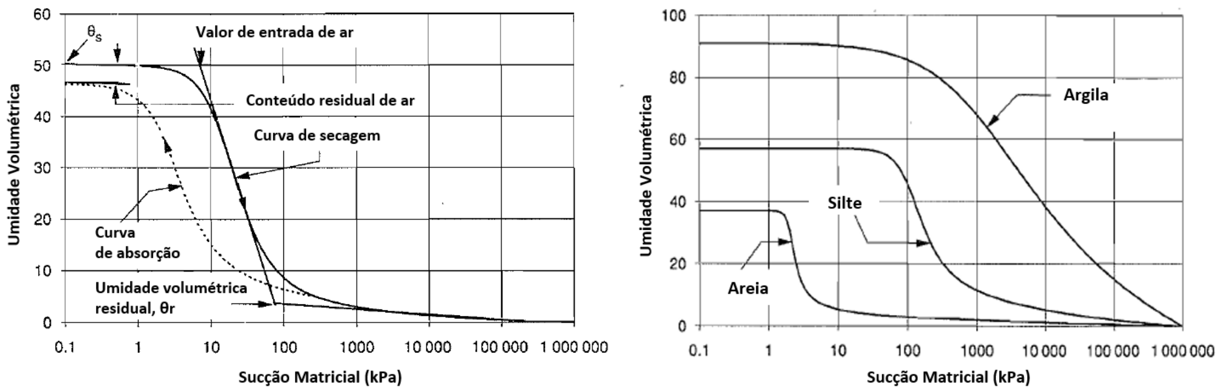

Figura 3 - Elementos da Curva de Retenção de Água (SWRC) típica e exemplos de SWRC de solo arenoso, siltoso e argiloso (adaptado de Fredlund et. al., 1994)

Existem diferentes modelos para representar a SWRC matematicamente através de uma função ajustada a medidas de umidade volumétrica e sucção. O modelo de Fredlund e Xing (1994) é particularmente interessante por apresentar bom resultado de ajuste ao longo de todo o espectro de sucção, que varia de 0 kPa, na condição de saturação, à 10^6 kPa, na condição teórica de solo totalmente seco (Leong et al., 1997, Fredlund et. al, 1994). O modelo de ajuste de Fredlund e Xing (1994) é dado pela equação:

$$\theta = \theta_s \left[1 - \frac{ln\left(1 + \frac{\psi}{h_r}\right)}{ln\left(1 + \frac{10^6}{h_r}\right)}\right] \left[\frac{1}{ln\left[e + \left(\frac{\psi}{a}\right)^n\right]}\right]^m \qquad [2]$$

Na equação 2, θ é a umidade volumétrica, θ_s umidade volumétrica de saturação, ψ é a sucção (em kPa), "a" é um parâmetro do solo relacionado com a entrada de ar, "n" é um parâmetro relacionado com a taxa de extração de água no solo assim que o valor de entrada de ar é excedido, "m" é um parâmetro do solo relacionado com a umidade volumétrica residual, e h_r é a sucção na umidade residual. O valor típico da sucção na umidade residual é 1500 kPa (Fredlund et. al., 1994). O efeito dos parâmetros a, n e m na SWRC são mostrados na Figura 4:

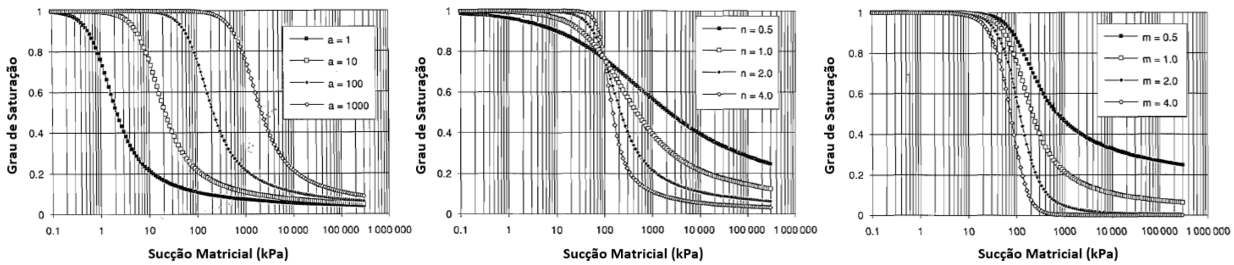

Figura 4 - Efeito dos parâmetros a, n e m na SWRC (adaptado de Fredlund e Xing, 1994)

Com a definição da SWRC, é possível estimar a função condutividade hidráulica não saturada do solo sob uma determinada sucção matricial. Fredlund, Xing e Huang (1994) propuseram a seguinte equação para a função condutividade hidráulica não saturada em função da sucção matricial:

$$K(\psi) = \frac{\int_{\ln(\psi)}^{\ln(10^6)} \frac{\theta(e^y) - \theta(\psi)}{e^y} \theta'(e^y) dy}{\int_{\ln(\psi aev)}^{\ln(10^6)} \frac{\theta(e^y) - \theta(\psi_{aev})}{e^y} \theta'(e^y) dy} \quad [3]$$

Na equação 3, K é a condutividade hidráulica não saturada, θ é a umidade volumétrica dada pela SWRC, ψ é a sucção em kPa, ψ_{aev} é a sucção no valor de entrada de ar e y é a variável de integração que representa o logaritmo da sucção (Fredlund et. al, 1994).

As equações 1, 2 e 3 podem ser resolvidas computacionalmente com o auxilio de software de elementos finitos. Nesta pesquisa o software utilizado é o PLAXIS LE v21.04.00.80.

3. ARTIGO CIENTÍFICO 1 - SWRC interpretation of iron ore tailings blends focusing on saturation assessment of filtered tailings piles

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Abstract

Blending slime tailings with coarser materials, such as flotation tailings, has gained popularity to overcome the problems of fine-grained material dry stacking. The problem is the maintenance of high degree of saturation, particularly at the base of these stacks, due to the water retention capacity. However, there is little information about the unsaturated hydraulic performance of these blends. Basic geotechnical characterization, compaction, oedometer and soil water retention tests were carried out on itabirite iron ore slime tailings, flotation tailings and their blends. The soil water retention curves (SWRC) and the unsaturated hydraulic conductivity functions, obtained using Fredlund and Xing's (1994) method, are analysed in an equilibrium situation over the depth of a hypothetical filtered tailings deposit. The paper assesses the effect of capillary rise in blends using water retention curves. Through the proper interpretation of the SWRC, it is verified that the pile thicknesses with a saturation degree above 80% of the blends are close to pure flotation tailings and significantly smaller than pure slime tailings. Therefore, for itabirite iron ore tailings, adding slime to the flotation tailings, up to 30% in mass, is a viable solution to minimise the effect of high degree of saturation in slime tailings.

Keywords: Dry-stacking; Filtered iron ore tailings; Soil Water Retention Curve; Saturation; Slope Stability; Unsaturated Soil Mechanics.

3.1. Introduction

In a dry stacking of filtered tailings from mineral concentration, the soil water retention curves (SWRC) and hydraulic conductivity parameters play fundamental roles in the stability. The determination of the SWRC and its proper interpretation positively contributes to understanding the distribution of water in the embankment and, thus, allows us to assess whether there is the possibility of saturation of the material and how to circumvent the possibility of liquefaction. The finer the gradation of the tailings, the greater the challenge of stacking safely. An alternative to mitigate the difficulty of disposing fine tailings is blending them with coarse tailings in proportions that do not significantly alter the geotechnical hydraulic performance of the resulting blend compared to pure coarse tailing. The risk this process incurs is a high degree of saturation within the stack. Thus, in the design of dry stacking of varied filtered materials, it is necessary to evaluate how the blend of different materials will affect the SWRC and its hydraulic conductivity function (HCF). The materials were prepared by mixing slurry tailings (silty clay) and flotation tailings (silty sands) in different proportions. The tests were carried out at the Technological Research Institute (IPT) of the State of São Paulo. This paper presents geotechnical data of tailings to be used in a dry stacking project of iron ore in the region of Minas Gerais (Brazil) and the analyses resulting from the interpretation of these data.

3.2. Literature Review

The disposal of the tailings generated in the mineral concentration constitutes an environmental challenge to the mining industry, a fundamental economic activity of human society. As mentioned by Leonida (2020), events involving accidents with tailings dams in the last decade generated concern regarding the various processes involved in the disposal of tailings. In particular, the disposal of wet material has led investors and governments to demand more sustainable processes. It is always important to emphasise that any type of tailings storage facility (TSF), if poorly planned and poorly managed, can induce problems that will impact both the environment and society as a whole.

The excessive number of catastrophic failures of slurry hydraulic disposal facilities is frequently a consequence of mismanagement of water and saturation within the facility. In other words, a lot of the failures are related to the high water content in tailings (e.g. Daliri et al., 2016; Garino et al., 2012; among others). Therefore, the technical path being followed towards a safer TSF is the dehydration of the tailings before disposal. In this regard, the tailings are classified into four categories based on water content: conventional, thickened, paste and filtered (Ulrich, 2019). There is no association in this classification with the geotechnical characteristics of the materials to be disposed of. So, the dewatering process alone does not guarantee adequate mechanical and hydraulic behaviour, even with proper compaction.

According to Li et al. (2016), for a gravimetric water content (dry base) above 70%, the tailings is considered slurry, between 35% and 70% is considered thickened tailings, between 25% and 35% is a paste and below 25% is considered filtered.

Figure 5 shows the different types of material states based on the moisture content, separating those materials that allow pumping from those that do not. For easy visualisation of the effect of water removal from the tailings, five of the many characteristics of each material are presented. It is important to highlight that filtered tailings can become saturated after compaction in the field. Yield stress, obtained using the shear vane test, was presented by Ulrich (2019). Classification based on yield stress offers a more practical meaning for field practice, for example, with regard to trafficability and pumpability. The saturation process may occur either through the infiltration of rainwater or through the capillary rise of water from the foundation. In the case of precipitation infiltration evaluation, a flow analysis coupled with local climatic aspects is necessary; however, the evaluation of the capillary rise saturation effect can be done directly from the SWRC interpretation. As shown by Garino et al. (2012), the degree of saturation is also an aspect that separates pumpable from non-pumpable materials. As is well known, materials used in compaction processes must have a saturation degree below 80%.

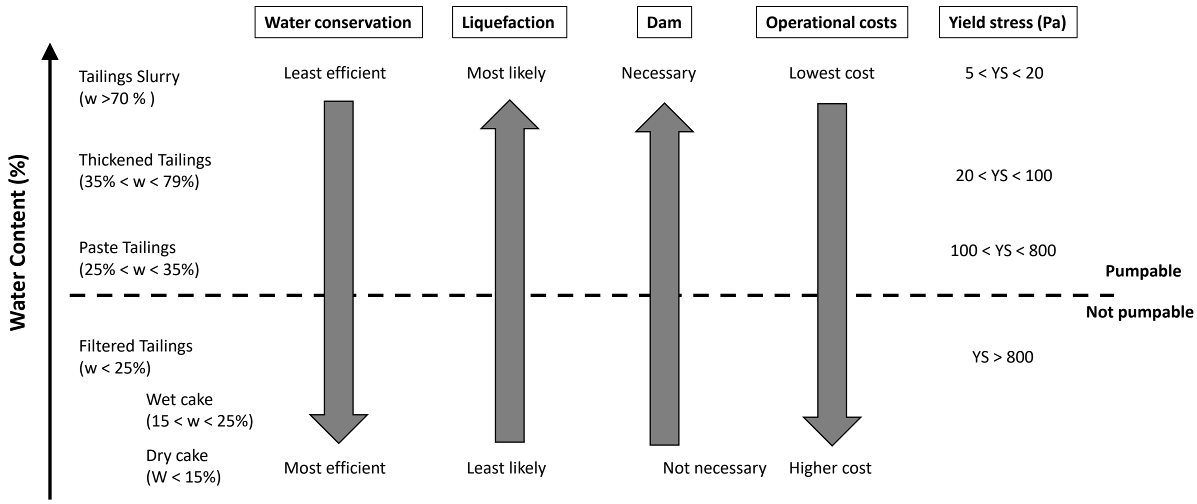

Figure 5 – Continuum of water content available for tailing management (modified from Li et al., 2016, and Ulrich, 2019)

In any type of TSF, a set of characteristics must be met. Climate, water availability, particle size distribution, mineralogy, local topography, foundation characteristics and regional water level are elements that must be analysed together (e.g. Caldwell et. al., 2015; Davies, 2011; Ulrich, 2019).

Even when using materials with lower water content, as is the case with paste tailings, the susceptibility to liquefaction is high, as the saturation degree at implantation can be very close to 100%. Although Davies (2011) mentions that the compacted landfill re-saturation process is difficult, it should be borne in mind, as already mentioned, that both the processes of water ingress from precipitation and capillary rises must be carefully understood. Changes in pore pressure are not only the result of water ingress, but they can occur due to loading (rising of the TSF), and this aspect must be evaluated (e.g. Caldwell and Crystal, 2015; Crystal et al., 2018). In other words, during the proper compaction process, the material must have a degree of saturation close to 80% for the pore pressure to be negative. This initial suction can be eliminated with advancing heightening (loading).

Crystal et al. (2018) suggest that the blend of materials can benefit the process as a whole. Furthermore, they also indicate that co-disposal can be an important element of tailings storage management. Regarding blending of different materials, this procedure can contribute to adjusting the water retention capacity of the material and to controlling, in a certain way, the saturation of the material.

Filtered tailings dry stacking appears to be the preferential disposal technique in the coming decade. In this context, while other techniques are almost only concerned with traditional saturated soil mechanics, appropriate filtered TSF design demands that the unsaturated soil mechanics also be considered.

3.3. Dry stacking of itabirite iron ore tailings

The itabirite iron ore of Minas Gerais usually has a natural concentration lower than commercial requirements, so it needs to be concentrated to comply with commercial requirements. After the separation of the granulated ore and sinter feed by screening, the main concentration process adopted for itabirite iron ore in Brazil is the cationic reverse flotation, i.e. the mineral sediment (Pellet feed, diameter smaller than 0.15 mm) and the silica gangue float as flotation tailings (da Silva et al., 2015). One of the main limitations of the performance of cationic reverse flotation of itabirite iron ore is the high presence of ultra-fine particles in the process' input. So, prior to the flotation process, the iron ore is passed through a desliming stage, in which slime tailings are generated (Ferreira, 2015). The slime tailings differ from flotation tailings in terms of gradation (da Silva et al., 2015), which causes a difference in the saturated permeability coefficient, soil water characteristic curve and unsaturated hydraulic conductivity.

Therefore, the concentration process of itabirite iron ore generates two different tailings with different hydraulic behaviour: slime tailings from the desliming process and flotation tailings. The slime tailings tend to retain a higher degree of saturation, which impedes the filtering process prior to dry stacking and later imposes a higher stability risk. An alternative to reduce the deleterious effects of slime tailings on the filtering and dry-stacking process is blending them with flotation tailings. The resulting blend tends to show an intermediate hydraulic performance between pure slime and pure flotation tailings, which can be satisfactory, depending on the proportion of slime to flotation tailings.

The maximum proportion of slime tailings that can be safely added to flotation tailings must be verified for each ore source and concentration process by analysing the saturated permeability coefficient, SWRC and unsaturated hydraulic conductivity of the resulting blend. The scope of this work is to analyse the effects on the unsaturated hydraulic properties following the addition of slurry tailings to flotation tailings of itabirite iron ore, at a proportion of up to 30% in mass.

3.4. Samples description

Eight different samples were analysed, including total tailings, pure slime, pure flotation tailings, and blends between flotation tailings and slime tailings. The total tailings (described below as TT) were collected from an existing hydraulic disposed itabirite iron tailings dam. The pure slime tailings and pure flotation tailings were collected at the exit of two iron ore beneficiation plants over three weeks every other day (to reduce the influence of fluctuations of the plant operation). The blends between slime tailings and flotation tailings were prepared on-field by mixing tailings generated in both beneficiation plants.

Table 1 shows the samples' nomenclature and description of their blend proportions and origins. The chemical composition of the flotation tailings collected at the exits of the beneficiation plants can be found in Silva et al. (2021).

Table 1 - Sample descriptions

Sample	Description
TT	Hydraulic disposed total tailings
90%FL+10%SL	90% Flotation tailings + 10% Slime tailings
80%FL+20%SL	80% flotation tailings + 20% Slime tailings
70%FL+30%SL	70% Flotation tailings + 30% Slime tailings
100%FL	100% Flotation tailings
100%SL	100% Slime tailings

3.5. Material Characterisation

3.5.1. Grain size distribution and plasticity

The grain size distribution curves are shown in Figure 6. As shown, the blends fall well within the range of the granulometry of the origin materials, i.e. 100%FL and 100%SL.

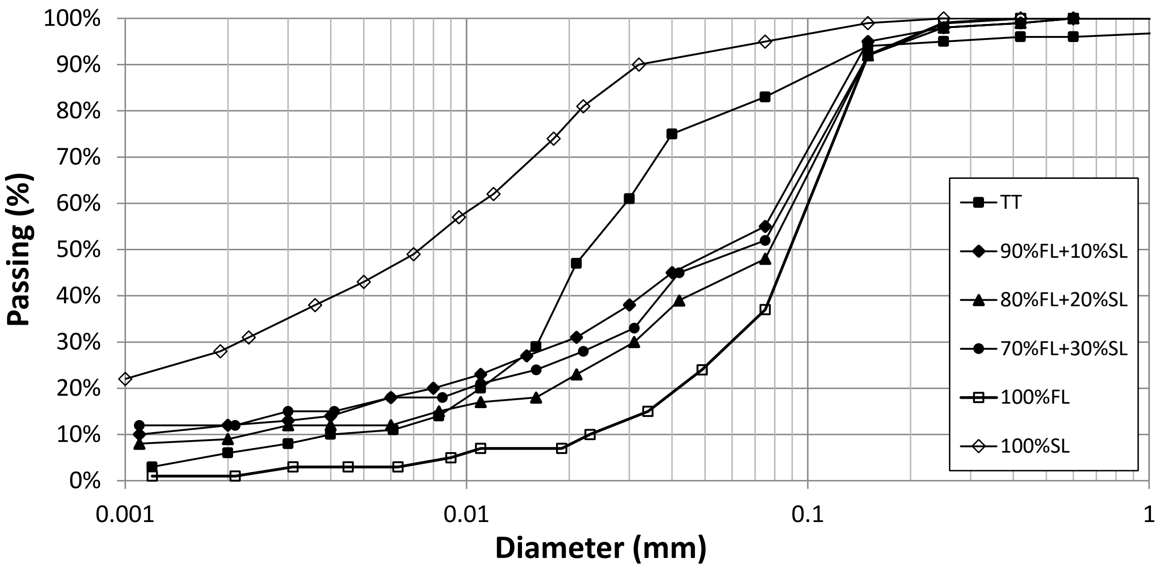

Figure 6 – Grain size distribution curves

Table 2 presents the uniformity coefficient, Cu, and coefficient of curvature, Cc, of the samples' gradation curves, the Atterberg limits and their particle densities. The only sample to present plasticity was the pure slime, i.e. the addition of slime tailings in a proportion of 30% or less, in mass, does not confer plasticity to the resulting blend.

Concerning the Cu, the blends between flotation tailings and slime tailings show a value one magnitude above the samples of pure flotation tailings and total tailings. A possible explanation for the low value of the total tailings Cu, similar to those of the tailings of a single origin, is the segregation that occurs on the beach, which causes a granulometric uniformization in a sampling point, despite the disuniformity of the material at the discharge point. The addition of slime to the flotation tailings generates a well-graded blend for the three different proportions, while the three samples of pure flotation tailings are poor graded. The results indicate high sensitivity of Cc regarding the addition of slime tailings to the flotation tailings. There is, however, low sensitivity to the proportion of the slime added.

Table 2 - Particle density, uniformity coefficient and coefficient of curvature of the samples

Sample	D_{10} [mm]	D_{30} [mm]	D_{60} [mm]	Cu	Cc	wl (%)	wp (%)	PI (%)
TT	0.004	0.016	0.03	7.5	2.1	NP	NP	NP
90%FL+10%SL	0.001	0.021	0.08	80	5.5	NP	NP	NP
80%FL+20%SL	0.002	0.031	0.09	45	5.3	NP	NP	NP
70%FL+30%SL	-	0.023	0.085	-	-	NP	NP	NP
100%FL	0.023	0.06	0.1	4.3	1.6	NP	NP	NP
100%SL	-	0.0022	0.011	-	-	32	21	11

wl: liquid limit; wp: plastic limit; PI: plasticity index

3.5.2. Compaction characteristics

In Figure 7, the Standard Proctor Compaction curves of the specimens are presented. It can be observed that, despite showing similar particle density to the blends (Table 3), the pure flotation tailings present a lower maximum dry bulk density than the other samples. Further, the pure slime tailing presents the highest optimum moisture. Among the blends, there is no clear tendency of maximum dry bulk density variation as a function of the proportion of slime to flotation tailings. The blends present optimum moisture values close to each other, lower than those presented by pure slime and flotation tailings. Table 3 presents the physical properties of the specimen moulding, where the void ratio reduction effect caused by the addition of the slime in the flotation tailings can be noted.

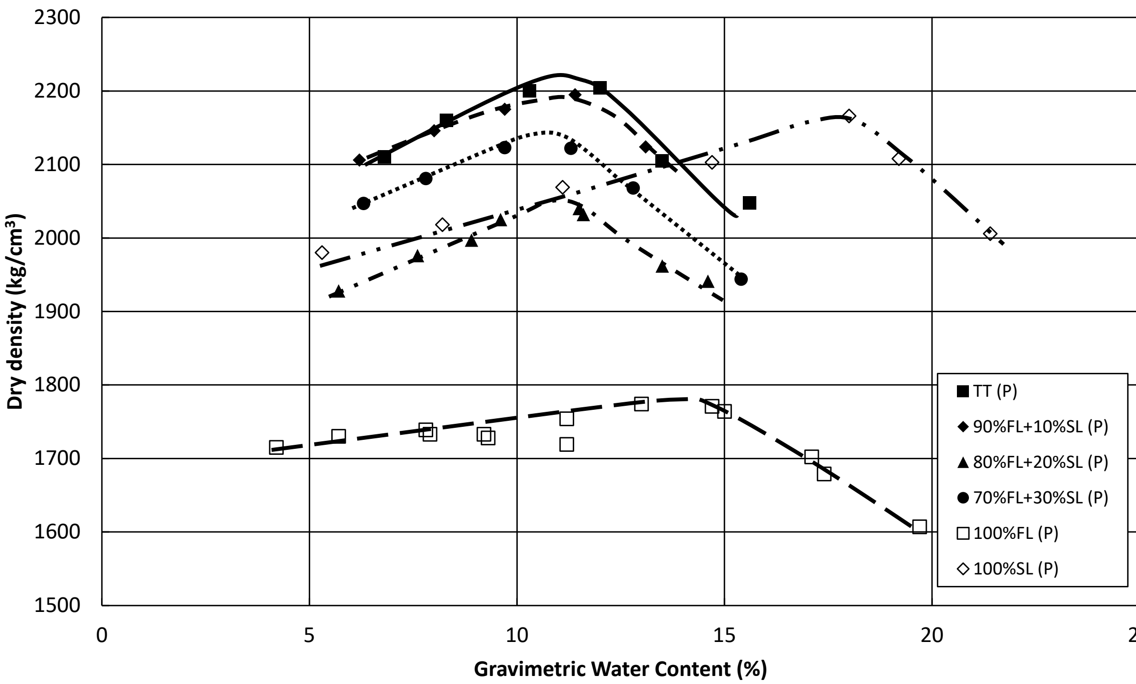

Figure 7 – Standard Proctor compaction test results

Table 3 - Compaction data of the samples

Sample	G_s	w_{opt} (%)	ρ_{dmax} (kg/m³)	S_{opt} (%)
TT	3.41	11	2220	70
90%FL+10%SL	3.15	11	2195	80
80%FL+20%SL	3.10	11	2055	67
70%FL+30%SL	3.12	10.5	2140	72
100%FL	3.06	14.5	1790	63
100%SL	3.82	18	2165	90

The specimens obtained for the oedometer tests and the SWRC were moulded from dynamic compaction specimens, calibrated to provide approximately 90% of the energy of the normal Proctor. This procedure was adopted to assess any possible poor compaction of the material. However, it must be verified whether the behaviour of the material during the shearing process is expansive or contractile when saturated. The data of the specimens used in these tests are presented in Table 4.

Table 4 - Moulding characteristics of the specimens for the SWRC test

Sample	Specimen dry density (Kg/m³)	Compaction Water Content (%)	DOC (%)
TT	1987	11.4	90
90%FL+10%SL	1977	11.1	90
80%FL+20%SL	1836	10.8	89
70%FL+30%SL	1917	10.6	90
100%FL	1575	14.7	88
100%SL	1935	18.0	89

3.5.3. Oedometer test

In Figure 8, the oedometer test results for the eight samples are presented. It can be seen that the blends present an intermediary compressibility between the pure flotation tailings, less compressible, and the pure slime tailings, more compressible. Thus, the addition of slime in flotation tailings generates a material of worse structural performance than the pure flotation tailings in terms of compressibility.

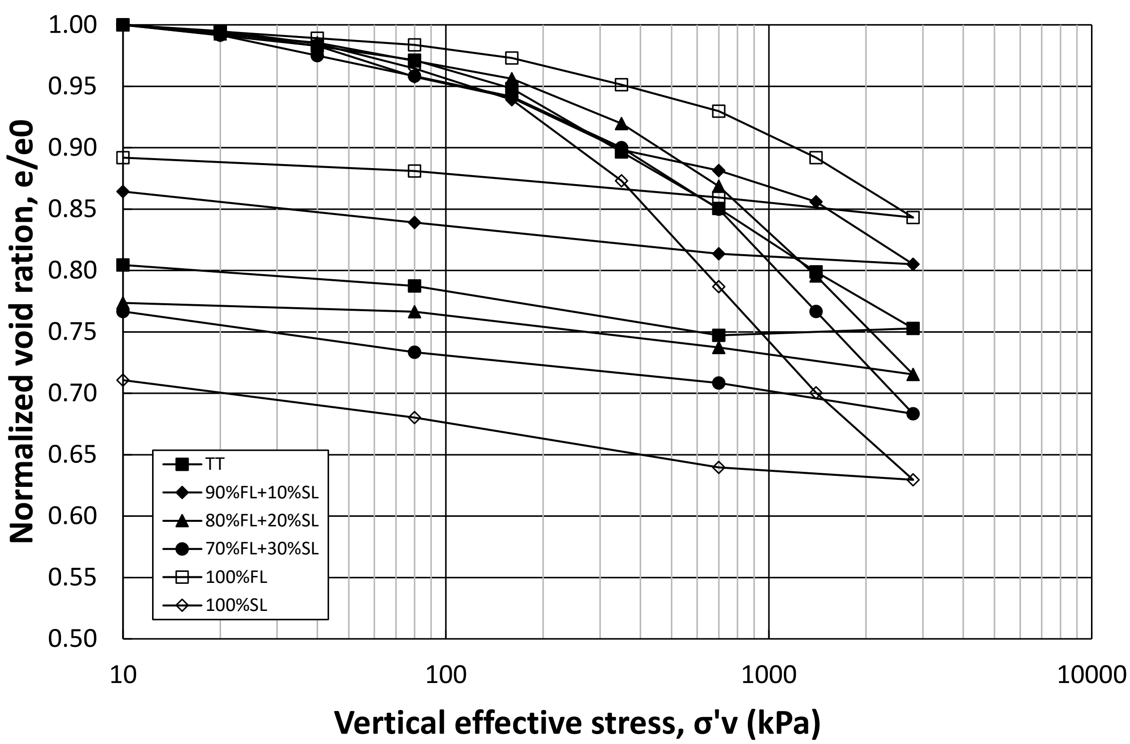

Figure 8 – Oedometer test results

The parameters obtained from the consolidation curve are presented in Table 5. The SWRC presented in the next section and used for this study were obtained with zero net stress (σ-u_a); however, it is important to evaluate the effect of loading on the material's water retention capacity.

Table 5 - Oedometer test parameters

Sample	Cc	Ce
TT	0.141	0.018
90%FL+10%SL	0.075	0.014
80%FL+20%SL	0.174	0.023
70%FL+30%SL	0.166	0.020
100%FL	0.133	0.023
100%SL	0.266	0.033

Cc: compression index; Ce: expansion index

3.5.4. Soil Water Retention

Figure 9 presents the results of the soil water retention tests on the eight samples, moulded as described in Table 4, resulting in the physical index shown in Table 3. For suction below 10 kPa, the suction plate technique was used; for suctions above 10 kPa, the suction was obtained using the pressure plate device, up to 1 MPa. The suction at the air-dry condition was assumed to be 35000 kPa.

Along almost all the suction values, the slime tailings present the highest volumetric moisture and the flotation tailings the lowest value, while the other sample presents intermediate values. It is interesting to observe the close volumetric moisture values between the three blends, indicating low sensitivity of the blend to the proportions between 10% and 30% of slime in mass.

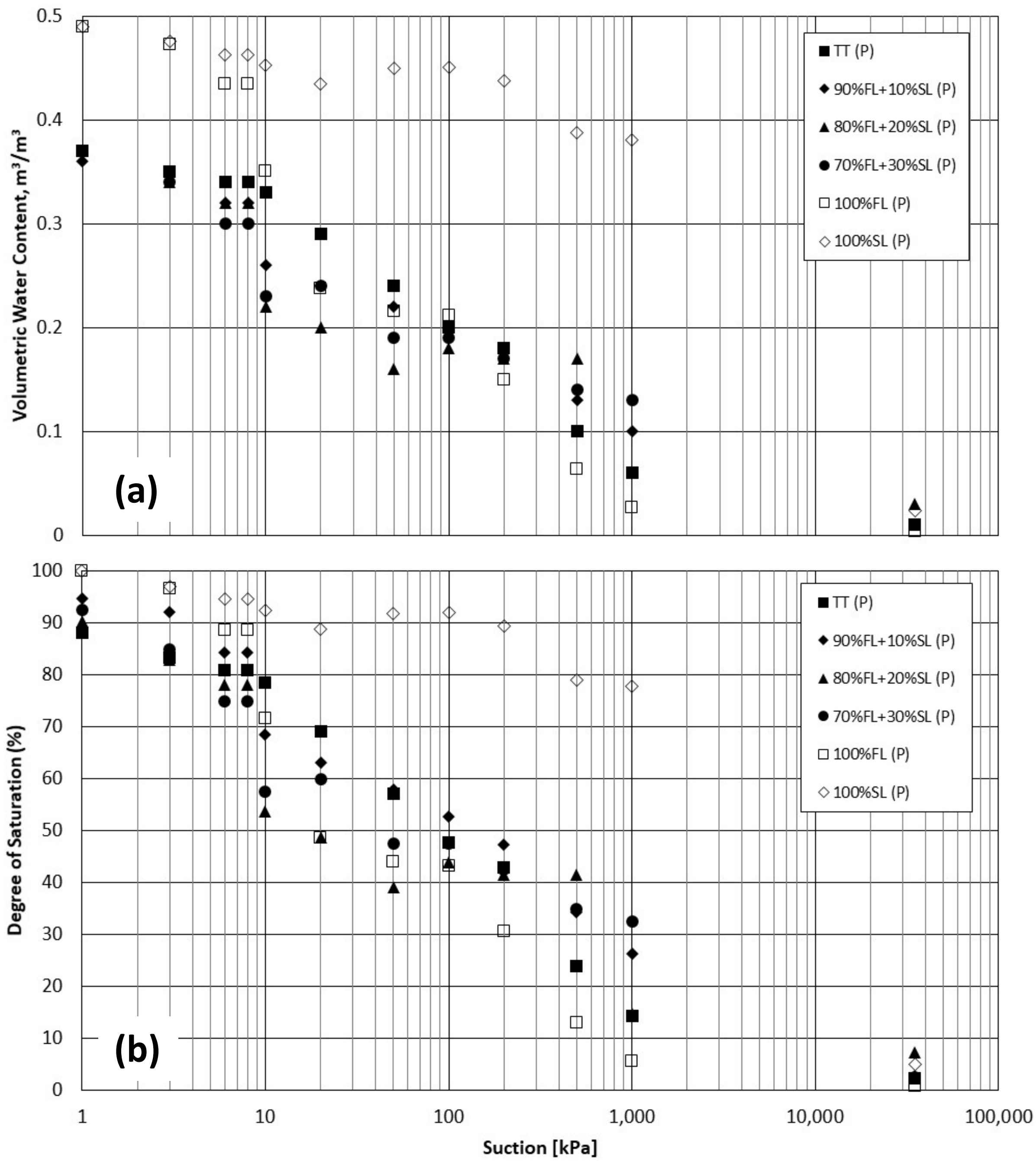

Figure 9 – Soil water retention test results

From the data presented in Figure 9 and adopting the Fredlund and Xing (1994) equation, through the software SoilVision Soils v21.03.01.02 (Bentley Systems, 2021), the adjustment parameters for the SWRC was obtained, as presented in Table 6. The adjusted curves resulting from the parameters are presented in Figure 10a and 10b in terms of volumetric water content and degree of saturation, respectively.

Here, note the similarity between the three blends' SWRC, which indicates the low sensibility of the retention curve to the proportion of flotation tailings and slime tailings, in slime proportions lower than 30% in mass. The three blends presented air entry values close to pure flotation tailings and magnitudes below pure slime tailings. This result agrees with Fredlund and Rahardjo, 1993: the air entry value is a function of the size of the biggest pores of granular structure, i.e. the addition of slime to the flotation tailings' structure does not alter the maximum size of the pores significantly and, consequently, does not alter the desaturation suction value of the resulting blend.

Table 6 - SWRC adjustment parameters, Fredlund and Xing model (1994)

Sample	**$k_{sat,360\ kPa}$** (m/s)	**af** (kPa)	**nf**	**mf**	**hr** (kPa)	θ_{sat}	θ_r	**Residual Suction** (kPa)	**AEV** (kPa)
TT	2.6 E-7	1321	0.46	7.13	1633	0.422	0.028	1598	4.0
90%FL+10%SL	1.6 E-7	9	0.76	0.88	707	0.380	0.092	640	1.8
80%FL+20%SL	5.9 E-7	2	1.51	0.44	43	0.409	0.166	42	1.1
70%FL+30%SL	1.2 E-6	2	1.41	0.42	80	0.396	0.161	58	1.0
100% FL	1.4 E-5	50	0.39	4.16	385	0.495	0.030	461	0.4
100% SL	9.6 E-8	2500	1.08	2.05	15179	0.490	0.026	15885	472.5

$k_{sat,360kPa}$: saturated permeability coefficient; af, nf, mf, hr: Fredlund and Xing (1994) adjustment parameters; Res. VWC: residual volumetric water content; Res. Suction: residual suction; AEV: air entry value

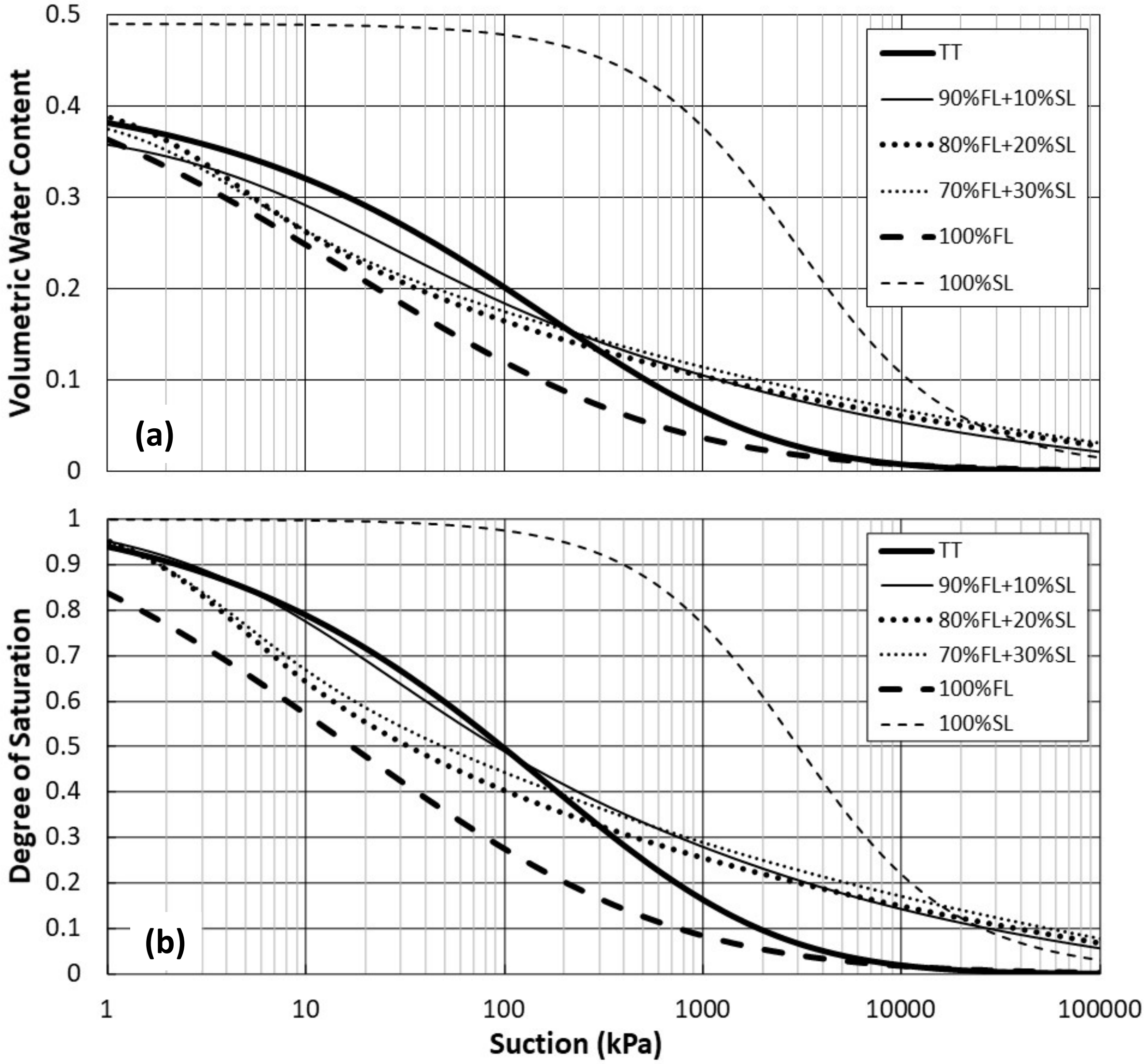

Figure 10 - SWRC adjustment based on the equation of Fredlund and Xing (1994)
(a) Volumetric water content, (b) Degree of saturation

3.5.5. Hydraulic Conductivity

Another geotechnical performance attribute possibly influenced by the proportion of slime to flotation tailings in the blend is the saturated hydraulic conductivity due to the change in diameter, shape and quantity of pores. The saturated hydraulic conductivity of the samples, presented in Figure 11, were obtained in the oedometer tests commented in section 3.3.

It can be observed in Figure 11 that the pure flotation tailings are more permeable than the other samples in the whole range of confining stress, while the slime tailings are less permeable along the range. The other samples present intermediate values for the saturated hydraulic conductivity between the pure slime and flotation tailings, but they are closer to the value presented by the pure slime tailings. This behaviour can be explained by the great influence of D_{10} on the permeability. Due to the same reason, the total tailings present saturated hydraulic conductivity similar to the blends.

The variation of saturated hydraulic conductivity with loading did not show a significant change. However, as mentioned above, the effect of loading on SWRC should be verified in future studies.

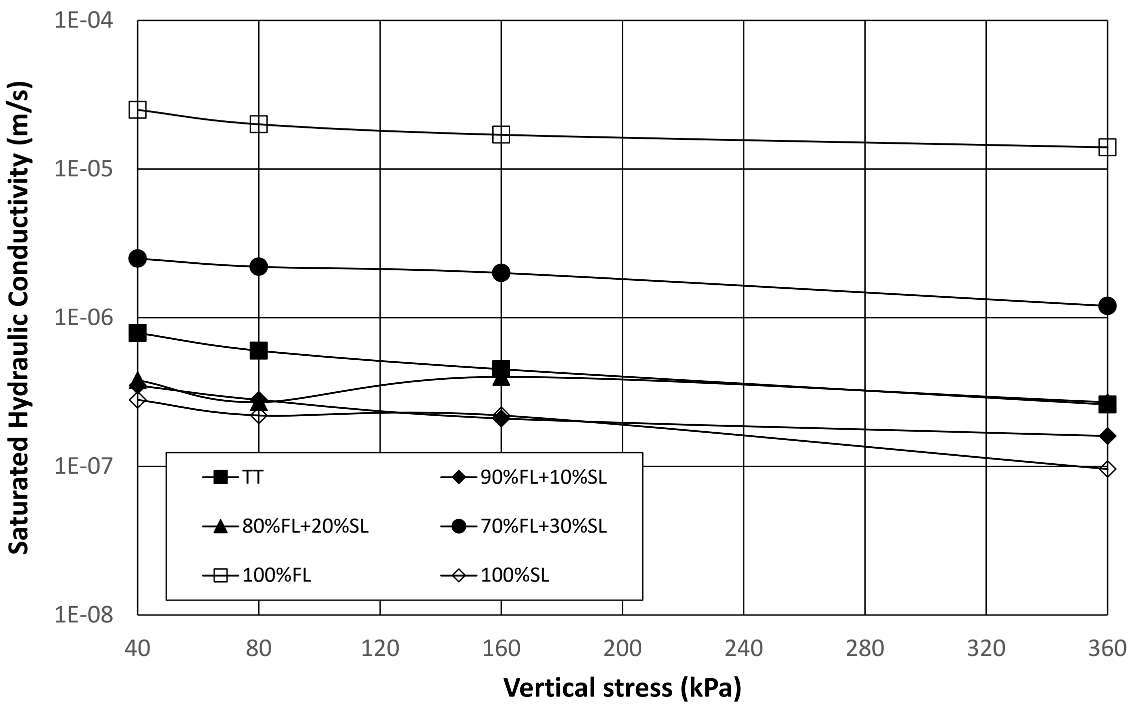

Figure 11– Saturated permeability coefficient vs Confining stress

Figure 12 presents the hydraulic conductivity of the samples, calculated using Fredlund and Xing's (1994) method. The unsaturated hydraulic conductivity of the blends is lower when compared with both pure materials, for suction above 5 kPa. The three blends present hydraulic conductivity functions similar to each other, which shows low sensitivity to the proportion of flotation tailings to slime tailings for less than 30% of slime tailings in mass.

It can be noted that the sample 100%SL, pure slime tailings, is the one that presents the highest values for unsaturated hydraulic conductivity for suction above 30 kPa, despite being the sample with the lowest saturated coefficient of permeability. This behaviour can be explained by the highest saturation degree of the pure slime under the same suction compared to the other samples (Figure 12); thus, it shows that the unsaturated hydraulic conductivity can be more sensitive to the saturation degree than the saturated coefficient of permeability.

The unsaturated hydraulic conductivity according to saturation degree is shown in Figure 13. The three blends present conductivity functions close to each other, without sensitivity to the proportion of slime added to the flotation tailings. The hydraulic conductivity of the blends is always lower than the pure flotation tailings. Compared to the pure slime tailings, for a saturation degree lower than 0.7, the hydraulic conductivity of the blends is lower than pure slime; for a saturation degree between 0.7 and 0.9, the hydraulic conductivity of the blends and the pure slime is similar; for a saturation degree higher than 0.9, the hydraulic conductivity of the blends is higher than pure slime.

It is interesting to note that, among all samples, the pure slime presents the least intense reduction of hydraulic conductivity with the decrease of the saturation degree. One possible explanation for this phenomenon is the higher preservation of the hydraulic continuity with the reduction of saturation degree in the pure slime due to a pattern of pore distribution formed by several micro canals. Coarse grains, instead, tend towards a pore distribution of a few high diameter canals; thus, they are more susceptible to the disruption of the hydraulic continuity within the pore (Matsuoka, 1999, as cited in Xu, 2013).

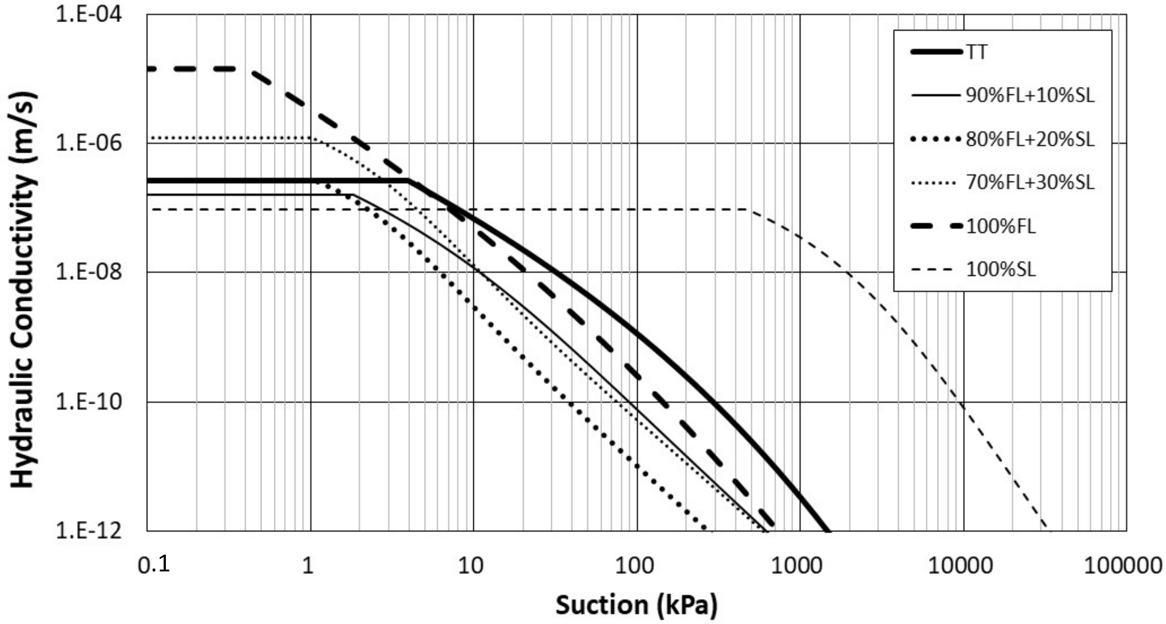

Figure 12 – Hydraulic conductivity versus Suction

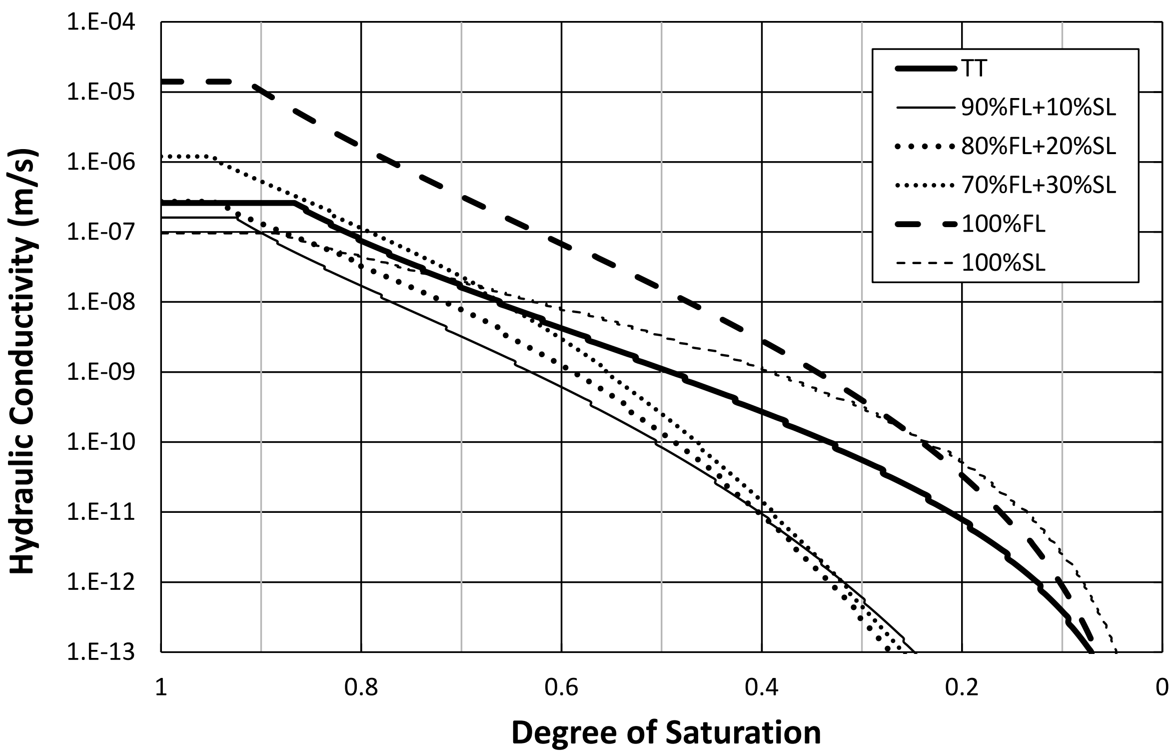

Figure 13 – Hydraulic conductivity vs Saturation degree

3.6. Equilibrium Saturation Degree and Hydraulic Conductivity above the water table

The equilibrium saturation degree and hydraulic conductivity in the first 100 meters above the water table are shown in Figure 14 and Figure 15, respectively. In Figure 14, it can be seen that the pure slime tailings maintain a higher saturation degree than all other materials 100 meters above the water table. The pure flotation tailings have the lowest equilibrium saturation degree, while the total tailings and the blends of pure slime and flotation tailings show intermediate saturation degrees with little difference between them. This means that the saturation degree profile above the water table has little sensitivity to the proportion of slime tailings in the blend, for 10–30% of slime tailings in mass.

The equilibrium hydraulic conductivity of the pure slime tailings is magnitudes higher than all the materials along all the 100 meters above the water table. As discussed previously, this phenomenon is probably attributed to the higher saturation degree, considering that the pure slime tailings have a lower saturated coefficient of permeability. On the other hand, the pure flotation tailings don't present significant differences from the blends in terms of hydraulic conductivity, which shows that the addition of slime tailings, up to 30% in mass, in the structure of flotation tailings has a low effect on the unsaturated hydraulic conductivity.

Regarding slope stability, the lowest possible saturation degree is desirable, preferably lower than 80%. The equilibrium saturation degree along the height (Figure 14) shows that the addition of slime in flotation tailings provides a slightly worse condition than the pure flotation tailings but still much better than the pure slime tailings. It is important to notice that there is no difference in saturation degree above the water table for blends with proportions between 10% and 30% of slime tailings in mass.

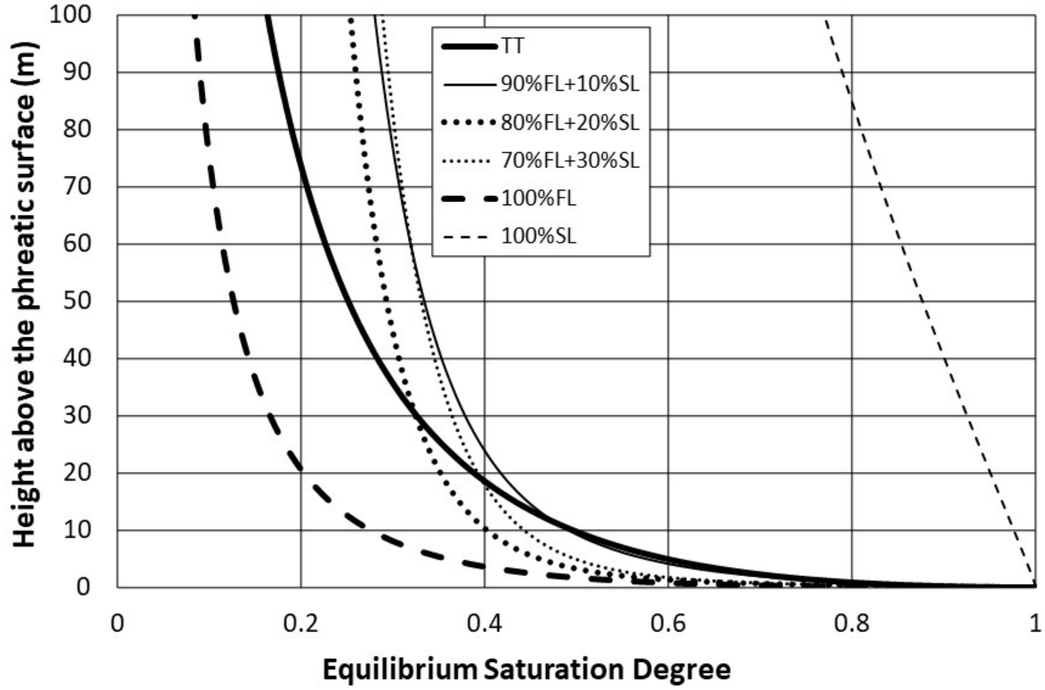

Figure 14 – Equilibrium saturation degree vs Height above the phreatic surface

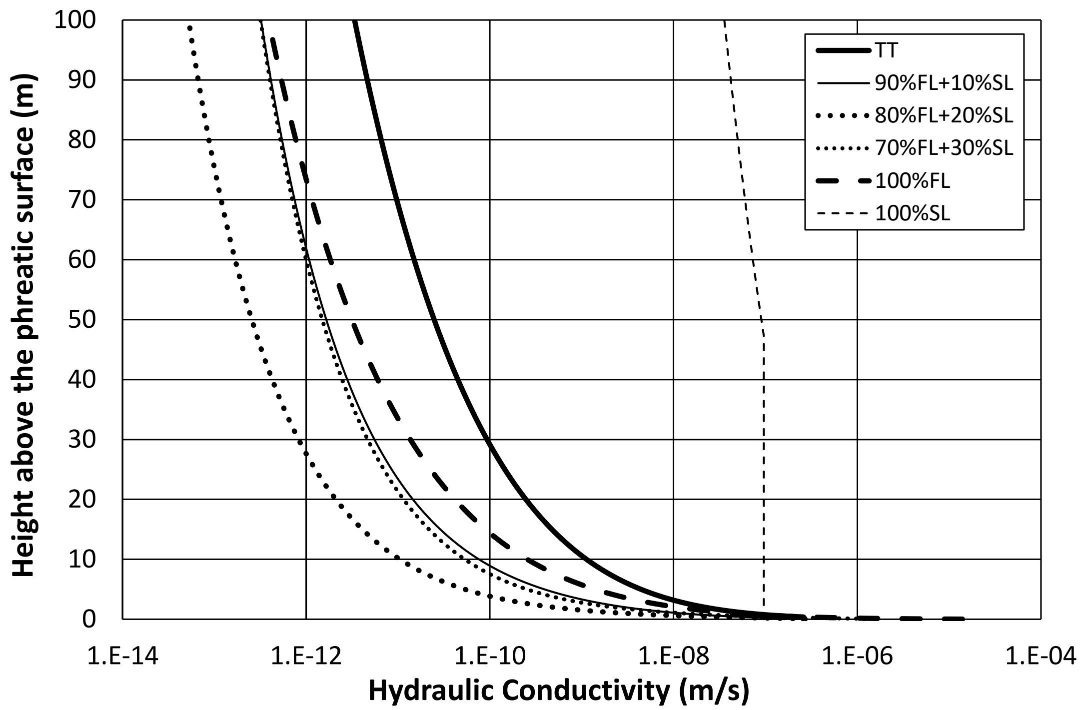

Figure 15 – Hydraulic conductivity vs Height above the phreatic surface

3.7. Conclusion

The geotechnical characterisation of the materials indicates no plasticity, except for one of the samples: the pure slime (100%SL). The content of particles smaller than 2 μm ranged from 1% to 29%, with all blends showing that over 5% particles are smaller than 2 μm. For the pure slime, the percentage of particles smaller than 2 μm was 29% and presented an optimum water content of 16.5%.

The blend of pure flotation (100%FL) with pure slime induced a reduction in the optimal moisture content, generating materials with optimal moisture content values of the order of 11% for all blends, a value very similar to the total tailings (TT). The maximum dry density of the blends ranged from 2055 kg/m^3 to 2195 kg/m^3; the total tailings presented a maximum dry density value of 2220 kg/m^3.

The consolidation test indicated that adding pure slime in the pure flotation reduces the compression index for 10% slime in mass but increases it for proportions of 20% slime or higher. The expansion index is strongly reduced in the blend with 10% slime in mass but slightly reduced in the blends of 20% and 30% slime.

The saturated permeability coefficient, Ksat, obtained during consolidation tests indicated little variation due to vertical stress. The pure flotation showed the highest Ksat, and the pure slime showed the lowest. The blends showed intermediate values, close to the one of pure slime tailings.

A fundamental aspect that emerged from the results obtained is the possibility of inferring the material's capacity to remain saturated or with a high degree of saturation. The value of the air entry suction, whether it is a real concept or a value derived from the adjustment of the retention curve data, controls the maintenance of a high degree of saturation in a capillary rise process, for example.

Regarding the degree of saturation maintained by the porous material, the results obtained indicate the following:

- The pure slime material has the greatest air entry suction and is, therefore, the one material that maintains a high degree of saturation in a capillary rise analysis. This material maintains a prejudicial degree of saturation above 80% up to a height of approximately 80 m, in an equilibrium state with no infiltration nor evaporation.

- The other materials tested have a thickness with a degree of saturation above 80% above the phreatic level lower than 1 m, although these thicknesses must be considered in the design.

- Thus, the blend of materials provides important improvements on the tailings' water retention performance compared to the pure slime tailings, reducing the thickness with the degree of saturation above the safe limit by capillary action.

The study demonstrated the usage of retention curves to assess possible capillary rise saturation. In a dry stacking of filtered tailings, to reduce landfill saturation problems, it is essential to carry out this analysis based on material retention curves, verifying the possibility of saturation by capillary rise or infiltration.

Pure slime tailings pose a challenge in this context; however, pure flotation tailings offer better results. Thus, a possible alternative for the disposal of slime tailings is to blend them up to 30% of slime in mass to the flotation tailings to dry stack the resulting blend. However, this article did not deal with evaluating the best compaction state of materials to guarantee not only an adequate saturation profile but also a material with a dilatant behaviour when saturated, which further research in the field can consider

3.8. References

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3.9. Acknowledgments

The authors are grateful to the Laboratory of Residues and Contaminated Areas (LRAC) of the Center of Geoenvironmental Technologies (CTGeo) of the Institute for Technological Research (IPT) for the laboratory tests performed. The authors are also grateful to VALE S.A. for its authorisation to publish the data used in this work.

4. ARTIGO CIENTÍFICO 2: Unsaturated seepage analysis of itabirite slime and flotation tailings under influence of capillary rise and rainfall

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Abstract

The dry stacking of mine tailings is increasing in the last decades, even in wet areas like Quadrilatero Ferrifero, in Brazil, that presents a pronunced rainy season. Due to the unsaturated nature of dry stack piles, unsaturated seepage analysis in such structures are needed to guarantee adequate saturation degree along all the structure lifespan. The Soil Water Retention Curve (SWRC), the unsaturated hydraulic conductivity function and environmental aspects such the position of the water table, rainfall and evaporation play fundamental roles on the pile internal saturation degree. Adopting the Fredlund and Xing (1994) model for the SWRC and the Belo Horizonte climate data, 1D unsaturated seepage analysis were performed on 100 m high columns of six different itabirite iron ore tailings: pure slime tailings, pure flotation tailings, total tailings and blends up to 30% of slime in mass. The results indicate that the pure slime tailings are not adequate to be dry stacked in terms of internal saturation degree; on the other hand, the pure flotation tailings and the blends offer satisfactory unsaturated hydraulic performance to be dry stacked. In this context, blending slime with flotation itabirite iron tailings, up to 30% of slime in mass, is presented as a possible solution to adequately dry stack slime tailings.

Keywords: unsaturated seepage; mine tailings; SWRC; saturation degree; capillary rise; dry stacking.

4.1. Introduction

In recent years, several slope failures of earth embankment have occurred during the rainy season in Minas Gerais state, in Brazil. Tailings dams, waste rock piles, filtered tailings piles and roadway slopes are examples of earth structures susceptible to these failures.

The occurrence of months with more than 300 mm of rain in the rainy season, in Minas Gerais, can be the explanation why such slope failures occur more frequently there than in regions with less intense rain. However, dams, piles and filtered stacks are designed according to the saturated soil mechanics, i.e., the rainfall is considered only to address the risk of overtopping and the control of surface erosion. Rainfall and evaporation are simply not considered in the analysis of saturation degree and pore pressures (saturated and unsaturated), and the consequent influence in the shear resistance (risk of liquefaction included).

As the water table is usually located several meters below the surface, the soil unsaturated hydraulic properties play a fundamental role on the influence of rainfall on pore pressures and saturation within the embankment.

Due to the increasing adoption of filtered dry stacking for the disposal of mining tailings in Minas Gerais, this study analyzes the differences in unsaturated hydraulic performance of itabirite iron ore slime tailings, flotation tailings and their blends. For this, 1D unsaturated seepage analyses are performed, considering rainfall and evapotranspiration data of the city of Belo Horizonte.

The hydraulic properties used in the analysis are the ones presented by Nadai et. al (2022), based on laboratory tests performed by the Technological Institute of Technology of the State of Sao Paulo (IPT).

4.2. Background

In soil embankments where the water table is located meters below the surface, the zones above the water table may be unsaturated. The saturation degree above the water table is not constant: it varies in depth and in time, under the influence of the water level location, rainfall and evaporation (e.g. Fredlund et. al., 1993). Different soils have different unsaturated hydraulic behaviour, with different hydraulic conductivity and water retention capacity, based mainly on their pore-size distribution and mineralogy. The smaller the pores of a soil, higher is its ability to hold water. Mixing materials with different grain size distributions changes the water holding capacity of the resulting material. Several studies can be found highlighting the effects of these mixtures, indicating that density also plays a role in retention capacity (e.g. Su et al., 2022; Sakaki & Smits, 2015; Marinho & Chandler, 1994). The flow of water in unsaturated media is governed by Richard's equation (Richards, 1931), which expresses the law of conservation of mass associated with Darcy's law. Darcy's law, in turn, considers the variation of hydraulic conductivity with suction, and the gradient becomes a function not only of gravity, but also of suction. The permeability function fundamentally depends on the SWRC.

The SWRC, is a function between the amount of water present in the soil pores (expressed as gravimetric or volumetric moisture content, or the degree of saturation) in relation to soil suction. The SWRC can be used to estimate the unsaturated hydraulic behaviour of soils using some model (e.g. Van Genutchen, 1980; Fredlund and Xing, 1994; among others). The hydraulic conductivity function can be empirically predicted using the saturated coefficient of permeability and the SWRC. In general, SWRC is used in the drying path, as is the case of the present study.

There are different fitting equation for the SWRC (e.g. Brooks and Corey, 1964; van Genutchen, 1980; Fredlund and Xing, 1994; among others). In this work the Fredlund and Xing model is adopted. The Fredlund and Xing (1994) SWRC equation is presented below in Equation 4:

$$\theta = \theta_s \left[1 - \frac{ln\left(1 + \frac{\psi}{h_r}\right)}{ln\left(1 + \frac{10^6}{h_r}\right)}\right]\left[\frac{1}{ln\left[e + \left(\frac{\psi}{a_f}\right)^{n_f}\right]}\right]^{m_f} \quad [4]$$

In the Fredlund and Xing (1994) equation, θ is the volumetric water content, θs is the saturated volumetric water content, ψ is the soil suction value (in kPa), af is a parameter of the soil related to the air-entry value, nf is a parameter of the soil related to the rate of water extraction once the air-entry value is exceeded and mf is a parameter of the soil related to the residual water content, and hr is the suction at residual moisture. The typical value of hr is 1500 kPa (Fredlund et. al., 1994).

The negative pore-water pressure head, i.e. suction, is a function of the distance to the water table and the vertical flux (Fredlund et. al. 1993). The flow due to precipitation and evaporation in a porous medium can be divided into three parts. The one associated with the active zone, where there is an influence of the climate on the behaviour of the profiles both of suction and degree of saturation, a region called inactive (or region of saturation equilibrium) and the region affected by capillary rise (e.g. Srivastava, 1991). The active zone is the length below the surface, usually three to five meters, where the infiltration and evapotranspiration cause variation on the degree of saturation (e.g. Nelson et al., 2001). The inactive zone is the intermediary zone, below the active zone, where the degree of saturation is a function of the net infiltration. The capillary fringe is the zone right above the water table and below the inactive zone, where the capillary rise causes saturation degree higher than the one caused by the net infiltration.

Regarding the practical problem of dry stacking mining tailings, it is needed to avoid the occurrence of saturation degree that brings risk to stability (liquefaction suceptibility, for example) and difficulties to the traficability on the pile. A practical manner to reduce the risk of liquefaction is to maintain the degree of saturation always below 85% all along the pile (e.g. Crystal, 2018). On the other hand, the trafficability demands saturation degree even lower, below 80% close to surface.

In this work, results of numerical analyses performed in a 1D model are presented, comparing the behaviour of both suction and degree of saturation profiles of different tailings mixtures. In the analysis, a pattern of precipitation and evaporation obtained from the region of Quadrilatero Ferrifero of the estate of Minas Gerais (Brazil) is applied, with the simplification of a uniform distribution of rain. This implies a conservative analysis of the problem.

4.3. Methodology

To study the influence of rainfall, evapotranspiration and capillary rise on itabirite tailings dry stack pile, 1D unsaturated seepage analyses were made using climate data representative of the Quadrilatero Ferrifero region of Brazil. The software used is PLAXIS LE v21.04.00.80. The climate data was obtained from the INMET meteorological station number 83587 (Belo Horizonte), between 1981 and 2010, and is presented in the Table 7:

Table 7 - Montly Rainfall, Potencial Evapotranspiration, Mean air temperature and Mean air relative humidity of the INMET station number 83587 (Belo Horizonte), between 1981-2010

INMET Station n. 83587	Rainfall (mm)	Potencial Evapotranspiration (mm)	Mean air temperature (Celsius)	Mean air relative humidity (%)
January	329	154	23.4	73
February	181	132	23.8	70
March	198	133	23.4	71
April	75	112	22.5	69
May	28	95	20.5	67
June	10	76	19.3	66
July	8	82	19.1	62
August	106	106	20.3	58
September	125	125	21.6	60
October	147	147	22.6	64
November	141	141	22.7	71
December	150	150	22.9	74

The 1D column adopted in the seepage analysis is 100 meters high. The 1D mesh has 100 nodes, with a denser distribution at the top and the bottom, in the vicinity of the two boundaries. The adopted boundary conditions are no lateral flux (i.e., 1D analysis), rainfall and evapotranspiration at the top of the column and zero pore pressure at the bottom (Figure 16). Runoff was allowed, with zero ponding.

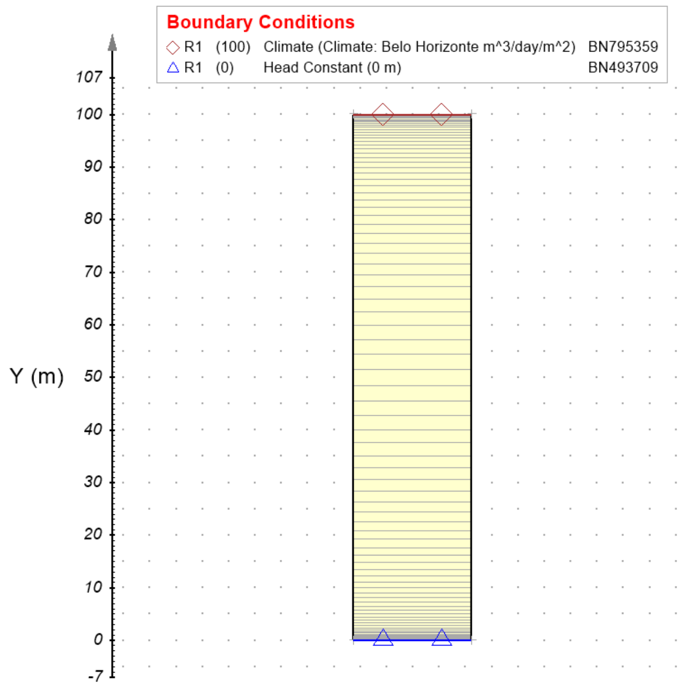

Figure 16 - Mesh, node distribuition and boundary conditions of the 1D column

The experimental data used in the present work are presented in more detail in Nadai et al. (2022). The material are tailings generated in cationic reverse flotation beneficiation process, typically adopted for itabirite iron ore in Quadrilatero Ferrifero. Two different types of tailings are generated in this process: slime tailings (fine grained) and flotation tailings (coarse-grained). Total tailings are the uncontrolled mixture of the two types of tailings. Table 8 presents the proportions used in each mixture and the description of the material.

Table 8 - Material used for the study

Material	Description
TT	Hydraulic disposed total tailings
90%FL+10%SL	90% Flotation tailings + 10% Slime tailings
80%FL+20%SL	80% Flotation tailings + 20% Slime tailings
70%FL+30%SL	70% Flotation tailings + 30% Slime tailings
100%FL	100% Flotation tailings
100%SL	100% Slime tailings

As mentioned before, the geotechnical parameters required to perform the unsaturated seepage analysis are the saturated permeability coefficient and the adjusted Soil Water Retention Curve (SWRC). From these parameters the Unsaturated Hydraulic Conductivitiy Function is calculated according to the volumetric water content along the height of the column. The adjustment method of the SWRC adopted is the Fredlund and Xing model (1994) and the parameters are presented in the Table 9. No volume change was considered in the analysis.

Table 9 - SWRC adjustment parameters, Fredlund and Xing model (1994)

Sample	**$k_{sat,360\ kPa}$** (m/s)	**af** (kPa)	**nf**	**mf**	**hr** (kPa)	**θ_{sat}**	**θ_r**	**Residual Suction** (kPa)	**AEV** (kPa)
100% TT	2.6 E-7	1321	0.46	7.13	1633	0.422	0.028	1598	4.0
90%FL+10%SL	1.6 E-7	9	0.76	0.88	707	0.380	0.092	640	1.8
80%FL+20%SL	5.9 E-7	2	1.51	0.44	43	0.409	0.166	42	1.1
70%FL+30%SL	1.2 E-6	2	1.41	0.42	80	0.396	0.161	58	1.0
100% FL	1.4 E-5	50	0.39	4.16	385	0.495	0.030	461	0.4
100% SL	9.6 E-8	2500	1.08	2.05	15179	0.490	0.026	15885	472.5

$k_{sat,360kPa}$: saturated permeability coefficient; af, nf, mf, hr: Fredlund and Xing (1994) adjustment parameters; Res. VWC: residual volumetric water content; Res. Suction: residual suction; AEV: air entry value

The time unit adopted for the analysis is day, so the montly rainfall presented in the Table 7 was divided by 30 to be used in the seepage model. The Actual Evaporation was calculated using the Wilson Empirical Equation (Wilson et. al., 1997) from the data of potencial evaporation, air temperature and air relative humidity. At the surface, the suction was corrected by the PLAXIS LE adjustment factor estimation and the gradient was limited to 100.

Starting from the initial pore pressure condition of -60 kPa all along the column, the analysis was performed running 50 years in order to obtain the equilibrium profile within the column. After that, an additional annual analysis was performed, recording the results at the end of March, June, September and December. With this process, it is possible to verify, along the year for each material, the equilibrium saturation degree in the column, the depth of the active zone and the influence of the annual climate cycle on the saturation degree.

4.4. Results

Figure 17 shows the results of the analyzes for the six materials studied, showing the variation in the degree of saturation in depth. In the figure we can see the active zone, the upper band where the weather effect is predominant. In the cases analyzed, the observed active zone, up to 20 meters, is much higher than the cases found in the literature, which indicates an active zone ranging from 2 to 4 meters for similar climates. The reason for this deeper active zone is probably related to the imposition of an average daily rain during the period that generates great infiltration, leaving the analysis very conservative. However, for the purpose of comparison between materials, this aspect does not create any difference. It is observed in Figure 17 that the blends 10%SL+90%FL, 20%SL+80%FL and 30%SL+70%FL present similar behavior in relation to the active zone. The 100%FL and 100%TT materials indicate greater variation for the dry branch and also a smaller active zone. The 100%SL material shows a very different behavior, with the material maintaining a high degree of saturation throughout the period.

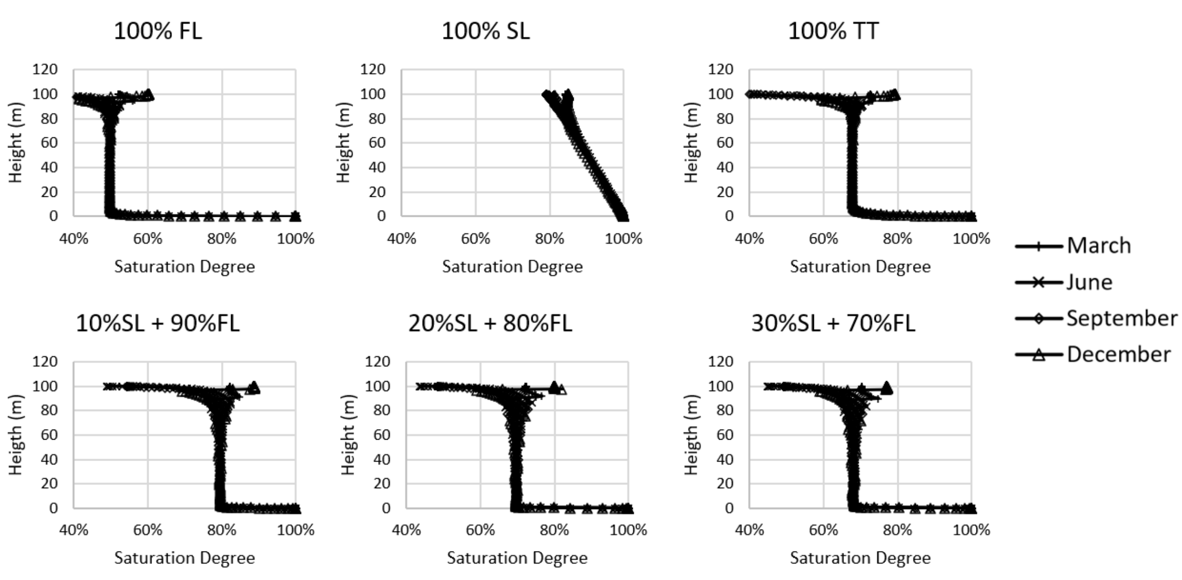

Figure 17 – Saturation degree along the heigth of the column at the end of March, June, September and December

Figure 18 focus on the lower section of the profile, base up to 5 m above the imposed water table. In this Figure the effect of capillary rise is highlighted. In the case of the pure slime tailings (100%SL), the capillary rise makes all the 5 meters to be 100% saturated. In the other cases there is a reduction in the degree of saturation that is similar in the blends 10%SL+90%FL, 20%SL+80%FL and 30%SL+70%FL, reaching a height of approximately 1 m. In the case of pure flotation tailings (100%FL) this effect goes up to approximately 3 m. And for the total tailing (100%TT), the capillary effect is close to 5 m. The behavior of the 100%SL, strongly affected by capillarity generating saturation degree of 100% along the height, is in agreement with the analysis performed directly using the water retention curve presented by Nadai et al. (2022).

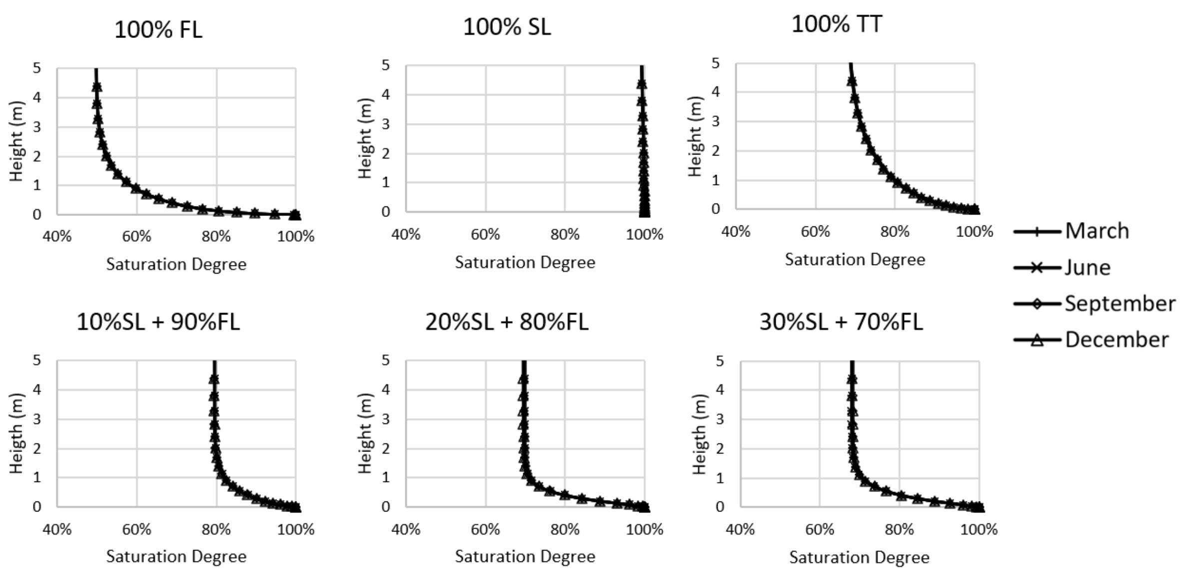

Figure 18 – Saturation degree at the column bottom at the end of March, June, September and December

Figure 19 shows a detail of the results focusing on the upper section, close to the active zone. In this figure, only the upper section associated with the active zone is shown.

For the pure flotation tailings (100%FL), the active zone is 30 meters and the degree of saturation ranges from 40% in June and September (dry season) to 60% in December (rainy season). For the pure slime tailings (100%SL), the active zone is 40 meters deep and the degree of saturation near the top ranges between 78% to 85%. For the total tailings (100%TT), the active zone is 20 meters high and the saturation degree ranged between 40% and 80%. The values of the active zone are high probably due to the imposed precipitation condition. The result for the blend with 10% of slime tailings (10%SL +90%FL) presented an active zone of 40 meters, with saturation degree ranging between 50% and 90%. The blend with 20% of slime tailings (20%SL+80%FL) presented an active zone of 40 meters, with saturation degree ranging from 50% to 80%. The blend with 30% of slime tailings (30%SL+70%FL) presented an active zone of 40 meters, with saturation degree ranging from 45% to 75%.

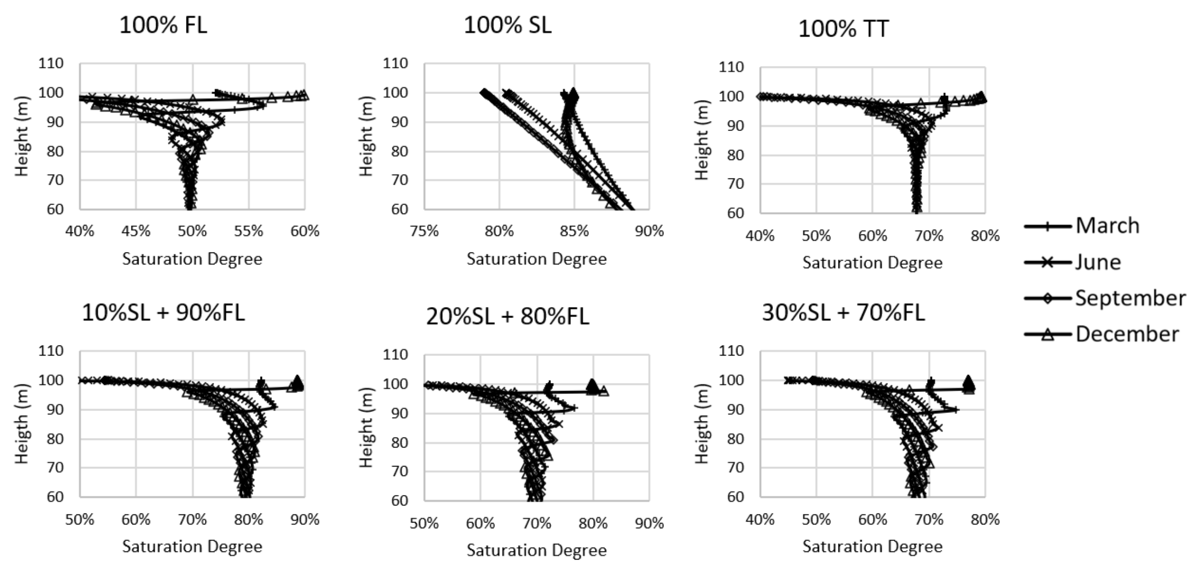

Figure 19 - Saturation degree in the column top at the end of March, June, September and December

4.5. Conclusion

An 1D transient numerical analysis was performed on a 100 m long column. The parameters used were from itabirite iron tailings and the objective was to evaluate the viability of dry stacking with saturation degree below 80%, under the influence of capillary rise and rainfall. The tailings analyzed were pure flotation tailings, pure slime tailings, total tailings and blends between flotation and slime tailings, up to 30% of slimes in mass.

The results indicate that, due to water retention characteristic, the pure slime tailings (100%SL) remain with a high degree of saturation due to capillary rise. This degree of saturation is always above 80% and very close to 100% in most of the profile. On the other hand, pure flotation tailings, total tailings and the blends presented capillary rise affecting only the first meter of the bottom of the column, equilibrium saturation degree in the inactive zone of less than 80% and active zone saturation degree ranging below 80%. The only exception is the blend with 10% of slime, that presented up to 90% saturation degree in the superior 10 meters (at the active zone) in the rainy season.

Thus, it is concluded that it is possible to compose a blend that guarantees degree of saturation below 80%, under the influence of capillary rise and precipitation. It should be noted, however, that in the case of capillary rise, the saturated thickness must be evaluated in order to avoid saturation even in a small thickness at the pile's base. In addition, it is necessary to evaluate, based on resistance tests, the limit degree of saturation that should be considered as the upper limit.

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4.7. Acknowledgments

The authors are grateful to the Laboratory of Residues and Contaminated Areas (LRAC) of the Center of Geoenvironmental Technologies (CTGeo) of the Institute for Technological Research (IPT) for the laboratory tests performed. The authors are also grateful to VALE S.A. for its authorisation to publish the data used in this work.

5. CONSIDERAÇÕES FINAIS

A mineração de ferro tende a continuar a ser uma atividade fundamental para as sociedades humanas nas próximas décadas. Porém, reguladores e opinião pública dos territórios nos quais ocorre mineração cada vez mais exigem técnicas de disposição de rejeitos mais seguras em relação ao risco de colapso geotécnico. Nesse contexto, o empilhamento de rejeito filtrado vem ganhado popularidade nos últimos anos, especialmente na região do Quadrilátero Ferrífero em Minas Gerais.

Diferente de outros métodos de disposição de rejeito, como lançamento hidráulico e rejeito em pasta, o empilhamento de rejeito filtrado permanece em condição não saturada. Por isso, essa técnica exige estudos geotécnicos adicionais que levam em consideração a mecânica dos solos não saturados e a capacidade de retenção de água. Estudos de fluxo não saturado são necessários para uma adequada verificação do grau de saturação interno ao longo da vida útil da pilha de rejeito filtrado. Fenômenos como subida capilar e infiltração de chuva exercem grande influência no grau de saturação interno do rejeito em condição não saturada.

Neste trabalho foi apresentado o uso de curva de retenção de água (SWRC) do rejeito para a verificação de possível saturação por subida capilar. Foram também realizadas análises de percolação não saturada que confirmaram a eficácia da verficação por SWRC.

Foi feita a caracterização geotécnica de diferentes amostras de rejeitos de minério de ferro itabirítico concentrados por flotação catiônica reversa: rejeito de deslamagem, rejeito de flotação, e misturas entre eles. A caracterização constituiu-se de granulometria, ensaio de compactação Proctor normal, ensaio edométrico, permeabilidade saturada, SWRC e função condutividade hidráulica não saturada ajustada pelo método de Fredlund and Xing (1994). A SWRC adotada foi a de secagem.

O uso direto das curvas de retenção de água se mostrou uma ferramenta muito importante para uma análise preliminar do problema de retenção de água nos materiais, como demostrado no primeiro artigo apresentado.

A SWRC e a função condutividade hidráulica também foram usadas em análises de percolação transiente 1D, simulando uma coluna de rejeito. Este estudo permitiu avaliar o grau de saturação ao longo de 100 metros de altura de pilha no decorrer de um ano. Este estudo levou em consideração tanto a influência da ascensão capilar como a pluviometria anual representativa do Quadrilátero Ferrífero. A análise de percolação foi feita em 1D pois, além de no centro da pilha o fenômeno de percolação ser essencialmente unidimensional, funções unidimensionais de grau de saturação pela altura da pilha são mais fáceis de serem visualizadas e comparadas entre si, em comparação com resultados gráficos de percolação 2D e 3D.

Concluiu-se que o rejeito de deslamagem puro mantém um grau de saturação acima de 80% ao longo dos 100 metros de altura da coluna, devido à ascensão capilar, o que o torna inadequado para o empilhamento a seco devido a risco de liquefação e problemas de trafegabilidade. Tanto a análise simplificada (artigo 1), como a obtida pela análise numérica (artigo 2) demostraram este comportamento. Por outro lado, rejeito flotado puro e as misturas entre rejeito flotado e de deslamagem mostraram desempenho mais adequado com relação ao grau de saturação. Nestes casos, a ascensão capilar que satura o material foi de cerca um metro e saturação na zona ativa menor que 80% ao longo de todo o ano. Destaca-se a importância de se avaliar o trecho saturado mesmo quando ele se apresenta em uma camada pouco espessa.

No que se refere ao grau de saturação em pilhas de rejeito itabirítico filtrado, sugere-se como uma das possíveis soluções para o empilhamento de rejeito de deslamagem a sua mistura com rejeito de flotação de mesma origem, numa composição até 30% em massa de rejeito de deslamagem. Entretanto, não foram analisados aspectos relacionados a compactação adequada para a garantia de comportamento dilatante, o que requer estudos adicionais.

6. SUGESTÃO DE FUTUROS ESTUDOS

O foco deste trabalho foi no desempenho hidráulico e grau de saturação interno no empilhamento de rejeito filtrado de minério de ferro itabirítico. Entretanto, aspectos como deformabilidade e resistência ao cisalhamento também são de suma importância na adoção dessa técnica de disposição de rejeito.

Outro aspecto de suma importância é o fenômeno de histerese das SWRC: no presente trabalho foi adotado a curva de secagem, porém o fenômeno de percolação não saturada no interior da pilha envolve tanto secagem como umedecimento.

Além disso, os equipamentos e métodos de compactação atualmente adotados no empilhamento de rejeitos filtrados de mineração são melhor representados pelo ensaio de compactação Proctor modificado.

Ademais, há rejeitos de outros minérios que também são passíveis de disposição por empilhamento filtrado.

Assim, sugere-se como possível continuação dessa pesquisa:

- A investigação da resistência e deformabilidade de misturas entre rejeito de deslamagem e flotação de minério de ferro itabirítico, em comparação com esses materiais puros. Sugere-se que estas investigações sejam realizadas tanto na condição saturada quanto na não saturada, definindo o grau de saturação máximo a ser adotado de modo a minimizar uma possível liquefação.

- O estudo de influência da histerese da SWRC no fenômeno de percolação não saturada que ocorre no interior das pilhas de rejeito filtrado de minério de ferro itabirítico.
- A realização de ensaios de compactação Proctor modificado em amostras de misturas entre rejeito flotado e de deslamagem de minério de ferro itabirítico.
- A comparação da SWRC e função condutividade hidráulica entre rejeitos de diferentes origens minerais e processos de concentração, para a verificação de similaridades e diferenças.

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8. ANEXOS

8.1. Comprovantes de submissão do artigo 1

Gmail

Felipe Moschem de Nadai <felipemdenadai@gmail.com>

Submission confirmation for article 'SWRC interpretation of iron ore tailings blends focusing on saturation assessment of filtered tailings piles'

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