DIEGO TASSINARI

PARÂMETROS FÍSICOS E MECÂNICOS DE SOLOS EM ÁREASALTERADAS PELA MINERAÇÃO DE FERRO NO MUNICÍPIO DE SABARÁ, MG

LAVRAS - MG
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Dissertação apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra para a obtenção do título de Mestre.

Orientador

PhD. Moacir de Souza Dias Junior

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APROVADA em 28 de janeiro de 2015.

Dr. Geraldo César de Oliveira UFLA

Dr. Wellington Willian Rocha UFVJM

PhD. Moacir de Souza Dias Junior
Orientador

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2015

Para meus pais.

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“Let no one say, and say it to your shame,
That all was beauty here, until you came.”

RESUMO GERAL

Este trabalho avaliou a qualidade física de solos reconstruídos em pilhas de estéril provenientes da mineração de ferro no município de Sabará, MG, Sudeste brasileiro, comparando-os com outros solos sob vegetação nativa (floresta semidecidual Atlântica, formação de Cerrado e vegetação de canga) e floresta de *Eucalyptus* sp. Foram avaliadas características do solo, como textura e densidade de partículas, bem como diversas propriedades físicas: densidade do solo; estabilidade de agregados em água; distribuição de poros por tamanho; curva de compressão do solo; pressão de pré-consolidação; e capacidade de suporte de carga. Os locais avaliados diferiram significativamente em seus atributos físicos. Os solos reconstruídos sofreram alterações inclusive em atributos intrínsecos (textura e densidade de partículas), o que condicionou modificações em sua qualidade física. O solo recuperado com maiores quantidades de solo original apresentou melhor qualidade física dentre os solos reconstruídos, sendo semelhante fisicamente ao solo sob Cerrado. A estabilidade de agregados foi sempre menor nos solos reconstruídos, que apresentaram maior microporosidade (maior retenção de água disponível). A densidade do solo variou significativamente nos diferentes usos da terra e influenciou o comportamento compressivo do solo ao longo de todas as pressões aplicadas. A pressão de pré-consolidação no potencial matricial de -10 kPa variou pouco entre os tratamentos. A capacidade de suporte de carga dos solos foi bastante distinta entre os diferentes usos da terra e profundidades, tendo também sido largamente afetada pelas diferentes texturas dos solos. Os solos argilosos tenderam a apresentar maior capacidade de suporte de carga, enquanto os solos mais siltosos e arenosos apresentaram menor taxa de decaimento da pressão de pré-consolidação em função do aumento da umidade. Em geral as condições físicas dos solos reconstruídos não são restritivas às plantas, sendo variáveis em função dos materiais empregados na construção.

Palavras-chave: Compactação do solo. Recuperação de áreas mineradas. Estrutura do solo.

GENARAL ABSTRACT

This work evaluated the physical quality of soils reconstructed on waste dumps originated from iron mining in the municipality of Sabará, MG, Southeast of Brazil, comparing these to other soils under native vegetation (Semideciduous Atlantic Forest, Cerrado formation and Canga vegetation) and *Eucalyptus* sp. forest. Soil traits such as texture and particle density, as well as several physical properties: soil bulk density; aggregate stability in water; pore size distribution; soil compression curve; precompression stress and load bearing capacity were evaluated. The locations evaluated differed significantly in their physical attributes. The reconstructed soils underwent alterations including intrinsic attributes (texture and particle density), which conditioned modifications in their physical quality. The recovered soil with higher amounts of original soil presented better physical quality among the reconstructed soils, being physically similar to the soil under Cerrado. Aggregate stability was always lower in the reconstructed soils, which also presented higher microporosity (higher retention of available water). Soil bulk density varied significantly in the different land uses and influenced the compressive behavior of the soil over all of the applied pressures. The precompression stress at -10 kPa water potential varied little between treatments. The load bearing capacity of the soils was significantly distinct between the different land uses and depths, also being largely affected by the different soil textures. The clayey soils tended to present higher load bearing capacity, while the soils with higher sand and silt contents presented lower ratios of decrease on precompression stress with increase on water content. In general, the physical conditions of the reconstructed soils are not restrictive to plants, varying in function of the materials employed in the construction.

Keywords: Soil compaction. Recovery of mining areas. Soil structure.

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LISTA DE SÍMBOLOS E SIGLAS

Dp	Densidade de partículas
SOC	Carbono orgânico do solo
GMD	Diâmetro médio geométrico
ASC	Silte + argila agregados
Db	Densidade do solo
n	Porosidade total
Macro	Macroporosidade
Meso	Mesoporosidade
Micro	Microporosidade
θ	Umidade com base em volume
θ_{FC}	Umidade na capacidade de campo
AFP	Porosidade livre de água
σ	Pressão
U	Umidade com base em peso

SUMÁRIO

PRIMEIRA PARTE

1 INTRODUÇÃO

Atualmente existe um vasto legado de terras degradadas pela mineração que necessitam de restauração (BRADSHAW, 1997). A recuperação de áreas mineradas é um desafio pelo alto grau de perturbação destes locais, sendo que o processo deve almejar a sustentabilidade dos ecossistemas no longo prazo (SHRESTHA; LAL, 2011). A revegetação de áreas mineradas começa com a reconstrução da zona de crescimento de raízes, que consiste principalmente em solo original ou resíduo recuperado, sobrepondo uma camada de resíduo ou estéril (HUANG; BAUMGARTL; MULLIGAN, 2012).

Os solos de áreas mineradas apresentam baixa qualidade física em relação aos solos não perturbados, uma vez que tanto os materiais (BRADSHAW, 1997; PARADELO; MOLDES; BARRAL, 2008; ZIPPER et al., 2013) quanto as técnicas (ACTON et al., 2011) empregados na recuperação destes locais favorecem a ocorrência de compactação do solo. Esta tem sido um entrave à restauração de áreas mineradas, geralmente demandando o emprego de práticas mecânicas de alívio, como a subsolagem (ASHBY, 1997; CASSELMAN et al., 2006; KINYUA et al., 2010; SKOUSEN et al., 2009; SZOTA et al., 2007; WILSON-KOKES; SKOUSEN, 2014). A compactação do solo também tem ocorrido para atendimento a exigências legais em alguns casos, uma vez que é necessária a estabilização geotécnica dos solos reconstruídos, o que é conseguido compactando-se os materiais depositados (ACTON et al., 2011). A compactação do solo em áreas mineradas altera a hidrologia dos cursos d'água na bacia hidrográfica, pois reduz a infiltração e aumenta o escoamento superficial (SIMMONS et al., 2002). Em áreas mineradas de regiões com ocorrência de seca ao longo do ano, a compactação do solo é especialmente prejudicial, pois ao limitar o crescimento do sistema radicular, limita também o acesso à água armazenada em maiores profundidades (BENIGNO; DIXON; STEVENS, 2013).

O objetivo deste trabalho foi avaliar diversos indicadores de qualidade física em solos reconstruídos após a mineração de ferro na mina de Córrego do Meio, município de Sabará, MG, comparando-os com outros usos da terra.

2 REVISÃO DE LITERATURA

2.1 Qualidade dos solos reconstruídos após a mineração

O material utilizado na recuperação de áreas mineradas influencia as propriedades do solo imediatamente após a aplicação da estratégia de recuperação e também no longo prazo. As propriedades físicas do solo são alteradas, inclusive a sua composição granulométrica. Solos recuperados geralmente apresentam maior quantidade de fragmentos grosseiros (maiores que 2 mm) em relação aos solos naturais (ZIPPER et al., 2013). As mudanças texturais, como redução do teor de fração argila, devem-se à substituição do solo nativo por estéreis de mineração, que contêm teores elevados de areia e cascalho (SHRESTHA; LAL, 2011). A distribuição granulométrica influencia muitas propriedades físicas e químicas do solo, como infiltração de água, condutividade hidráulica, capacidade de retenção de água, capacidade de troca de cátions, e afeta profundamente o sucesso da recuperação de áreas mineradas (PARADELO; MOLDES; BARRAL, 2008). Na recuperação de solos afetados pela mineração, o uso de materiais com maiores teores de argila favorece o acúmulo de C orgânico no solo e podem aumentar a atividade e a biomassa microbiana (CHODAK; NIKLIŃSKA, 2010). Os solos de áreas mineradas também apresentam menores teores de C e N orgânicos, e aumento do pH, da condutividade elétrica e da densidade do solo (SHRESTHA; LAL, 2011).

Não existe uma distribuição granulométrica ótima para todas as plantas, mas um meio de crescimento ideal deve conter areia suficiente para que tenha aeração adequada e seja solto o bastante para permitir o crescimento radicular, e argila suficiente para adequada retenção de água e nutrientes (PARADELO; MOLDES; BARRAL, 2008). Avaliando diversos materiais disponíveis para reconstrução de solos em áreas de mineração de ferro no Quadrilátero Ferrífero, MG, Silva et al. (2006) observaram que o filito, devido à granulometria fina, apresentou maior retenção de água e menor condutividade hidráulica que o saprolito de itabirito, mais arenoso; podendo ser utilizado na cobertura de pilhas de rejeito, porém seu uso deve ser muito criterioso, pois favorece a ocorrência de encrostamento, escoamento superficial, erosão e instabilidade das pilhas. A adição de areia residuária pode modificar a textura do rejeito de mineração aplicado, aproximando-se assim da textura dos solos não perturbados (COURTNEY; HARRINGTON; BYRNE, 2013). O uso de materiais já intemperizados favorece o desenvolvimento de vegetação, sendo que estéreis já intemperizados, em comparação a não intemperizados, em geral, resultam em melhores resultados no crescimento de vegetação arbórea nos primeiros anos (ZIPPER et al., 2013).

Ao reconstruir um sistema para crescimento de raízes, é imprescindível adequada estrutura do solo para bom desempenho das funções hídricas ao longo da zona radicular (ZIPPER et al., 2013). Posteriormente, a capacidade biológica do solo e as interações ecológicas (ciclagem de C e N) poderão se restabelecer, integrando a zona de crescimento das raízes à comunidade de plantas (HUANG; BAUMGARTL; MULLIGAN, 2012). A cobertura vegetal influencia fortemente o comportamento hidrológico de solos recuperados de mineração (HERAS; MERINO-MARTÍN; NICOLAU, 2009), sendo que maior cobertura vegetal está associada a escoamento superficial retardado, aumento na capacidade de infiltração de água no solo, e redução das perdas de solo. Os autores propõem um limite mínimo de 50% de cobertura vegetal herbácea, o que propiciaria o controle biótico satisfatório da resposta hidrológica.

A agregação e a formação de estrutura são processos lentos, sendo que a evolução pedológica de solos reconstruídos, com intemperismo e formação de horizontes, pode levar milhares de anos (BRADSHAW, 1997). A falta de desenvolvimento estrutural significativo após a recuperação limita a infiltração de água e a aeração, processos essenciais para as plantas se estabelecerem (ZIPPER et al., 2013).

2.2 Atributos físicos e mecânicos do solo em áreas afetadas pela mineração

A avaliação da qualidade do solo demanda o estabelecimento de indicadores e de valores de referência para os mesmos (ARSHAD; MARTIN, 2002). Porém, a definição de padrões com relação a solos de áreas mineradas é difícil devido à ampla diversidade de materiais e técnicas comumente empregados na recuperação e à carência de resultados de pesquisas (HAIGH, 1995). A qualidade física do solo se manifesta de várias maneiras, influenciando sobremaneira processos químicos e biológicos que ocorrem no solo, tendo, portanto, papel central em estudos de qualidade do solo (DEXTER, 2004).

2.2.1 Densidade do solo

A densidade do solo é provavelmente o indicador de qualidade física do solo mais comumente empregado (ALVES; SUZUKI; SUZUKI, 2007). O valor de 1,6 g cm^{-3} foi recomendado como limite crítico da densidade do solo em áreas mineradas por Haigh (1995), indicando necessidade de intervenção quando esta se encontrar acima deste valor. Contudo, a densidade do solo é fortemente influenciada pela textura (BRADY; WEIL, 2008; MARCOLIN; KLEIN, 2011), e a adoção de um único valor de referência para decidir a respeito da adoção de uma intervenção sem levar em consideração esta variação não seria adequado. Por exemplo, para Latossolos brasileiros da região do Cerrado sob vegetação natural, com teores de argila variando de 152 a 716 g kg^{-1}, Severiano et al. (2013) obtiveram valores de densidade do solo variando de 1,36 a 0,86 g cm^{-3} respectivamente.

Aumentos de até 54% na densidade do solo em relação a áreas não perturbadas foram relatados por Shrestha e Lal (2011) para solos recuperados após mineração de carvão, enquanto Krümmelbein e Raab (2012) reportam valores de densidade do solo, também em áreas de mineração de carvão, variando de 1,4 a 2,0 g cm^{-3}. Foi observado por Hu et al. (2009) que o tráfego de maquinário promoveu maior compactação na superfície da área de deposição e no solo com um ano de recuperação, mas a densidade do solo diminuiu como tempo de recuperação, sendo que, após cinco anos, ela aproximou-se da densidade do solo não perturbado. Porém, Quinõnes et al. (2008) não observaram diferenças significativas entre áreas com dois e 24 anos de recuperação nos atributos físicos avaliados: textura, densidade do solo e condutividade hidráulica. Para os autores, a densidade do solo elevada indica alto grau de compactação do solo, promovida pelo intenso tráfego de máquinas passadas durante o processo de reconstrução e favorecida pela textura argilosa do material.

2.2.2 Estabilidade de agregados em água

A compreensão dos fenômenos de formação, dinâmica e estabilidade da estrutura do solo é importante, pois ela determina e influencia muitos processos no solo, como a dinâmica de água, ar e calor; decomposição de resíduos; processos de transporte; ocorrência, sobrevivência e atividade dos organismos do solo e sistema radicular (KOOISTRA; TOVEY, 1994).

A estabilidade de agregados expressa a resistência dos mesmos à quebra quando submetidos a algum processo potencialmente destrutivo (HILLEL, 1998). Para que os resultados tenham implicação prática, as forças destrutivas devem estar relacionadas a forças esperadas no campo (KEMPER; ROSENAU, 1986). A determinação da estabilidade de agregados em água e da distribuição de agregados por tamanho correlaciona-se com a resistência dos agregados ao transporte pela água (FERREIRA, 2010). A formação e estabilidade de agregados originam-se tanto de reações físico-químicas quanto da atividade de organismos (ALEKSEEVA et al., 2009), sendo um importante indicador da suscetibilidade do solo à erosão (NCIIZAH; WAKINDIKI, 2014).

Foi observado por Courtney, Harrington e Byrne (2013) que, apesar da adubação orgânica ter favorecido a agregação do solo, os agregados mais estáveis foram observados apenas após nove anos de recuperação em área de mineração de carvão, atribuindo-se este fato à maior atividade biológica, acúmulo de carbono recalcitrante e menor sódio trocável após este período. O sucesso na recuperação de áreas mineradas deve envolver estratégias que reduzam as perdas de C orgânico e a compactação do solo e aumentem o sequestro de C (SHRESTHA; LAL, 2011).

2.2.3 Compressibilidade do solo, pressão de pré-consolidação e modelos de capacidade de suporte de carga

Para determinado volume de solo, existe uma relação entre a pressão aplicada e a deformação resultante (HORN; LEBERT, 1994), que caracteriza seu comportamento compressivo. O ensaio de compressão uniaxial geralmente é empregado para caracterizar o comportamento compressivo do solo (TANG et al., 2009). Um parâmetro frequentemente utilizado para indicar a capacidade de suporte de carga do solo é a pressão de pré-consolidação. Quando a curva de compressão do solo é plotada na forma de razão de vazios ou densidade do solo em função do logaritmo da carga aplicada, ela apresenta duas regiões distintas: uma porção de deformações elásticas associada a menores cargas; e uma região de deformações plásticas, associadas a pressões mais elevadas (GREGORY et al., 2006). A pressão de pré-consolidação é o ponto que divide a curva de compressão nestas duas regiões (CAVALIERI et al., 2008). Em áreas recuperadas de mineração de carvão, Lima et al. (2012) observaram que o tratamento com hemártria ("limpo-grass"), gramínea com sistema radicular bastante ativo e vigoroso, promoveu redução da densidade do solo e também resultou em menor pressão de pré-consolidação e comportamento compressivo diferenciado em relação aos demais tratamentos.

A capacidade de suporte de carga do solo é controlada principalmente pela umidade, tendo sido identificado que a pressão de pré-consolidação decresce exponencialmente com o aumento do conteúdo de água do solo (DIAS JUNIOR, 1994). Os valores de R^2 para a relação que descreve o decréscimo da pressão de pré-consolidação em função do aumento na umidade do solo frequentemente situam-se acima de 0,80 ou até mesmo 0,90, valores esses que indicam que a variação na umidade explica 80 a 90% da variação da pressão de pré-consolidação de determinado solo. Devido à influência preponderante da umidade do solo na pressão de pré-consolidação, a comparação entre diferentes solos ou manejos tem utilizado amostras equilibradas em diferentes umidades 90 (DIAS JUNIOR et al., 2007; IORI et al., 2012; MARTINS et al., 2012; PAIS et al., 2011; PIRES et al., 2012), em diferentes potenciais matriciais (AJAYI et al., 2009; SEVERIANO et al., 2013), em um único potencial matricial, frequentemente 10 kPa (CAVALIERI et al., 2008; KELLER et al., 2011) ou próximas à capacidade de campo (KELLER et al., 2004). Não obstante, têm sido empregadas também amostras com umidade de campo para avaliação do impacto do tráfego de maquinário agrícola (DIAS JUNIOR et al., 2007) ou para comparação com outras de avaliações *in situ* (IORI et al., 2013; KELLER; ARVIDSSON, 2007).

Em solos tropicais, especialmente em Latossolos, a textura e a mineralogia agem conjuntamente na determinação da estrutura do solo e de suas propriedades físicas (FERREIRA; FERNANDES; CURI, 1999a, 1999b), o que também afeta a capacidade de suporte de carga do solo. Latossolos com estrutura em blocos apresentam maiores valores de pressão de pré-consolidação em relação aos Latossolos com estrutura granular (AJAYI et al., 2009; SEVERIANO et al., 2013). A estrutura em blocos é favorecida pela mineralogia predominantemente caulinítica da fração argila, enquanto teores mais elevados de gibbsita favorecem a estrutura granular (FERREIRA; FERNANDES; CURI, 1999b). A estrutura granular tende a ser mais bem expressa nos Latossolos gibbsíticos mais argilosos, enquanto os solos com textura mais grosseira tendem à estrutura em blocos (SEVERIANO et al., 2013).

Os modelos de capacidade de suporte de carga relacionam a pressão de pré-consolidação à umidade do solo e têm sido utilizados para avaliar a qualidade física do solo em diversos ambientes (IORI et al., 2012; MARTINS et al., 2012; SEVERIANO et al., 2008), avaliar a suscetibilidade do solo à compactação (AJAYI et al., 2009), e o efeito de práticas de manejo no estado de compactação do solo para diversas culturas (ARAÚJO JUNIOR et al., 2011; DIAS JUNIOR et al., 2007; PAIS et al., 2011; PIRES et al., 2012; SEVERIANO et al., 2010).

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SEGUNDA PARTE - ARTIGOS

ARTIGO 1 Soil physical quality on sites disturbed by iron mining and other land uses from Sabará, Minas Gerais, Southeastern Brazil

Qualidade física do solo em locais afetados pela mineração de ferro e outros usos da terra de Sabará, Minas Gerais, sudeste do Brasil.

Diego Tassinari[1]
Moacir de Souza Dias Junior[2]
Geraldo César de Oliveira[2]
Wellington Willian Rocha[3]
Ayodele Ebenezer Ajayi[4]
Fátima Maria de Souza Moreira[2]
Zélio Resende de Souza[1]

ARTIGO FORMATADO DE ACORDO COM A NORMA PARA SUBMISSÃO DO PERIÓDICO CIÊNCIA E AGROTECNOLOGIA.

[1] Masters graduate student, Departamento de Ciência do Solo (DCS), Universidade Federal de Lavras (UFLA), Lavras-MG.
[2] Professor, DCS, UFLA, Lavras-MG.
[3] Professor, Departamento de Agronomia, Universidade Federal dos Vales do Jequitinhonha e Mucuri, Campus JK, Diamantina, MG.
[4] Senior Researcher, Department of Agricultural and Environmental Engineering, Federal University of Technology, Akure, Nigeria.

1. ABSTRACT

Mining activities severely disturb natural landscapes, and after mine closure the sites must be recovered. Poor soil physical quality is common on reclaimed mine sites, where soil compaction frequently hinders plant growth. Different soil physical quality attributes were evaluated, including bulk density, aggregates stability analysis and pore size distribution, on different overburden piles with reconstructed soil and on other land uses (natural forest, Cerrado, *Eucalyptus* sp. forest). Soil texture was significantly altered on constructed piles, what largely affected other soil properties. Soils constructed with a mixture of phyllite and BIF (banded iron formation) saprolite were loam to sandy loam and natural soils had higher clay contents. Soil aggregate stability was reduced on constructed soils, but much more severely on the 20-25 cm layer than on the 0-5 cm layer. The constructed pile with higher clay content (Pile 2), that seems to have received higher amounts of topsoil, showed a similar physical quality to the undisturbed soil from Cerrado. Physical quality declined on constructed soils, but soil compaction does not seems to be restricting plant growth, although it may be impairing other soil functions to an unknown extent.
Index terms: soil compaction, bulk density, aggregate stability, mine soil reclamation

2. RESUMO

A mineração provoca perturbações muito severas nas paisagens naturais e, depois que uma mina é fechada, o local deve ser recuperado. Baixa qualidade física do solo é comum em áreas de mineração recuperadas, o que frequentemente compromete o crescimento das plantas. Diferentes atributos de qualidade física do solo, como densidade, estabilidade de agregados e

distribuição de poros por tamanho, foram avaliados em solos reconstruídos sobre diferentes pilhas de estéril provenientes da mineração de ferro e em outros usos da terra (floresta natural, Cerrado, floresta de *Eucalyptus* sp.). A textura do solo foi alterada significativamente nas pilhas construídas, o que afetou diversas outras propriedades. Os solos construídos com uma mistura de saprolito de filito e itabirito apresentaram textura franca a franco-arenosa, enquanto os solos nos locais não perturbados apresentaram maiores teores de argila. A estabilidade de agregados foi reduzida nas pilhas construídas, mas foi muito mais severamente afetada na camada de 20-25 cm em relação à camada de 0-5 cm. A pilha de estéril que apresentou maior teor de argila (Pilha 2), que parece ter sido recuperada com maiores quantidades de solo original, apresentou qualidade física semelhante ao solo sob Cerrado. A qualidade física do solo piorou nos solos reconstruídos, mas não parece ser restritiva ao crescimento das plantais, ainda que não se saiba até que ponto outras funções do solo foram afetadas.
Termos para indexação: compactação do solo, densidade do solo, estabilidade de agregados, recuperação de solos minerados.

3. INTRODUCTION

Soil quality has long been recognized as the soil capacity to perform its functions (DORAN; PARKIN, 1994), which include sustaining life and biodiversity; storage and transformations of water, carbon and nutrients within the biogeochemical cycles; as well as productive functions. Mining activities are among the greatest disturbances soils can suffer (SHRESTHA; LAL, 2011), and soils affected by it usually perform much poorly its functions if not properly recovered (HENEGHAN et al., 2008).

Soil physics plays an important role on overall soil quality (DEXTER, 2004) and soil compaction is the major cause of soil physical degradation

(BATEY, 2009; OLDEMAN; ENGELEN; PULLES, 1991). Soil compaction on mine sites may affect both soil productive and environmental functions. Soil compaction impedes root development and reduces tree survival and growth, what restricts the use of restored sites with profitable plant species, like hardwood trees (ZIPPER et al., 2011). Watersheds affected by mining also present changes on its hydrological behavior because of soil compaction, which reduces infiltration and increases runoff (SIMMONS et al., 2002). Reduced infiltration decreases plant available water within the soil profile and groundwater recharge, while increased erosion compromises water quality and abundance. Impeding soil layers may restrict root growth and limit its access to water storage at greater depths. Loss of macropores also decreases soil aeration (HILLEL, 1998), which may enhance N losses by denitrification.

Soil compaction is a very common issue on restoration and reclamation of mine sites (ZIPPER et al., 2013). Some materials often used, such as overburden and tailings, are highly susceptible to compaction and surface crusting (COURTNEY; HARRINGTON; BYRNE, 2013; HAIGH; SANSOM, 1999; PARADELO; MOLDES; BARRAL, 2008; SILVA et al., 2006. Restoration practices, which frequently involve traffic of heavy machinery like bulldozers, also contribute on further deteriorating soil physical quality (SHRESTHA; LAL, 2011; ZIPPER et al., 2011). Soil compaction may be even mandatory by law, in order to promote slope stability and prevent soil losses. Soil conditions may become so severe that native vegetation hardly ever flourishes, what forces the use of exotic aggressive herbaceous species that provide good soil cover (ACTON et al., 2011).

Definition of standards regarding mine soil restoration is difficult to obtain because of shortage of research data and tremendous variability of reclaimed surface mining sites (HAIGH, 1995) and there is a notion that the currently available soil quality indicators need to be tested on different soil, climate, ecosystem, land use and management conditions (ARSHAD; MARTIM, 2002).

The present study aimed to evaluate different soil physical quality indicators on reclaimed waste rock (overburden) dump piles and compare than to other areas under natural (forest and savannah) and exotic forest (*Eucalyptus* sp.) vegetation.

4. MATERIAL AND METHODS

The study was conducted at the Córrego do Meio iron mine on the city of Sabará, Minas Gerais state, southeastern Brazil. This mine has been explored since the late 1940's and was closed on 2005. By that time, the company Vale owned the mine (since 2000) and started closure procedures, which included topographic conformation of overburden piles, geotechnical stabilization and vegetation (beginning in 2006). After mine decommissioning, the area was converted into a center for biodiversity research and conservation. By the time of sampling, these constructed piles were vegetated predominantly with *Melinis minutiflora* grass.

Samples were collected on overburden piles and other land uses, as described on Table 1, and at two soil depths, 0-5 and 20-25 cm. Soil cores (diameter of 6.4 cm and height of 2.5 cm) and clods were collected after careful removal of vegetation and litter, at three sampling points per land use. Clods were stored on plastic bags and soil cores were wrapped on plastic film and covered with paraffin wax, thus preventing water loss and disturbance during transportation. Clods were air dried and sieved, with the aggregates that passed throw an 8.0 mm opening sieve and that were retained on a 4.75 mm opening sieve being used for aggregate stability analysis. Aggregates smaller than the later were crushed, passed throw a 2.0 mm opening sieve and used for granulometric, particle density and organic carbon analysis (results can be seen on Table 2).

Table 1. Description of land uses evaluated (Forest, Cerrado, Eucalypt and Piles 1, 2 and 3) from Córrego do Meio iron mine, Sabará, MG, southeastern Brazil.

Land use	Site description
Forest	Secondary semi deciduous Atlantic Forest, with small rock fragments on some sites.
Cerrado	Typical Brazilian savannah formation, with small quartz gravel on several sites.
Eucalypt	Unmanaged *Eucalyptus* sp. forest, with abundant undergrowth of small trees and bushes.
Pile 1	Samples collected on berm footslope, with a thin sandy layer on the surface. Frequent rock fragments.
Pile 2	Samples collected on berm footslope, with abundant rock fragments of several sizes.
Pile 3	Samples collected on berm midslope, with abundant rock fragments of several sizes.

For granulometric analysis, 10 g of soil were dispersed with 10 mL of NaOH 1.0 M and slowly shaken for 16 h at 30 rpm. The suspension was then washed throw a 0.053 mm opening sieve, where the sand fraction was retained. Silt and clay were separated by sedimentation and clay was determined by the pipette method (GEE; BAUDER, 1986). After oven drying (105-110 ºC for 24 h), the sand fraction was passed throw a 0.25 mm sieve for determination of coarse and fine sand. Particle density was determined on 50 mL pycnometers using deaerated distilled water (BLAKE; HARTGE, 1986b). Organic carbon content was determined after wet combustion with $K_2Cr_2O_7$ (DONAGEMA et al., 2011).

Table 2. Particle density (Dp) and soil organic carbon content (SOC) values for the evaluated land uses (Forest, Cerrado, Eucalypt and Piles 1, 2 and 3) at each soil layer (0-5 and 20-25 cm) from Córrego do Meio iron mine, Sabará, MG, southeastern Brazil.

Land use	Soil layer (cm)	Dp g cm^{-3}	SOC g kg^{-1}
Forest	0-5	2.56	27.7
	20-25	2.65	21.3
Cerrado	0-5	2.67	22.2
	20-25	2.76	13.7
Eucalypt	0-5	2.58	29.6
	20-25	2.7	21.6
Pile 1	0-5	3.33	19
	20-25	3.03	7.48
Pile 2	0-5	2.86	15.1
	20-25	2.92	12.2
Pile 3	0-5	3.26	12.9
	20-25	3.31	4.99

Soil aggregates (25 g, ranging from 8.0 to 4.75 mm diameter) were slowly moistened on sand bed prior to the water stability analysis, which was performed on a Yoder device with five sieve openings: 2.0, 1.0, 0.75, 0.50 and 0.105 mm (KEMPER; ROSENAU, 1986). Aggregates were sieved on water for

15 minutes at a rate of 30 cycles per minute. The material retained at each sieve was oven dried (105-110 ºC for 48 h) and weighted, after which all the fractions were united and slowly shaken for 16 h at 30 rpm with10 mL of NaOH 1.0 M for dispersion. After this, the coarser fractions (sand and gravel) were separated with a 0.053 mm opening sieve and oven dried. These analyses were conducted on triplets. From these data, the geometric mean diameter (equation 1) (MAZURAK, 1950), the proportion of aggregates at each size class and the content of aggregated silt and clay (equation 2) were calculated.

$$GMD = 10^{(\Sigma(ni*logdi)/\ \Sigma n)} \qquad (1)$$

where

GMD = geometric mean diameter (mm);

ni = proportion of aggregates on size class i (%);

di = mean diameter on size class i (mm);

$$ASC = (wagg - wsand)*100/(wsample - wsand) \qquad (2)$$

where

ASC = aggregated silt and clay (%);

wagg = weight of aggregates retained on all sieves (g);

wsand = weight of sand determined after dispersion (g);

wsample = dry weight of the initial sample (g).

The soil cores used for bulk density and porosity measurements were prepared at the laboratory, being the excess soil carefully removed from the outer part of the metal rings. The samples were then slowly saturated with distilled water. After this, samples were subjected to suctions of 6 kPa on porous funnels and 1,500 kPa on pressure plate extractors for determining the water content at each of these suctions (KLUTE, 1986). From the capillary equation (equation 3) modified from Or and Wraith (2002), the equivalent pore diameter was calculated, what allowed determining the pore size distribution, divided in three classes: macropores (pores with equivalent diameter higher than 50 μm what corresponds to 6 kPa suction), micropores (pores with equivalent diameter from 0.2 to 50 μm) and cryptopores (pores with equivalent diameter smaller than 0.2 μm what corresponds to 1500 kPa suction) as defined by Klein and Libardi (2002). After this, samples were oven dried (105-110 ºC for 48 h) for determining water content (GARDNER, 1986) and bulk density (BLAKE; HARTGE, 1986a).

$$de = 297/h \qquad (3)$$

de = equivalent pore diameter (μm);

h = suction (kPa).

Data was subjected to analysis of variance and when statistically significant differences were observed, Skott-Knott tests at 5% significance were applied using the software Sisvar (FERREIRA, 2011).

5. RESULTS AND DISCUSSION

Soil texture was significantly different among land uses (Table 3). Higher clay content was observed on the Eucalypt forest (almost 450 g g^{-1}), where the soil was classified as clay. On Forest, Cerrado and Pile 2, clay contents were lower than on Eucalypt (within a narrow range around 350 g g^{-1}) and the soil textural classification was clay loam. Among the constructed soils, Pile 2 presented the higher clay content (350 and 300 g kg^{-1} at 0-5 and 20-25 cm layers, respectively), while Piles 1 and 3 had clay contents usually below 150 g kg^{-1}. Silt contents were high throughout all the land uses, being close to 500 g g^{-1} on the 20-25 cm layer from the constructed piles, which showed the highest values.

Table 3. Soil granulometric fractions on the different land uses and at two soil depths (0-5 and 20-25 cm) from Córrego do Meio iron mine, Sabará, MG, southeastern Brazil.

Land use	Clay	Sand Total	Sand Coarse	Sand Fine*	Silt	
	---------------------	g kg^{-1}	---------------------			
			0-5 cm			
Forest	348 B	231 Ba	80 Ca	151 B	421	
Cerrado	316 B	293 Ba	108 Ca	185 B	391	
Eucalypt	429 A	201 Ba	95 Ca	107 C	369	b
Pile 1	116 C	515 Aa	209 Ba	305 A	370	
Pile 2	351 B	204 Ba	89 Ca	114 C	446	
Pile 3	110 C	475 Aa	316 Aa	159 B	415	
			20-25 cm			
Forest	381 B	205 Ba	61 Ba	144 B	414	
Cerrado	348 B	226 Ba	60 Ba	166 B	426	
Eucalypt	438 A	173 Ba	65 Ba	108 C	389	a
Pile 1	114 C	380 Ab	150 Ab	230 A	507	
Pile 2	300 B	207 Ba	71 Ba	135 C	494	
Pile 3	154 C	304 Ab	171 Ab	133 B	542	

*Equivalent diameter smaller than 0.25 mm.
Capital letters compare land uses within the same soil layer ($p<0.05$ Skott-Knott test). Small letters compare soil layers ($p<0.05$ Skott-Knott test) within the same land use (when one letter is shown for each value) or considering the mean from all land uses (when only one letter is shown for the whole column).

Soil texture is a key component on mined land restoration and higher clay contents may favor organic matter build up and microbial activity (CHODAK; NIKLIŃSKA, 2010), what significantly enhances restoration (SHRESTHA; LAL, 2011). On the present case, restoration could lead Pile 2 towards a state similar to that of undisturbed sites; while on Piles 1 and 3, reclamation may lead to a steady state, but it would hardly resemble the undisturbed sites. The texture on reconstructed soils from mined sites is dependent upon the material used (ZIPPER et al., 2013), but in general the overall trends are decrease on the clay fraction and increase on coarse fragments, such as sand and gravel (SHRESTHA; LAL, 2011). It can be inferred that Pile 2 was constructed with a considerable amount of topsoil, while piles 1 and 3 were constructed mainly with phyllite and BIF (banded iron formation) saprolite from mine overburden. When topsoil is applied, restoration is much easier, but it is not always available (ZIPPER et al., 2011). Phyllite is a very common overburden on iron mines from this region, as it is commonly associated to BIF occurrence (ROSIÈRE; CHEMALE JUNIOR, 1995). These overburden materials were physically characterized by Silva et al. (2006), and clay, silt and sand contents reported for phyllite are respectively 136, 195 and 597 g g^{-1}, while for BIF saprolite these are 126, 552 and 226 g g^{-1}. Piles 1 and 3 are probably a mixture from these two materials, as both sand and silt contents are high. This notion is reinforced by the values from particle density: while Silva et al. (2006) observed values of 3.75 g cm^{-3} for BIF saprolite and 2.61 g cm^{-3} for phyllite, our values (3.23 g cm^{-3} on average for piles 1 and 3) are intermediary to these (Table 1).

Aggregate stability was remarkably different between natural and constructed soils (Table 4). The geometric mean diameter (GMD), the amount of aggregated silt and clay (ASC) and the proportion of larger aggregates (8.0-2.0 mm size class) were significantly higher under Forest, Cerrado and Eucalypt in comparison to the constructed Pile soils. There was also a significant effect of sampling depth on aggregate stability. The 0-5 cm soil layer resulted in significantly higher values for GMD, ASC and ratio of larger aggregates in comparison to the 20-25 cm soil. On the 0-5 cm layer, GMD from Forest, Cerrado and Eucalypt was on average 15% higher than the GMD from Pile soils; on the 20-25 cm layer, this difference was much more expressive, with the former showing an average GMD almost 60% higher than the later.

According to Bell (2001), soil functions based indices are a key component for assessing ecosystem rehabilitation on mined sites and should also include measures of soil resistance to erosion. As aggregate stability is considered a suitable indicator of soil erodibility (NCIIZAH; WAKINDIKI, 2014), it may be considered a good indicator when evaluating restoration practices on soils affected by mining. It is important to develop strategies that may favor aggregate stabilization on restored mine soils, thus preventing soil losses. It can be seen that aggregation was enhanced on the surface layer, where organic carbon content was higher. Aggregation and aggregate stability on mined sites are favored by organic carbon accumulation over the time (HERAS; MERINO-MARTÍN; NICOLAU, 2009; WICK; INGRAM; STAHL, 2009), organic amendments (COURTNEY; HARRINGTON; BYRNE, 2013) and grass vegetation (LUNARDI NETO et al., 2008).

Table 4. Aggregate stability analysis results, showing geometric mean diameter (GMD), proportion of aggregates at each size class after wet sieving and aggregated silt + clay (ASC) under different land uses and at two soil depths (0-5 and 20-25 cm) from Córrego do Meio iron mine, Sabará, MG, southeastern Brazil.

	GMD	Aggregates at size classes (mm)						ASC
		8.0 - 2.0	2.0 - 1.0	1.0 - 0.5	0.5 - 0.25	0.25 - 0.105	< 0.105	
	mm	%						
				0-5 cm				
Forest	4.76 A	98.2 A	0.54 B	0.31 B	0.32	0.21	0.46 B	99.4 A
Cerrado	4.83 A	98.9 A	0.29 B	0.14 B	0.08	0.12	0.50 B	99.1 A
Eucalypt	4.87 A	99.4 A	0.05 B	0.04 B	0.04	0.06	0.47 B	99.4 A
Pile 1	4.42 B	96.1 B	0.62 B	0.46 B	0.45	0.66	1.70 A	97.0 B
Pile 2	3.88 B	90.5 B	1.63 A	1.74 A	1.52	1.44	3.20 A	95.2 B
Pile 3	4.30 B	95.0 B	0.80 A	0.85 A	0.68	0.65	2.03 A	95.4 B
	a	a	b	b				a

Table 4.Conclusion.

20-25 cm													
Forest	4.71 A		97.3 A		1.02 B		0.59 B		0.34	0.35	0.35 B	99.5 A	
Cerrado	4.39 A		94.5 A		1.76 B		1.20 B		0.77	0.62	1.14 B	98.4 A	
Eucalypt	4.82 A	b	98.8 A	b	0.25 B	a	0.12 B	a	0.26	0.07	0.48 B	99.4 A	b
Pile 1	2.88 B		84.2 B		1.54 B		1.46 B		1.47	1.99	9.30 A	86.6 B	
Pile 2	2.93 B		78.9 B		3.09 A		3.36 A		2.11	3.18	9.35 A	87.6 B	
Pile 3	3.01 B		82.5 B		2.56 A		2.73 A		2.17	1.76	8.30 A	86.5 B	

Capital letters compare land uses within the same soil layer ($p<0.05$ Skott-Knott test). Small letters compare soil layer considering the mean from all land uses, with only one letter being shown for the whole column ($p<0.05$ Skott-Knott test).

Soil bulk destiny was also significantly affected by mining (Table 5), being lower on Forest and Eucalypt (0.98 and 0.91 g cm^{-3} respectively on the 0-5 cm layer) and higher on Pile 1 and Pile 3 (1.62 and 1.60 g cm^{-3} respectively on the 0-5 cm layer). The soil from Cerrado and Pile 2 resulted in intermediary values (1.14 and 1.25 g cm^{-3} respectively on the 0-5 cm layer). Soil bulk density on reclaimed mine sites may reach values higher than 2.0 g cm^{-3}(ACTON et al., 2011).Bulk density values (measured on graduated cylinder with disturbed samples) of 1.67 and 1.1 g cm^{-3}were found by Silva et al. (2006) BIF (banded iron formation) and phyllite saprolite, materials commonly available for iron mine reclamation. The values here reported on the 0-5 cm layer from Pile 1 and on Pile 3 are close to the values reported for BIF saprolite, but yet somewhat smaller, even though the aforementioned bulk density values were obtained with loose, disturbed samples. A value of 1.6 g cm^{-3} was recommended as standard for mine soil reclamation by Haigh (1995), who suggested that soils with bulk density values above this should be considered “in need of treatment”. However, the author do not present any additional information concerning for which textural classes this value is acceptable, and a single value would hardly be well suitable for the whole range of different clay, silt and sand contents. Total porosity showed the same trends, with a general tendency of Forest ~ Eucalypt > Cerrado ~ Pile 2 > Pile 1 ~ Pile 3. Macroporosity was always higher on the 0-5 cm layer in comparison to the 20-25 cm layer, and the lowest average value was 0.16 cm^3 cm^{-3} on Pile 1 (20-25 cm layer). Although it may not be considered detrimental for plant growth as it stands above the benchmark value of 0.10 or 0.14 cm^3 cm^{-3} (REYNOLDS et al., 2009) it is unknown how severely this reduction might hinder water infiltration. Microporosity, which is associated to available water storing pores, was higher on the constructed piles (0.16 cm^3 cm^{-3} on average) than on the other soils (0.115 cm^3 cm^{-3} on average), what represents an increase of 4.5 mm of available water for each10 cm of soil profile.

Cryptopores, which hold water with such a high energy that makes it unavailable for plants (KLEIN; LIBARDI, 2002), were significantly higher on Forest, Cerrado and Eucalypt than on the constructed piles, probably because of higher clay contents.

Table 5. Soil bulk density (Db), total porosity (n) and macro-, micro- and cryptopores content (Macro, Micro and Crypto, respectively) under different land uses and at two soil depths (0-5 and 20-25 cm) from Córrego do Meio iron mine, Sabará, MG, southeastern Brazil.

	Db	n	Macro	Micro	Crypto	Db	n	Macro	Micro	Crypto
			$ø_{eq}$>50μm		$ø_{eq}$<0.2μm			$ø_{eq}$>50μm		$ø_{eq}$<0.2μm
	g cm^{-3}	------------ cm^3 cm^{-3} ------------				g cm^{-3}	------------ cm^3 cm^{-3} ------------			
	0-5 cm					20-25cm				
Forest	0.98 Ca	0.62 A	0.26 Ba	0.10 Bb	0.25 A	1.07 Ca	0.60 A	0.21 Bb	0.13 Ba	0.27 A
Cerrado	1.14 Ba	0.57 B	0.24 Ba	0.12 Bb	0.21 A	1.19 Ba	0.58 B	0.19 Bb	0.14 Ba	0.24 A
Eucalypt	0.91 Ca	0.65 A	0.35 Aa	0.08 Bb	0.22 A	1.05 Ca	0.61 A	0.24 Ab	0.12 Ba	0.25 A
Pile 1	1.62 Aa	0.51 C	0.20 Ca	0.16 Ab	0.15 B	1.30 Bb	0.57 C	0.16 Cb	0.18 Aa	0.23 B
Pile 2	1.25 Ba	0.56 B	0.24 Ba	0.11 Ab	0.21 B	1.23 Ba	0.58 B	0.23 Bb	0.18 Aa	0.17 B
Pile 3	1.60 Aa	0.51 C	0.21 Ca	0.17 Ab	0.14 B	1.58 Aa	0.52 C	0.18 Cb	0.17 Aa	0.17 B

Capital letters compare land uses within the same soil layer ($p<0.05$ Skott-Knott test). Small letters compare soil layers within the same land use ($p<0.05$ Skott-Knott test).

Soil aggregates stability and soil structure were highly correlated to soil texture and organic matter content (Table 5). Clay and organic matter contents were significantly correlated to each other, and both were significantly correlated to increase on aggregate stability. Soil bulk density and total porosity only were not correlated to silt content. Macroporosity was favored by higher clay and organic matter contents, while cryptopores content was only positively correlated to clay content. Microporosity was positively correlated to silt content.

Table 6. Pearson correlation coefficient between granulometric fractions (clay, total sand, coarse sand and fine sand) and soil organic carbon (SOC) content and the soil physical quality attributes geometric mean diameter (GMD), proportion of aggregates at each size class (8-2, 2-1, 1-0.5, 0.5-0.25, 0.25-0.105, <0.105 mm), aggregated silt + clay (ASC), bulk density (Db), total porosity (n) and macro-, micro- and cryptopores (Macro, Micro and Crypto, respectively) under different land uses from from Córrego do Meio iron mine, Sabará, MG, southeastern Brazil.

	DMG	8-2	2-1	1-0.5	0.5-0.25	0.25-0.105	<0.105	ASC	Db	n	Macro	Micro	Crypto
Clay	0.52*	0.46	-0.23	-0.31	-0.40	-0.45	-0.52	0.58	-0.80	0.74	0.59	-0.69	0.62
Total	-0.09	-0.01	-0.13	-0.09	-0.03	0.03	0.08	-0.14	0.78	-0.72	-0.36	0.43	-0.63
Coarse	-0.09	-0.01	-0.09	-0.04	0.01	0.00	0.05	-0.15	0.76	-0.68	-0.20	0.33	-0.67
Fine	-0.07	0.00	-0.13	-0.13	-0.08	0.06	0.08	-0.09	0.52	-0.52	-0.43	0.40	-0.35
Silt	-0.78	-0.79	0.60	0.69	0.75	0.76	0.80	-0.79	0.22	-0.19	-0.48	0.56	-0.13
SOC	0.64	0.57	-0.54	-0.52	-0.51	-0.44	-0.57	0.61	-0.66	0.62	0.66	-0.58	0.35

*Shaded cells indicate significance at 1% on bi-lateral t test.

6. CONCLUSIONS

Soil texture is significantly altered during post mining recovery, as the materials used may differ from the original soil. This strongly affects soil physical quality on the evaluated overburden piles, which seen to have been constructed from a mixture of phyllite and BIF (banded iron formation) saprolite.

Soil aggregate stability is reduced on constructed soils, but much more severely on the 20-25 cm layer than on the 0-5 cm layer, what could be associated to decrease on organic carbon contents.

The constructed pile with higher clay content (Pile 2), that seems to have received higher amounts of topsoil, has a similar physical quality (bulk density, porosity and pore size distribution) in comparison to the undisturbed soil from Cerrado, except for aggregate stability.

The evaluated soils do not present any severe limitation to plant growth and could be reforested in order to perform more properly other soil functions, such as C stocking and biodiversity conservation, specially the soil from Pile 2.

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ARTIGO 2 Soil compressive behavior and precompression stress on sites disturbed by iron mining and on other land uses from Sabará, Minas Gerais, Southeastern Brazil

Qualidade física do solo em locais afetados pela mineração de ferro e outros usos da terra em Sabará, Minas Gerais, sudeste do Brasil.

Diego Tassinari[1]
Moacir de Souza Dias Junior[2]
Geraldo César de Oliveira[2]
Wellington Willian Rocha[3]
Pedro Andrade Carvalho[4]
Júlia Mesquita Ribeiro[4]

ARTIGO FORMATADO DE ACORDO COM A NORMA PARA SUBMISSÃO DO PERIÓDICO CIÊNCIA E AGROTECNOLOGIA.

1 Masters graduate student, Departamento de Ciência do Solo (DCS), Universidade Federal de Lavras, Lavras-MG.
2 Professor, DCS, UFLA, Lavras-MG.
3 Professor, Departamento de Agronomia, Universidade Federal dos Vales do Jequitinhonha e Mucuri, Campus JK, Diamantina, MG.
4 Undergraduate students, UFLA.

1. ABSTRACT

After mining activities have ceased, the severely disturbed natural landscapes must be recovered. The materials and practices commonly employed often lead to soil compaction and poor soil physical quality. Water content at field capacity, soil compressive behavior and precompression stress were evaluated on samples from different iron mining overburden piles with reconstructed soil and on other land uses (natural forest, Cerrado, *Eucalyptus* sp. forest). Water content at field capacity varied significantly between land uses, being smaller on the sandy loam soil layers (0-5 cm from Piles 1 and 3). Soil bulk density was significantly different between land uses and soil layers. It was higher on Piles1 and 3 (12% clay on average) and lower on Forest and Eucalypt (clayey soils). Cerrado and Pile 2, constructed with topsoil rich material, were similar. Soil behavior during compression was strongly related to soil initial conditions and to soil moisture, to a lesser extent. Soil precompression stress was only slightly different between the evaluated land uses, being higher on Pile 1, which showed higher bulk density values on both soil layers. Additional compaction on Piles 1 and 3 would result in detrimental bulk density conditions, while on the rest of the land uses, higher pressures (>400 kPa) would be needed to induce severe soil compaction.
Index terms: soil compaction, uniaxial compression test, mine soil reclamation.

2. RESUMO

A mineração provoca perturbações muito severas nas paisagens naturais e, depois que uma mina é fechada, o local deve ser recuperado. Baixa qualidade física do solo é comum em áreas de mineração recuperadas, o que frequentemente compromete o crescimento das plantas. O conteúdo de água na capacidade de campo, a compressibilidade do solo e a pressão de pré-consolidação foram avaliados em amostras provenientes de pilhas de estéril de mineração de ferro com solo reconstruído, bem como em outros usos da terra (floresta natural, Cerrado, floresta de *Eucalyptus* sp.). A umidade do solo na capacidade de campo variou significativamente entre os usos da terra, sendo menor nos solos franco arenosos (camada de 0-5 cm das Pilhas 1 e 3). A densidade do solo foi significativamente diferente entre usos da terra e camadas do solo. Maiores valores foram encontrados nas Pilhas 1 e 3 (12% de argila em média) e menores valores foram observado na Floresta e no Eucalipto (solos argilosos). O Cerrado e a Pilha 2, construída com material mais rico em solo original, foram semelhantes entre si. O comportamento compressivo do solo foi fortemente influenciado pelas condições iniciais e, em menor grau, pelo conteúdo de água. A pressão de pré-consolidação variou pouco entre os usos da terra, sendo Maior na Pilha 1, que também apresentou os maiores valores de densidade do solo em ambas as camadas. Compactação adicional nas Pilhas 1 e 3 resultaria em condições restritivas de densidade do solo, enquanto nos outros usos da terra apenas pressões bem maiores (acima de 400 kPa) resultariam em compactação severa.

Termos para indexação: compactação do solo, ensaio de compressão uniaxial, recuperação de áreas mineradas.

3. INTRODUCTION

Soil physical quality plays a major role in general soil quality (DEXTER, 2004), and soil compaction is the most important cause of soil physical degradation (BATEY, 2009; OLDEMAN; ENGELEN; PULLES, 1991). Soil compaction poses a threat to reclamation of mine sites, hindering plant growth and soil functioning (SKOUSEN et al., 2009;ZIPPER et al., 2013). Mine soils are prone to compaction because of both their intrinsic attributes, which make then highly susceptible to compaction (PARADELO; MOLDES; BARRAL, 2008; SHRESTHA; LAL, 2011), and their handling during reclamation practices, which often involve traffic with heavy bulldozers (ZIPPER et al., 2011). High compaction degrees may be intentionally created to enhance slope stability, as a part of some national mandatory procedures (ACTON et al., 2011).

Soil bulk density is probably the most commonly employed soil physical quality indicator (ALVES; SUZUKI; SUZUKI, 2007) but there is a large set of soil quality indicators available and that need to be tested one against another on different soil conditions (ARSHAD; MARTIN, 2002). Among these, are the soil compressive behavior and the precompression stress. Each soil volume has a characteristic relation between applied pressures and the resultant deformation, termed the soil stress-strain relation, which is usually evaluated through the soil compression curve (HORN; LEBERT, 1994). Assessing the soil compressive behavior has considerably grown in importance in recent years, as it may be used not only in diagnostics, but also in prevention strategies (DIAS JUNIOR et al., 2007). The precompression stress is determined from the soil compression curve (CAVALIERI et al., 2008)and represents the maximum stress that may be applied to the soil without additional compaction (KELLER et al., 2004; KOOLEN; KUIPERS, 1983). Precompression stress and soil compressive behavior have recently became more common on soil quality studies (IORI et al., 2012; MARTINS et al., 2012; PAIS et al., 2011). Significant changes on soil compressive behavior were observed by Lima et al. (2012) on soils reconstructed after coal mining with different plant covers, indicating its suitability for environmental quality studies on mine sites. Reconstructed mine soils may largely differ from the original soils on its intrinsic attributes, such as soil texture (SHRESTHA; LAL, 2011; ZIPPER et al., 2013) which is known to affect soil compressive behavior (SEVERIANO et al., 2013).

The aim of this work was to evaluate the soil compressive behavior on different sites affected by mining activities (overburden piles with reconstructed soils) and on other land uses from an inoperative iron mine in Sabará, MG, southeastern Brazil.

4. MATERIAL AND METHODS

This study employed samples from a landscape affected by iron mining on southeastern Brazil and evaluated different land uses that are currently present on the Córrego do Meio mine, localized on the city of Sabará, Minas Gerais (MG) state. Mine closure procedures started on 2006, when overburden and rock spoil piles were stabilized and vegetated. The material, comprised mostly of topsoil, phyllite and BIF (banded iron formation) fragments, was distributed on steep slope berms. After topographic and geotechnical stabilization, piles were vegetated and they currently present a dense ground cover provided by the aggressive *Melinis minutiflora* grass and scarcely spaced leguminous shrubs. Reforestation attempts were made in the past as a part of environmental education projects with local schools (the mine was actually converted to a center for biodiversity research and conservation by Vale Co., its owner since the year 2000). Other land uses evaluated were also within the mine property, and included (i) areas with mostly secondary semideciduous Atlantic forest (Forest); (ii) sites where *Eucalyptus* sp. trees were planted but are now abandoned, with abundant bush growth under the canopy; (iii) sites with Cerrado formation (Brazilian savannah) that often presented abundant quartz gravel scattered within the soil mass. Samples were collected on three different points within each land use, that included three constructed piles (Piles 1, 2 and 3), the natural semideciduous forest (Forest), the *Eucalyptus* sp. forest (Eucalypt) and the Cerrado formation (Cerrado). Soil characterization from these sites can be seen on table 1.

Table 1. Soil granulometric distribution, particle density (Dp) and soil organic carbon content (SOC) on the evaluated land uses and soil depths (0-5 and 20-25 cm) from Córrego do Meio iron mine, Sabará, MG, southeastern Brazil.

Land use	Clay	Sand			Silt	SOC	Dp	Clay	Sand			Silt	SOC	Dp
		Total	Coarse	Fine*			($g cm^{-3}$)		Total	Coarse	Fine*			($g cm^{-3}$)
	--------------------- $g\ g^{-1}$ ---------------							--------------------- $g\ g^{-1}$ ---------------						
	0-5 cm							20-25 cm						
Forest	348	231	80	151	421	27.7	2.56	381	205	61	144	414	21.3	2.65
Cerrado	316	293	108	185	391	22.2	2.67	348	226	60	166	426	13.7	2.76
Eucalypt	429	201	95	107	369	29.6	2.58	438	173	65	108	389	21.6	2.70
Pile 1	116	515	209	305	370	19.0	3.33	114	380	150	230	507	7.48	3.03
Pile 2	351	204	89	114	446	15.1	2.86	300	207	71	135	494	12.2	2.92
Pile 3	110	475	316	159	415	12.9	3.26	154	304	171	133	542	4.99	3.31

* Smaller than 0.25 mm equivalent diameter.

Undisturbed soil samples were collected on metal rings (diameter of 6.4 cm and height of 2.5 cm) with Uhland sampler. Six samples were collected at each sampling point, half at 0-5 cm and half at 20-25 cm, with a total of 36 undisturbed samples (6 land uses x 2 soil layers x 3 sampling points). Soil cores were wrapped on plastic film and covered with paraffin wax.

Samples were prepared at the laboratory, when the soil exceeding the ring volume was carefully removed. This sparing soil was air dried and sieved (2.0 mm opening) and then used on granulometric (pipette method), particle density (pycnometer method) and organic carbon content (wet combustion with $K_2Cr_2O_7$) analyses according to Brazilian standards (DONAGEMA et al., 2011).

Soil rings were slowly saturated with distilled water on plastic trays and then equilibrated to 10 kPa suction on porous plate extractors. After equilibrium, samples were used on confined drained uniaxial compression tests with compressed air consolidometers (S450 Dhurham Geoslope, USA). Pressures of 25, 50, 100, 200, 400, 800 and 1600 kPa were applied on sequence until 90% of maximum deformation was reached (determined by the square root of the time method)(TAYLOR, 1948). Samples were then oven dried (105-110° C for 48 h) and water content (GARDNER, 1986) and bulk density (BLAKE; HARTGE, 1986) were determined. Soil compression curves were represented with bulk density as a function of the applied pressure on logarithmic scale. Precompression stress was calculated from spreadsheets through linear regressions (DIAS JUNIOR; PIERCE, 1995). Bulk density, total porosity and air filled porosity were determined for each load using recorded strains and simple mass-volume calculations. Air filled porosity (AFP) was calculated as AFP = n - θ, where “n” is total porosity and “θ” is the water content on volume basis.

Water content at field capacity, bulk density and precompression stress values were used on analysis of variance and Skott-Knott comparison tests ($p < 0.05$). Data normalization was done by dividing bulk density, porosity and AFP at each load step by the initial value to better illustrate increments on attributes values during compression. Porosity and normalized data were represented graphically and the mean standard error was calculated from each three repetitions.

5. RESULTS AND DISCUSSION

Water content at 10 kPa suction was not statistically different among land uses on the 20-25 cm depth, but it was significantly lower on Piles 1 and 3 on the 0-5 cm layer (0.28 and 0.26 $cm^3\ cm^{-3}$ respectively), with coarser texture (silt loam) than the others (loam and clay loam). Initial bulk density values on the 20-25 cm layer were higher on Pile 3 (1.58 g cm^{-3}) and lower on Eucalypt (1.03 g cm^{-3}), with the rest of the treatments (Forest, Cerrado, Piles 1 and 2) falling within an intermediary class, not differing significantly from each other (averaging from 1.18 to 1.30 g cm^{-3}). On the 0-5 cm layer, three significantly distinct classes were also observed: (i) Forest and Eucalypt presented the lowest values (1.05 and 0.91 g cm^{-3} respectively); (ii) Piles 1 and 3 the highest ones (1.62 g cm^{-3} on average), and (iii) Cerrado and Pile 2 with intermediary values (1.15 and 1.25 g cm^{-3} respectively). When evaluating different materials commonly available for iron mine reclamation, Silva et al. (2006) found bulk density values (measured on graduated cylinder with disturbed samples) of 1.67 and 1.1 g cm^{-3} for BIF (banded iron formation) and phyllite saprolite. The values here reported on the 0-5 cm layer from Pile 1 and on Pile 3 are close to the values reported for BIF saprolite. On several recovered sites, the coarse sand fraction was dominated by BIF fragments, and the higher bulk density could be due to higher particle density allied to coarser texture. On the surface layer (0-5 cm) of reclaimed coal mine soils, Shrestha and Lal (2011) also found bulk density values close to these, ranging from of 1.40 to 1.69 g cm^{-3} on loam and sandy loam soils; while Barros et al. (2013) reported an average bulk density value of 1.33 g cm^{-3} after soil recovery from bauxite mining with clayey topsoil, which is actually close to what was fond on Pile 2, amended with larger contents of topsoil.

Table 2. Water content at 10 kPa suction (θ_{10kPa}) and bulk density values (Db) before compression (Dbi) and at each pressure (Db_{σ}, σ = applied pressure, kPa) on the two soil layers (0-5 and 20-25 cm) under different land uses on Córrego do Meio iron mine, Sabará, MG, southeastern Brazil.

	θ_{10kPa}	Dbi	Db_{25}	Db_{50}	Db_{100}	Db_{200}	Db_{400}	Db_{800}	Db_{1600}
Land uses	cm3 cm-3		--------------------------------------- $g\ cm^{-3}$ ---------------------------------------						
					0-5 cm				
Forest	0.32 Aa	1.05 Ca	1.05 Ca	1.08 Ca	1.13 Ca	1.21 Ca	1.32 Ca	1.42 Ca	1.53 Ca
Cerrado	0.33 Aa	1.15 Ba	1.15 Ba	1.18 Ba	1.23 Ca	1.30 Ca	1.40 Ca	1.48 Ca	1.58 Ca
Eucalypt	0.37 Aa	0.91 Ca	0.92 Ca	0.97 Ca	1.05 Ca	1.12 Ca	1.20 Ca	1.28 Ca	1.37 Da
Pile* 1	0.28 Bb	1.62 Aa	1.63 Aa	1.67 Aa	1.73 Aa	1.80 Aa	1.88 Aa	1.97 Aa	2.06 Aa
Pile 2	0.32 Aa	1.25 Ba	1.26 Ba	1.30 Ba	1.37 Ba	1.46 Ba	1.56 Ba	1.64 Ba	1.73 Ba
Pile 3	0.26 Bb	1.62 Aa	1.63 Aa	1.66 Aa	1.71 Aa	1.76 Aa	1.82 Aa	1.88 Aa	1.96 Aa

Table 2.Conclusion.

	20-25 cm								
Forest	0.36 Aa	1.21 Ba	1.21 Ba	1.23 Ba	1.26 Ba	1.32 Ba	1.41 Ba	1.50 Ba	1.60 Ba
Cerrado	0.36 Aa	1.18 Ba	1.19 Ba	1.21 Ba	1.26 Ba	1.33 Ba	1.42 Ba	1.51 Ba	1.61 Ba
Eucalypt	0.35 Aa	1.03 Ca	1.04 Aa	1.08 Ca	1.13 Ba	1.21 Ba	1.30 Ba	1.38 Ba	1.47 Ba
Pile 1	0.40 Aa	1.30 Bb	1.31 Bb	1.33 Bb	1.37 Bb	1.42 Bb	1.47 Ba	1.54 Bb	1.61 Bb
Pile 2	0.34 Aa	1.23 Ba	1.24 Ba	1.28 Ba	1.33 Ba	1.39 Ba	1.45 Ba	1.52 Ba	1.60 Ba
Pile 3	0.31 Aa	1.58 Aa	1.59 Aa	1.62 Aa	1.65 Aa	1.70 Aa	1.76 Aa	1.82 Aa	1.88 Aa

*constructed overburden piles

Capital letters compare land uses within the same soil layer (p<0.05 Skott-Knott test). Small letters compare soil layers within the same land use (p<0.05 Skott-Knott test).

Soil behavior during compression was somewhat homogenous considering the differences between the treatments, i.e. the values were ranked very similarly throughout the stress levels. Bulk density values were very similar between the two soil layers, 0-5 and 20-25 cm, except for Pile 1, which showed significantly higher values on the 0-5 cm layer in comparison to the 20-25 cm layer throughout the whole stress range.

The same trends were observable on compression curve graphics (Figure 1), while the normalized compression curves indicated that the relative amount of deformation was inversely related to the initial bulk density. On the 0-5 cm layer, samples from Forest and Eucalypt suffered a 50% increase on soil bulk density in comparison to samples from Piles 1 and 3, with an increase around 25% on bulk density during compression. On the 20-25 cm soil layer, the Eucalypt maintained the lowest bulk density values and Pile 3 the highest, while the other stood closer together. Bulk density increase was somewhat lower on this layer in comparison to the surface (0-5 cm) layer, being around 40% for Eucalypt, 35% for Forest and 20% for Pile 3. A bulk density value of 1.7 g cm^{-3} was suggested by Wilke (2010) as a critical limit above which only detrimental effects of soil compaction would arise for soil biological processes and soil organisms. The bulk density value above which Haigh (1995) suggests the need for intervention on reclaimed mine sites, that is 1.6 g cm^{-3}, would be easily exceeded by only small amounts of soil compaction on Pile 1 (0-5 cm) and on Pile 3 (both layers), although it seems unlikely that a single bulk density value may be suitable for the whole range of soil textures. The other land uses wouldn’t reach such a critical state not even with the highest applied pressures. When evaluating Latosols with different textures from the Cerrado region of Brazil, Severiano et al. (2011) observed that critical bulk density values, regarding macropore volume and the least limiting water range (an indicator that comprises water availability, aeration and resistance to penetration), were strongly related to soil texture. For soils with loam texture, critical bulk density values would be in the range of 1.6 and 1.75 g cm^{-3}, which is close to the aforementioned values. For soils with clay contents higher than 350 g g^{-1}, critical bulk density values would be lower than 1.6 g cm^{-3}. This value could be reached on the top layer (0-5 cm) of piles 1 and 3 with only 200 kPa pressure and would be exceeded with higher loads.

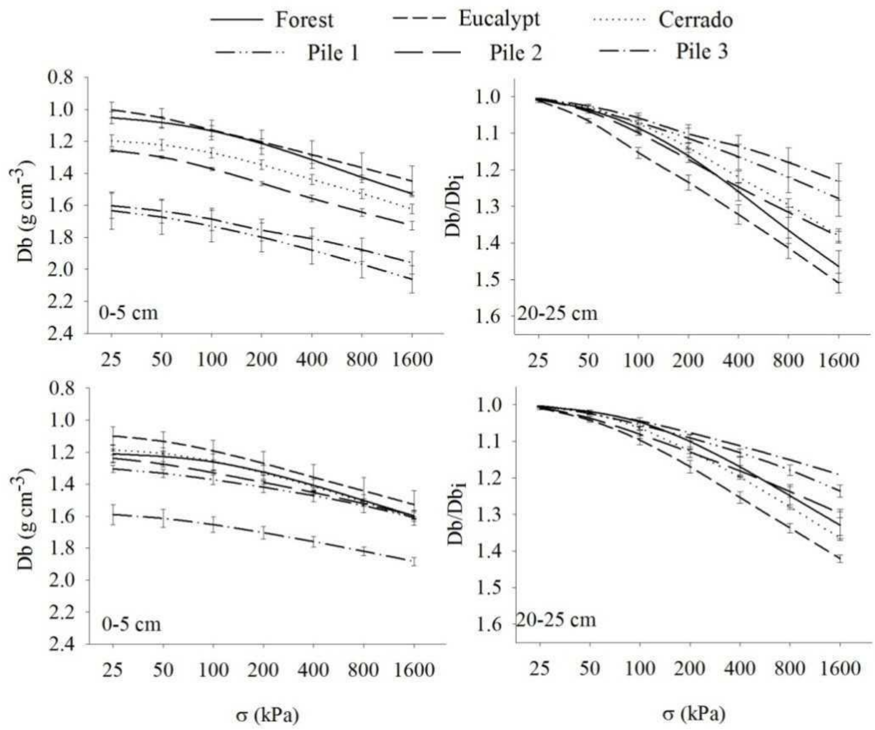

Figure 1. Soil compression curves (left) and normalized compression curves (right) for the different land uses evaluated and on two soil layers (0-5 and 20-25 cm) on Córrego do Meio iron mine, Sabará, MG, southeastern Brazil. Abscise axis on logarithmic scale. Vertical bars represent mean standard error.

Precompression stress was only significantly higher on Pile 1 (Figure 2), which also presented higher bulk density values on both soil layers (Table 2). Compression curves from this site were always apart from most of the rest and it suffered the smallest increases on bulk density during compression (Figures 1). There was a significant depth effect, with the 20-25 cm layer presenting higher values than the 0-5 cm layer. Precompression stress may be considered high in comparison to the values reported by Krümmelbeinand Raab(2010) on recovered coal mining sites, which ranged from 30 to 70 kPa (bulk density values ranging from 1.4 to 2.0 g cm^{-3}), but fall within the range determined by Lima et al. (2012), also on reclaimed coal mine soils, that averaged from 71 to 120 kPa (bulk density values averaging from 1.36 to 1.48 g cm^{-3}). Precompression stress was only slightly different between land uses (differences between soil layers were non-significant), indicating similar soil strength throughout these (Figure 2). However, soil response to any additional compaction would be very different. As can be seen from the compression curves, a given amount of compaction would be much more detrimental for the soil on Pile 3 and on surface layer (0-5 cm) from Pile 1 than on the rest of the soils, because bulk density is already close to proposed critical values of 1.6 and 1.7 g cm^{-3}(HAIGH, 1995; WILKE, 2010). It outlines the importance of linking strength parameters to soil structure and soil functioning, what was done with the soil stress-strain behavior assessed by the soil compression curve.

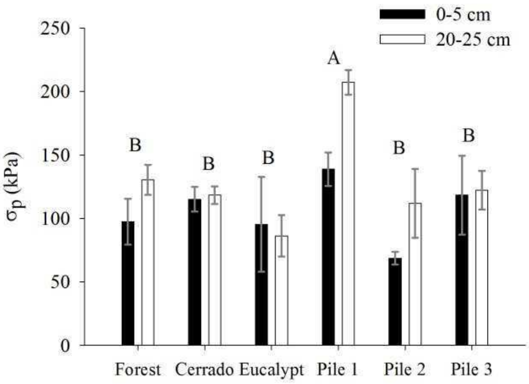

Figure 2. Soil precompression stress for the different land uses evaluated on the 0-5 and 20-25 cm layers on Córrego do Meio iron mine, Sabará, MG, southeastern Brazil. Capital letters compare land uses ($p<0.05$ Skott-Knott test). Vertical bars indicate mean standard error.

Changes on soil total porosity and air filled porosity during compression are represented on Figures 3 and 4 respectively. Total porosity was usually higher on Eucalypt during most of the compression path, decreasing to 70% of the original value at the end of the test. On the 20-25 cm layer, soil from Piles 1 and 3 showed the smaller reduction on porosity during compression, reaching near 85% of the initial value, as their coarser texture and higher bulk density already resulted on lower porosity.

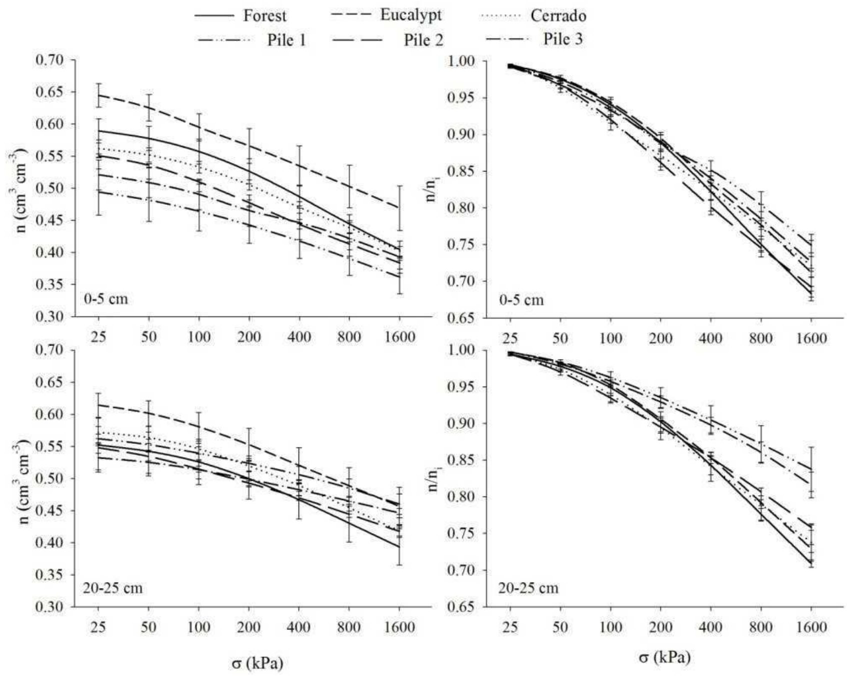

Figure 3. Changes on soil total porosity (n) and on normalized porosity (n/n_i) during confined uniaxial compression tests (samples at 10 kPa water suction) for the different land uses evaluated on the 0-5 and 20-25 cm layers on Córrego do Meio iron mine, Sabará, MG, southeastern Brazil. Abscise axis on logarithmic scale. Vertical bars indicate mean standard error.

Air filled porosity (AFP) decreased during compression (Figure 4), but detrimental values, below 0.10 or 0.14 cm^3 cm^{-3}(REYNOLDS et al., 2009) were generally only obtained with high pressures. Initial values ranged from 0.20 to 0.30 cm^3 cm^{-3} on the 0-5 cm layer, and were somewhat lower on the 20-25 cm layer, ranging from 0.15 to 0.25 cm^3 cm^{-3}. On the 0-5 cm layer, it took almost 400 kPa pressure to reduce AFP to detrimental values on Piles 1 and 3, and almost 800 kPa on the other land uses. On the 20-25 cm layer, Pile 3 suffered the smallest decrease on AFP, and Forest, the highest, but both showed detrimental conditions of soil air porosity from 200 kPa on, while on the other land uses it took near 400 kPa (Eucalypt and Pile 2) and 800 kPa (Cerrado and Pile 1).

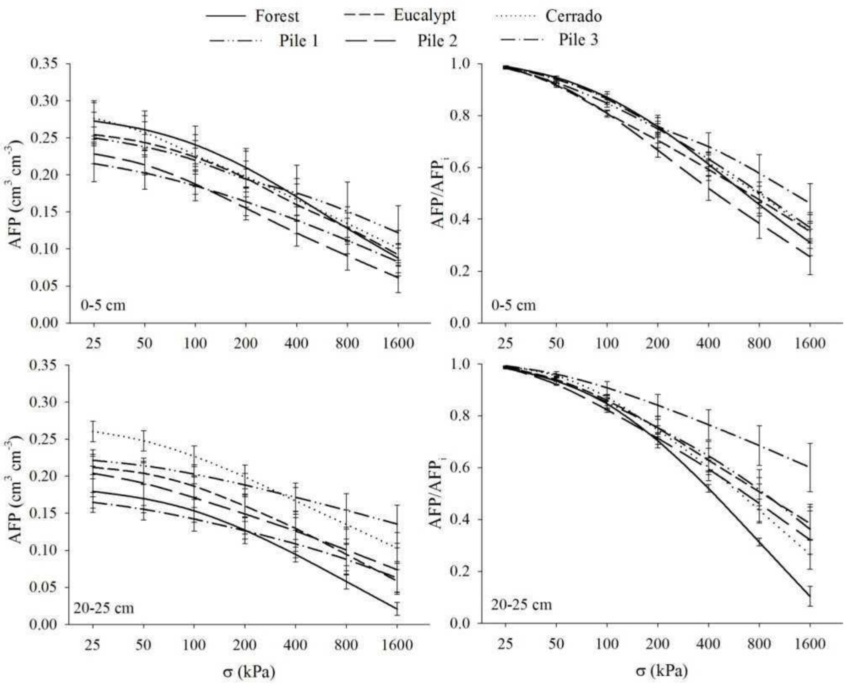

Figure 4. Changes on soil air filled porosity (AFP) during confined uniaxial compression tests (samples at 10 kPa water suction) for the different land uses evaluated on the 0-5 and 20-25 cm layers on Córrego do Meio iron mine, Sabará, MG, southeastern Brazil. Abscise axis on logarithmic scale. Vertical bars indicate mean standard error.

Soil bulk density, total porosity and AFP values at any pressure were strongly correlated to the initial values, while bulk density and total porosity were also strongly related to the water content (Table 3). This is probably because of differences on soil texture: coarser soils had lower water content values and higher initial bulk density values, while total porosity was higher on soils with more clay, that also had the highest water contents on firld capacity.

Table 3. Pearson correlation coefficient betwee bulk density (Db), total porosity (n) air filled porosity (AFP) at each load step (σ) and the soil water content and the initial values (Dbi, ni, AFPi).

Comparison	σ (kPa)						
	25	50	100	200	400	800	1600
Db x θ	-0.666	-0.670	-0.679	-0.694	-0.715	-0.741	-0.760
n x θ	0.652	0.932	0.921	0.901	0.835	0.741	0.636
AFP x θ	-0.328	-0.343	-0.385	-0.410	-0.469	-0.490	-0.489
Db x Dbi	0.999	0.999	0.995	0.991	0.985	0.976	0.968
n x ni	0.999	0.675	0.709	0.748	0.752	0.723	0.672
AFP x AFPi	0.999	0.995	0.975	0.939	0.847	0.722	0.601

6. CONCLUSIONS

Water content at 10 kPa suction varied significantly between land uses, being smaller on the silt loam soil layers (0-5 cm from Piles 1 and 3). Soil bulk density was significantly different between land uses and soil layers. It was higher on Piles 1 and 3 (12% clay on average) and lower on Forest and Eucalypt (clayey soils). Cerrado and Pile 2, constructed with topsoil rich material, were similar.

Soil behavior during compression was strongly related to soil initial bulk density and to soil moisture, to a lesser extent. Soil strength was different between the evaluated land uses, being higher on Pile 1, which showed the highest bulk density values on both soil layers.

Additional compaction on Piles 1 and 3 would result in detrimental bulk density conditions, while on the rest of the land uses, higher pressures (>400 kPa) would be needed to induce severe soil compaction.

7. ACKNOWLEDGMENTS

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(VERSÃO PRELIMINAR)

ARTIGO 3 Load bearing capacity on soils disturbed by iron mining and on other land uses in Sabará, Minas Gerais, Southeastern Brazil

Capacidade de suporte de carga em solos afetados pela mineração de ferro em Sabará, Minas Gerais, sudeste do Brasil

Diego Tassinari[1]
Moacir de Souza Dias Junior[2]
Geraldo César de Oliveira[2]
Wellington Willian Rocha[3]
Fátima Maria de Souza Moreira[2]
Gustavo de Paula Silva[4]

ARTIGO FORMATADO DE ACORDO COM A NORMA PARA SUBMISSÃO DO PERIÓDICO CIÊNCIA E AGROTECNOLOGIA.

[1] Masters graduate student, Departamento de Ciência do Solo (DCS), Universidade Federal de Lavras, Lavras-MG.
[2] Professor, DCS, UFLA, Lavras-MG.
[3] Professor, Departamento de Agronomia, Universidade Federal dos Vales do Jequitinhonha e Mucuri, Campus JK, Diamantina, MG.
[4] Undergraduate student, UFLA.

1. ABSTRACT

Soil compaction is a common occurrence on reconstructed mine soils and may lead to poor soil physical quality. Soil strength attributes, such as the precompression stress, are used for soil compaction studies and soil quality evaluation. The aim of this work was to determine precompression stress values from different land uses (four natural Atlantic forest sites, four Cerrado formation sites, two canga vegetation sites and four planted *Eucalyptus* sp. forest sites, respectively Forest, Cerrado, Canga and Eucalypt) and from reconstructed soils on overburden piles (four sites, termed Pile) after iron mining for determining the load bearing capacity models (LBCM) at each site. Soil precompression stress decreased exponentially with increase on water content, but rate of decrease greatly varied between land uses. Water content alone explained from 60 to 88% of variation on precompression stress. It was observed a significant correlation between the curves intercept ("a" parameter) and angular coefficient ("b" parameter) and soil clay and silt content, respectively. Silt loams and loams from constructed piles, the silt richer soils, presented flatter curves for the LBCM, which means a smaller rate of decrease on precompression stress with increase on water content. Soils with higher clay content presented higher precompression stress i.e. values (within comparable angular coefficient values). On LBCM curves from Pile sites precompression stress values usually were under 300 kPa (except for Pile 3 at 0-5 cm). The Canga 1 LBCM curve was shaped similarly to the ones from Pile sites. Eucalypt 3+4 presented the highest bearing capacity, with precompression stress values ranging from near 150 kPa (close to 0.50 g g^{-1} water content) to almost 500 kPa (0.07 g g^{-1} water content).

Index terms: precompression stress, uniaxial compression test, mine soil reclamation.

1 RESUMO

A compactação do solo é de ocorrência comum em áreas de mineração recuperadas e pode ocasionar condições de baixa qualidade física do solo. Atributos de força do solo, como a pressão de pré-consolidação, têm sido aplicados em estudos de compactação e de qualidade do solo. O objetivo deste trabalho foi determinar a pressão de pré-consolidação em diferentes usos da terra (quatro locais de floresta semidecidual Atlântica nativa, quatro locais com formações de Cerrado, dois locais com vegetação de canga e quatro locais com floresta plantada de *Eucalyptus* sp., respectivamente Floresta, Cerrado, Canga e Eucalipto) e também em solos reconstruídos em pilhas de estéril (em quatro locais, denominado Pilha) após a mineração de ferro para quantificação da capacidade de suporte de carga nos diferentes locais. A pressão de pré-consolidação decaiu exponencialmente com o aumento do conteúdo de água, mas a taxa de decaimento foi diferente para os diferentes usos da terra. O conteúdo de água explicou de 60 a 88% da variação nos valores de pressão de pré-consolidação. Foi observada correlação significativa entre o intercepto (parâmetro b) e o coeficiente angular (parâmetro a) das curvas com os teores de argila e silte, respectivamente. Os solos de textura franca a franco-arenosa das pilhas de estéril, os solos mais ricos em silte, apresentaram curvas menos inclinadas, que significa uma menor taxa de decaimento da pressão de pré-consolidação com o aumento no teor de água. Solos com maiores teores de argila apresentaram maiores valores de pressão de pré-consolidação (para condições comparáveis de coeficientes angulares). Nas curvas dos locais de Pilhas, a pressão de pré-consolidação esteve em geral abaixo de 300 kPa (exceto pra a Pilha 3 em 0-5 cm). A Canga 1 apresentou formato do modelo semelhante aos solos dos locais de Pilha. O Eucalipto 3+4 apresentou a maior capacidade de

suporte de carga, com valores de pressão de pré-consolidação variando de 150 kPa(umidade de 0.50 g g^{-1}) a quase 500 kPa (umidade de 0.07 g g^{-1})

Termos para indexação: pressão de pré-consolidação, ensaio de compressão uniaxial, recuperação de áreas mineradas.

2 INTRODUCTION

Materials used for land reclamation after mining activities are often prone to compaction or provide poor soil physical quality (PARADELO; MOLDES; BARRAL, 2008; ZIPPER et al., 2013). In addition, reclamation practices, which usually involve heavy bulldozers and excessive soil surface grading (ZIPPER et al., 2011), also contribute to severe compaction on mined soils. Soil compaction is also seem as a geotechnical solution for slope stability issues, and may be even mandatory on some national regulations (ACTON et al., 2011). Therefore, soil compaction has long been a problem on mined soil restoration, usually demanding alleviation practices, the most common being deep ripping (ASHBY, 1997; CASSELMAN et al., 2006; KINYUA et al., 2010; SKOUSEN et al., 2009; SZOTA et al., 2007; WILSON-KOKES; SKOUSEN, 2014).

Soil compaction significantly affects soil strength (CHAPLAIN et al., 2011; HAMZA; ANDERSON, 2005). Precompression stress is a soil strength property widely employed on environmental and agricultural soil research (ARAUJO JUNIOR et al., 2011; PAIS et al., 2011; SEVERIANO et al., 2008). Precompression stress is determined from soil compression curves (CAVALIERI et al., 2008), which are a representation of the soil stress-strain relation (HORN; LEBERT, 1994). Soil precompression stress and other soil strength properties are strongly affected by water content (KONDO; DIAS JUNIOR, 1999). Load bearing capacity models were developed to express the exponential decrease on soil precompression stress as a function of water content (DIAS JUNIOR, 1994; DIAS JUNIOR et al., 2005, 2007) or water potential (OLIVEIRA et al., 2003, SEVERIANO et al., 2013). They are being currently used for soil physical quality research on different natural and agricultural ecosystems (IORI et al., 2013; MARTINS et al., 2012; PIRES et al., 2012).

Soil structure and physical properties are strongly affected by both texture (SEVERIANO et al., 2013) and clay mineralogy (FERREIRA; FERNANDES; CURI, 1999a, 1999b) on tropical soils. Latosols with blocky structure present higher load bearing capacity than Latosols with granular structure (AJAYI et al., 2009; SEVERIANO et al., 2013). Blocky structure is favored by clay mineralogy essentially kaolinitic, while higher gibbsite contents favor granular structure (FERREIRA; FERNANDES; CURI, 1999b). Granular structure is better expressed on Latosols with higher clay contents, whereas Latosols with coarser texture tend to present blocky structure (SEVERIANO et al., 2013).

3 MATERIAL AND METHODS

Soil samples were collected at the Córrego do Meio iron mine in the city of Sabará, MG, southeastern Brazil. This mine started its activities back in the 1940’s and carried on until 2006, when it was decommissioned and became inoperative. Vale Co., its owner since 2000, converted the mine into a biodiversity research and conservation center, termed CeBio. Environmental education activities were held in CeBio with local schools and its plant nursery provided tree seedlings for reforestation attempts. Regardless of the efforts made, the overburden piles, constructed mostly with phyllite and BIF (banded iron formation) saprolite, presented by the time of sampling only a thick *Melinis* *minutiflora* grass coverage. Despite of its excellent ground cover, this exotic and aggressive grass is currently invading natural Cerrado areas (ROSSI; FIGUEIRA; MARTINS, 2010).

Four overburden piles were sampled (termed Piles 1, 2, 3, 4) on two soil layers, 0-5 and 20-25 cm (except for Pile 2, from which only the surface layer could be sampled). The other land uses evaluated were also sampled on different sites, and included: (i) four sites with Brazilian Atlantic forest formations (termed Forest 1, 2, 3, 4); (ii) four sites on Cerrado (Brazilian savannah) formations (termed Cerrado 1, 2, 3, 4); (iii) four *Eucalyptus* sp. forest sites (termed Eucalypt 1, 2, 3, 4), which haven't been managed and now present a rich shrub stratum growing beneath the tree canopy; (iv) and two sites with a quite rare plant formation (only 200 km^2 across Brazil) locally named "canga" (termed Canga 1 and 2), a highly diverse ecosystem that grows on ferruginous fields and on stony soils rich in iron (SKIRYCZ et al., 2014). Samples were also collected from two soil layers, 0-5 and 20-25 cm, except on Canga 1 and 2, which were only sampled on the surface layer. Chemical and physical characterization can be seen on table 1.

Table 1. Soil granulometric distribution (clay, sand and silt contents), particle density (Dp) and organic carbon content (SOC) from Córrego do Meio iron mine, Sabará, MG, southeastern Brazil.

	Dp [1]	Clay	Sand	Silt	SOC	Dp [1]	Clay	Sand	Silt	SOC
		---------- g kg^{-1} ----------					---------- g kg^{-1} ----------			
	0 - 5 cm					20 - 25 cm				
F1	2.54	406	172	422	24.9	2.65	433	156	411	16.6
F2	2.44	369	264	367	18.2	2.56	431	217	352	19.0
F3	2.53	348	226	427	26.7	2.62	351	240	410	24.9
F4	2.62	290	295	415	31.5	2.67	359	220	421	22.3
CE1	2.66	366	267	367	28.6	2.75	391	207	402	14.4
CE2	2.63	268	307	425	18.2	2.85	321	240	439	12.2
CE3	2.73	313	306	381	19.8	2.78	332	232	436	14.4
CE4	2.65	236	343	422	16.6	2.74	273	281	445	10.8
E1	2.65	243	436	321	21.5	2.66	335	277	388	12.2
E2	2.61	336	320	344	26.7	2.75	409	247	345	16.6
E3	2.55	420	117	463	29.5	2.61	386	133	481	24.0
E4	2.58	532	166	302	32.5	2.74	519	139	342	24.0
CA1	3.56	172	651	176	64.9	-	-	-	-	-
CA2	3.60	294	466	240	30.5	-	-	-	-	-
P1	3.33	116	515	370	19.0	3.03	114	380	507	7.5
P2	2.82	107	156	737	14.4	-	-	-	-	-
P3	2.86	351	204	446	15.1	2.92	300	207	494	12.2
P4	3.26	110	475	415	12.9	3.31	154	304	542	5.0

[1] g cm^{-3}.

F: Forest. CE: Cerrado. E: Eucalypt. CA: Canga. P: Pile. The number (1, 2, 3, 4) indicates the respective site.

Undisturbed soil samples were collected on metal rings (6.4 cm diameter and 2.5 cm height) with and Uhland sampler. From each layer, six samples were collected on Forest, Cerrado, Eucalypt and Canga sites, while eight samples were collected on Pile sites. Samples were taken from the same pit at each site, and then wrapped on plastic film and covered with paraffin was prior to transportation.

Laboratory work began with removal of exceeding soil from the volumetric rings, which was air dried and sieved (2.0 mm) and then used on granulometric (pipette method), particle density (pycnometer with distilled deaerated), and soil organic carbon content (wet combustion with $K_2Cr_2O_7$) analyses according to Brazilian standards (DONAGEMA et al., 2011).

Soil cores were saturated and/or air dried until the desired water content (ranging from 0.05 to 0.5 cm^3 cm^{-3}) was reached prior to uniaxial compression tests. These were performed on compressed air consolidometers (S-450 Durham Geo Slope, USA), being applied stresses of 25, 50, 100, 200, 400, 800, and 1600 kPa, standard sequence according to Bowles (1986) until 90% of maximum deformation was obtained (TAYLOR, 1948), what took from 4 to 15 minutes per load step. After load removal, soil cores were oven dried (105-110 °C for 48 hours). Precompression stress was calculated according to Dias Junior and Pierce (1995). Precompression stress (σ_p) and water content (U) values were used for generating the load bearing capacity models through fitting to the equation $\sigma_p = 10^{(a + bU)}$ (DIAS JUNIOR, 1994). Regressions and graphical procedures were performed on the software Sigma Plot (Jandel Scientific). Equations were compared to each other with the procedure for generalized linear models from Snedecor and Cochran (1989) that tests if differences on the equation parameters are significant.

4 RESULTS AND DISCUSSION

Statistical comparison of the generated models can be seen on Tables 2 to 4. Forest (Table 2), Cerrado (Table 2) and Eucalypt (Table 3) behaved alike. Differences between soil layers were non-significant, so data from both layers were merged into one data set per site. Sites were compared on pairs. On these three land uses, two groups with two sites each were divided. On Forest, they were non-significant, so all data were merged into one single data set for this land use. On Cerrado and Eucalypt, the two groups were significantly different and were kept apart on further comparisons.

Table 2. Comparison of load bearing capacity models ($\sigma_p = 10^{(a+bU)}$) from Forest and Cerrado sites. H: data homogeneity. ANG: angular coefficient ("b" parameter). INT: intercept ("a" parameter).

Comparison	H	ANG	INT	Comparison	H	ANG	INT
$F1_{0-5}$ x $F1_{20-25}$	H	ns	ns	C1S x C1P	H	ns	ns
$F2_{0-5}$ x $F2_{20-25}$	H	ns	ns	C2S x C2P	H	ns	ns
$F3_{0-5}$ x $F3_{20-25}$	H	ns	ns	C3S x C3P	H	ns	ns
$F3_{0-5}$ x $F3_{20-25}$	H	ns	ns	C4S x C4P	H	ns	ns
New models were generated for each site with data from both soil layers.				New models were generated for each site with data from both soil layers.			
F1 x F2	H	**	*	C1 x C2	H	ns	ns
F1 x F3	H	ns	ns	C1 x C3	H	ns	*
F1 x F4	H	ns	ns	C1 x C4	H	ns	*
F2 x F3	H	ns	ns	C2 x C3	H	ns	ns
F2 x F4	H	ns	ns	C2 x C4	H	ns	ns
F3 x F4	H	*	ns	C3 x C4	H	ns	ns
Sites were distributed in two sets of two groups, F1+F3 and F2+F4, and F1+F4 and F2+F3				Sites were distributed in two groups, C1+C2 and C3+C4			
F1+F3 x F2+F4	H	ns	ns	C1+C2 x C3+C4	H	**	ns
F1+F4 x F2+F3	H	ns	ns				

*Significant at 5%. **Significant at 1%. ns: non-significant.
F: Forest. CE: Cerrado. The number (1, 2, 3, 4) indicates the respective site.

The resultant models can be seen on Figure 1 and are compared statistically on Table 4. The models from Pile sites presented significant differences between soil layers, so further comparison took into account each site and layer on a separated model. The same was done with the Canga sites, that were statistically different and remained apart.

Table 3. Comparison of load bearing capacity models ($\sigma_p = 10^{(a+bU)}$) from Eucalypt, Canga and Pile sites. H: data homogeneity. ANG: angular coefficient ("b" parameter). INT: intercept ("a" parameter).

Comparison	H	ANG	INT
E1S x E1P	H	ns	ns
E2S x E2P	H	ns	ns
E3S x E3P	H	ns	ns
E4S x E4P	H	ns	ns
New models were generated for each site with data from both soil layers.			
E1 x E2	H	ns	ns
E1 x E3	H	*	**
E1 x E4	H	*	**
E2 x E3	H	ns	*
E2 x E4	H	ns	**
E3 x E4	H	ns	ns
Sites were distributed into two groups, E1+E2 and F3+F4.			
E1+E2 x E3+E4	H	ns	**
CA1 x CA 2	H	*	ns
P1S x P1P	H	**	**
P3S x P3P	H	*	ns
P4S x P4P	H	ns	*

*Significant at 5%. **Significant at 1%. ns: non-significant.
E: Eucalypt. CA: Canga. P: Pile. The number (1, 2, 3, 4) indicates the respective site.

Soil from Eucalypt 3+4 showed the highest load bearing capacity among undisturbed soils (Figure 1), followed by Cerrado 1+2 and Forest, which did not differ significantly from each other (Table 3). The soils with the lowest strength values were Eucalypt 1+2 and Canga 2, which also did not differ significantly from each other (Table 4). Canga 1 showed a very distinct behavior, with a much flatter curve, presenting the lowest value (in modulus) for load bearing capacity model angular coefficient, 0.87.

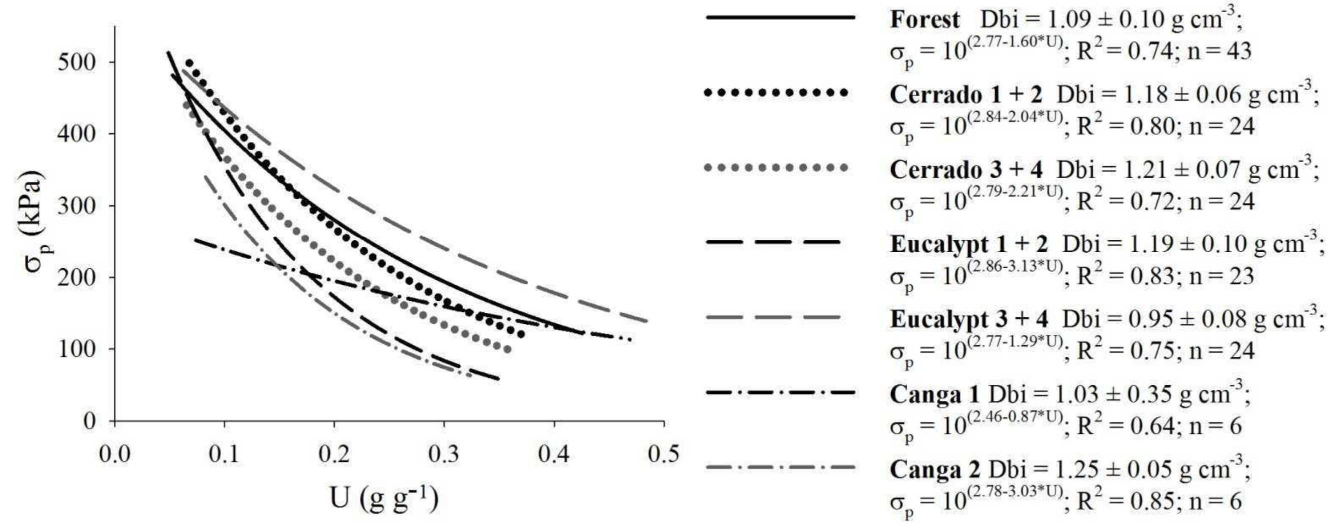

Figure 1. Load bearing capacity models from the soils under natural vegetation and from Eucalypt. σ_p: precompression stress (kPa). U: soil water content (g g^{-1}). Dbi: initial bulk density. n: number of samples on each model.

Table 4. Comparison between load bearing capacity models ($\sigma_p = 10^{(a+bU)}$) from the groups derived from Table 2. Cells on the above right compare the angular coefficients ("b" parameter), while cells on the bottom left compare the intercept ("a" parameter).

	Forest	CE1+CE2	CE3+CE4	E1+E2	E3+E4	CA1	CA2
Forest	-	ns	ns	**	ns	**	ns
CE1+CE2	ns	-	ns	*	ns	**	ns
CE3+CE4	**	*	-	ns	ns	**	ns
E1+E2	**	**	*	-	**	**	ns
E3+E4	ns	*	**	**	-	*	**
CA1	ns	ns	ns	ns	*	-	ns
CA2	**	**	*	ns	**	*	-

Angular coefficient (b)

Intercept (a)

*Significant at 5%. **Significant at 1%. ns: non-significant.
F: Forest. CE: Cerrado. E: Eucalypt. CA: Canga. The number (1, 2, 3, 4) indicates the respective site.

Some soils from several Pile sites also presented flattened curves as the one from Canga 1 (Figure 2). Load bearing capacity on the surface layer (0-5 cm) was higher on Piles 3and 2, while on the 20-25 cm layer higher values were observed on Pile 1. Differences between the 20-25 cm layer from Pile 4 and Pile 3 were non-significant (Table 5). Pile 4 at 0-5 cm layer showed the lowest bearing capacity, with precompression stress values below 200 kPa throughout the whole moisture range.

Table 5. Comparison between load bearing capacity models ($\sigma_p = 10^{(a+b*U)}$) from the Pile sites. Cells on the above right compare the angular coefficients ("b" parameter), while cells on the bottom left compare the intercept ("a" parameter).

	0-5 cm			
	P1	P2	P3	P4
P1	-	**	ns	ns
P2	**	-	**	ns
P3	*	*	-	**
P4	*	**	**	-

	20-25 cm		
	P1	P3	P4
P1	-	ns	ns
P3	**	-	ns
P4	**	ns	-

*Significant at 5%. **Significant at 1%. ns: non-significant.
P: Pile. The number (1, 2, 3, 4) indicates the respective site.

Intercept values ("a" parameter from the load bearing capacity model) ranged from 2.86 (Eucalypt 1+2) to 2.34 (Pile 4 at 20-25 cm), while the angular coefficient ("b" parameter) varied within a wider range, from -0.62 (Pile 1 at 20-25 cm) to -3.77 (Pile 3 at 0-5 cm).

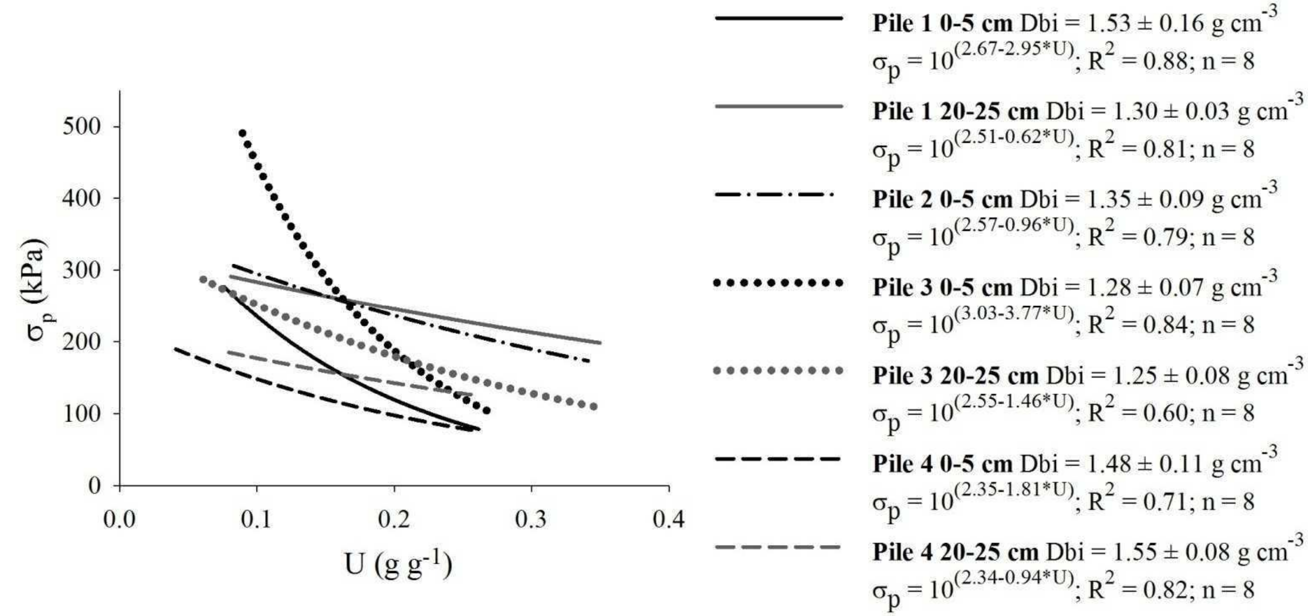

Figure 2. Load bearing capacity models from the reconstructed soils on overburden piles. σ_p: precompression stress (kPa). U: soil water content (g g^{-1}). Dbi: initial bulk density. n: number of samples on each model.

Soil texture appears to be exerting some control on load bearing capacity from these soils. The “a” parameter, termed the intercept, was positively correlated to clay content (Table 6) on a highly significant level ($r = 0.807$). This indicates that the higher the clay content, the higher the load bearing capacity model stands on the ordinate axis. Comparing models with similar angular coefficients, the higher the intercept value, than the higher the load bearing capacity would be throughout the whole moisture range. However, when both intercept and angular coefficient are different, comparison becomes more difficult. For example, Pile 3 at 0-5 cm showed the highest intercept value among the constructed soils, but its angular coefficient was also the highest (on modulus). Therefore, its load bearing capacity model started high above the others on the ordinate axis, but it also decreased on a much higher rate than the other curves, reaching lower precompression stress values at higher water contents.

The relation between soil strength and soil texture has been described in contradictory ways. For example, Severiano et al.(2013) found that clay content and soil load bearing capacity on Latosols from the Brazilian Cerrado (mostly Ustox) were inversely related. When evaluating the overall susceptibility of subsoils in Europe to compaction, Jones, Spoor and Thomasson (2003) employed a classification system which considered fine textured soils less susceptible to compaction than coarse the textured ones. The present results indicate that such comparisons should take into account the change on load bearing capacity with variation on water content. The overall trend we observed with the present data was that the more clayey soils had higher precompression stress values at low water contents (higher intercept value), but the load bearing capacity rapidly decreased with increase on soil moisture (higher angular coefficient on modulus). The loam, silty loam and sandy loam soils, on the other hand, generally presented flatter curves, with smaller angular coefficients (in modulus). Indeed, the angular coefficient was significantly related to silt content (Table 6). When water content was low, these soils generally presented lower precompression stress values than the more clayey soils, but they also presented a lower rate of decrease on strength with increase on moisture.

Table 6. Pearson correlation coefficient between the load bearing capacity model ($\sigma_p = 10^{(a+b*U)}$) intercept (a) and angular coefficient (b) and some soil characteristics.

	a	b
Dp	-0.524	-0.032
Clay	0.807**	0.471
Sand	0.003	0.337
Silt	0.397	0.659*
SOC	0.021	-0.068
Dbi	-0.439	0.107

Dp: particle density. Di: initial bulk density. SOC: soil organic carbon content. * and **: significant at 5 and 1%, respectively, in bilateral *t* test.

In general, higher intercept and higher angular coefficient (on modulus) values indicate higher load bearing capacity when the soil is dry and low strength when water content is high. This was the case for Eucalypt 1+2, Canga 2 and Pile 3 at 0-5 cm. When the intercept is not much high and the angular coefficient is low (on modulus), the load bearing capacity model has a flatten curve and soil strength may be comparably lower on the dry soil and higher on the moist soil (in comparison to a curve with the previously described behavior). This was the case for Canga 1 and Pile 3 at 20-25 cm. When both parameters have lower values, load bearing capacity is usually lower throughout the whole moisture range, what was the case for Pile 4 at both 0-5 and 20-25 cm.

5 CONCLUSIONS

Soil water content alone explained from 60 to 88% of variation on precompression stress (as given by the load bearing capacity models R^2).

Soil load bearing capacity models were significantly different between the evaluated land uses. Curves from Pile sites tended to be flatter and precompression stress values usually were under 300 kPa (except for Pile 3 0-5 cm). The Canga 1 curve was shaped similarly to ones from Pile sites. Eucalypt 3+4 presented the highest bearing capacity, with precompression stress values ranging from near 150 kPa (close to 0.50 g g^{-1} water content) to almost 500 kPa (0.07 g g^{-1} water content).

The load bearing capacity models fitting parameters intercept and angular coefficient were significantly related to clay and silt contents, respectively.

The higher the clay content, the higher the intercept and the higher the curve position on the ordinate axis. Higher the silt contents were related to curves becoming flatter.

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