Size effects on creep of unsaturated mine waste rock

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Abstract: In the long term, high mine waste rock piles are subjected to variable environmental conditions which have an impact on their time-dependent deformation. In order to characterize the compressibility, small-scale samples are usually tested. However, the results are affected by size effects due to particle crushing. Whereas previous studies have demonstrated that coarser samples show higher compressibility, the influence of size effects on time-dependent deformation is still poorly understood. The main objective of this paper is to identify the effects of particle size and suction on time-dependent deformation of unsaturated mine waste rock. We carried-out large and standard-sized oedometric compression tests on parallel graded samples. Results show that the coarser the material, the higher the amount of grain crushing, which is reflected in a larger compressibility. More interestingly, this paper present for the first time experimental evidence of size effects on creep strains, which significantly increase with particle size.

Introduction

Large volumes of waste rock (WR) are generated in open pit mines. WR is characterized as coarse oversized well-graded rockfill and is stored in piles that can reach hundreds of meters high (Valenzuela et al., 2008; Aubertin et al., 2002; Hawley and Cunning, 2017; Aubertin et al., 2021). The mechanical behavior of coarse crushed rocks has been largely studied in the past on small scale samples using the scalping or the parallel grading techniques (Marsal, 1967; Marachi et al., 1969; Linero et al., 2007; Ovalle et al., 2020; Girumugisha et al., 2024). Nevertheless, scale-samples are affected by size effects due to particle crushing, with decreasing dilatancy and peak shear strength, and increasing compressibility (Marachi et al., 1969; Alonso et al., 2005; Ovalle and Dano 2020). Experimental evidence has demonstrated that the coarser the rock particle, the higher the probability of presenting flaws, thus decreasing particle strength with increasing size. Fragmentation is triggered by crack propagation and preceded by the Stress Corrosion Cracking (SCC) mechanism (Atkinson, 1984; Oldecop and Alonso, 2003, 2007), involving tip crack corrosion by humidity. This phenomenon seems to cause time-delayed particle crushing and explain creep deformation in granular assemblies (Lade & Karimpour, 2010; Zhang &

Buscarnera, 2017; Ovalle, 2018). Despite of this, the effect of particle size on creep deformation remains poorly understood and empirical evidence on the impact of humidity are rare.

The main objective of this paper is to evaluate the effects of particle size and suction on time-dependent deformation of unsaturated mine waste rock. Saturated and unsaturated oedometric large and standard size oedometric tests carried-out on parallel graded samples are presented. The effects of stress, total suction and particle size on time-dependent deformation are described and discussed.

Mine waste rock material

Waste rock material was sampled in an iron mine of Pilbara region in Western Australia. The WR is composed by alluvial and colluvial sediments of iron deposits, formed after weathering, erosion and transportation of Banded Iron Formations rocks (Linero et al., 2017). The specific gravity is $Gs = 3.87$ for particles finer than 4.75 mm, and $Gs = 3.32$ in coarser fractions. X-ray Diffraction showed that prevalent minerals are Quartz and Hematite. As shown in Figure 1, two parallel graded samples were prepared with a coefficient of uniformity C_u =2, with maximum and minimum particle sizes of 50 and 9.5 mm for the coarse gravelly sample (G), and 2.36 and 0.3 mm for the sandy sample (S).

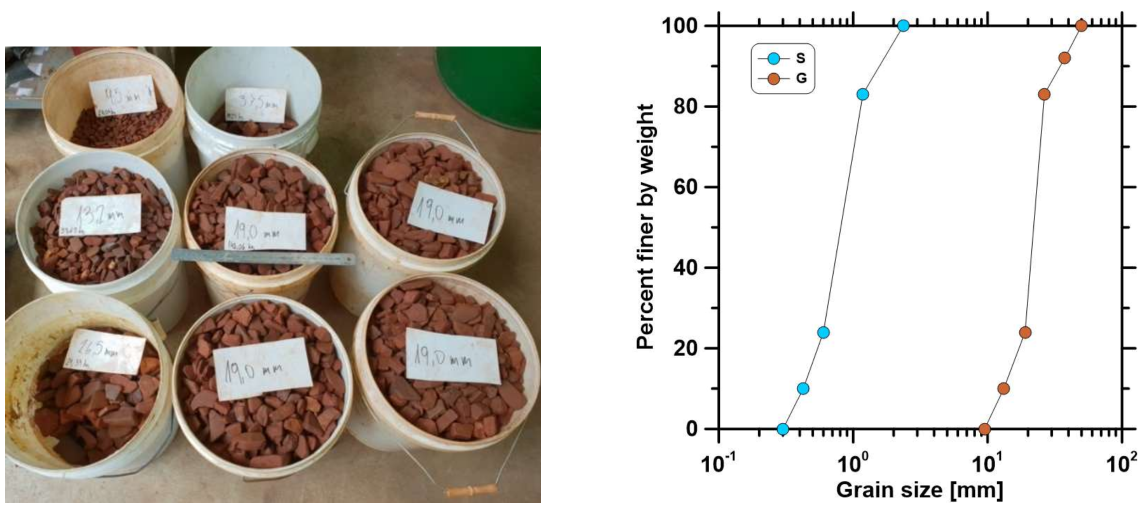

Figure 1: (a) Waste rock materials and (b) particle size distributions of S and G samples.

Oedometric tests

Sandy specimens (S) were tested in a standard oedometer cell of 48 mm in diameter and 20 mm in height. Samples were prepared by vibration under constant vertical stress of 11 kPa at an initial void ratio e_0 = 0.897. Specimens were prepared in layers of 5 mm in height to minimize variations in density. Vertical stress increments between 0.01 and 3.2 MPa were applied and kept for 24 hours whereas recording vertical displacements. Tests were carried-out at constant total suctions of ψ= 0 (fully saturated), 150, 200 and 330 MPa. Unsaturated conditions were controlled using the vapor transfer technique (Blatz et al., 2008), by means of a closed air-flow circuit passing through the sample, and a saline solution that applies a target relative humidity (RH) of the air phase. Before loading, the system was allowed to reach equalization of air humidity for 4 days. More details about the experimental setup can be found in Osses et al. (2021). Total suction ψ was estimated according to the Kelvin's law (Fredlund & Rahardjo, 1993):

$$\psi = s + \pi = -\frac{RT}{v_{w0}\omega_v} ln(RH) \tag{1}$$

where T is temperature, R is the universal gas constant (8.31432 J/[mol K]), v_{w0} is the specific volume of water ($v_{w0} = 1/\rho_w$) and ω_v is the molecular mass of the water vapor (18.016 kg/mol).

Oedometric tests on gravelly samples (G) were carried-out in a large square rigid box of 720 mm × 720 mm and 600 mm in height. The device is part of a large-scale direct shear developed at The University of Newcastle in Australia and described in Linero et al. (2020). G samples were prepared in 4 layers of homogeneous material. A wooden tamper was used for compaction until reaching an average void ratio of $e_0 = 0.930$. Tests were performed at constant total suctions of ψ: 0 (fully saturated), 30, 60 and 300 MPa, using the closed-air loop shown in Figure 2. To force air flow circulation through the sample, a pump was installed and controlled by software. Records of temperature and RH were obtained through two hygrometers incorporated in the vapour transfer system. To ensure RH homogenization in gravelly samples (G), an equalization period of at least 4 days was maintained, after which stable values were measured on the hygrometers. More details of the experimental procedure can be found in Osses et al. (2024). Table 1 presents the summary of the tests on S and G samples.

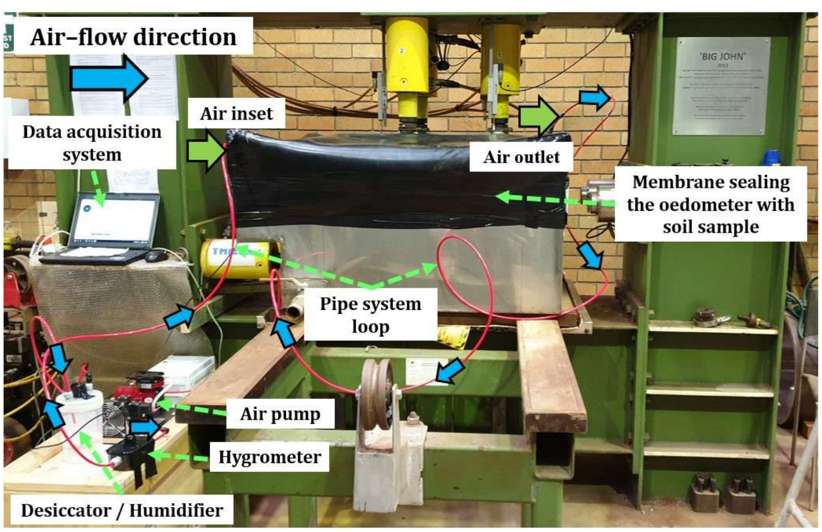

Figure 2: Experimental setup of the 720 mm x 720 mm box.

Table 1: Summary of tests.

Mat.	Test ID	ψ (MPa)	Max. σ_v (MPa)	e_0
S	S/0-1	0	3.2	0.925
	S/0-2	0	1.6	0.836
	S/150	150	3.2	0.925
	S/200	200	3.2	0.925
	S/330	330	1.6	0.873
G	G/0-1	0	3.2	0.906
	G/0-2	0	3.2	0.951
	G/30	30	3.2	0.935
	G/60	60	3.2	0.973
	G/300	300	3.2	0.886

Experimental results

Figure 3 presents the relationship between volumetric strain (ε_v) and vertical stress (σ_v) for all tests summarized in Table 1. As expected, gravelly samples are more compressible than sandy specimens due to higher particle breakage in the coarser material. This figure shows a strong influence of total suction (relative humidity) on the compressibility of G and S materials. Compressibility increases with decreasing total suction (increasing moisture content or relative humidity). Moreover, saturated samples always exhibit the higher deformation for a given stress state. Comparing the compressibility at vertical stress of 3.2 MPa, ε_v of saturated G samples for ψ=0 MPa is between 14% to 15%, while at ψ= 30, 60 and 300 MPa is 11.5%, 12.0% and 12.5%, respectively. This is consistent with the phenomenon of SCC promoted at high humidity. Figure 4 displays the particle size distributions after testing, where the mass of d_{min} size fraction is about 2% in saturated S samples and more than 13% in saturated G material.

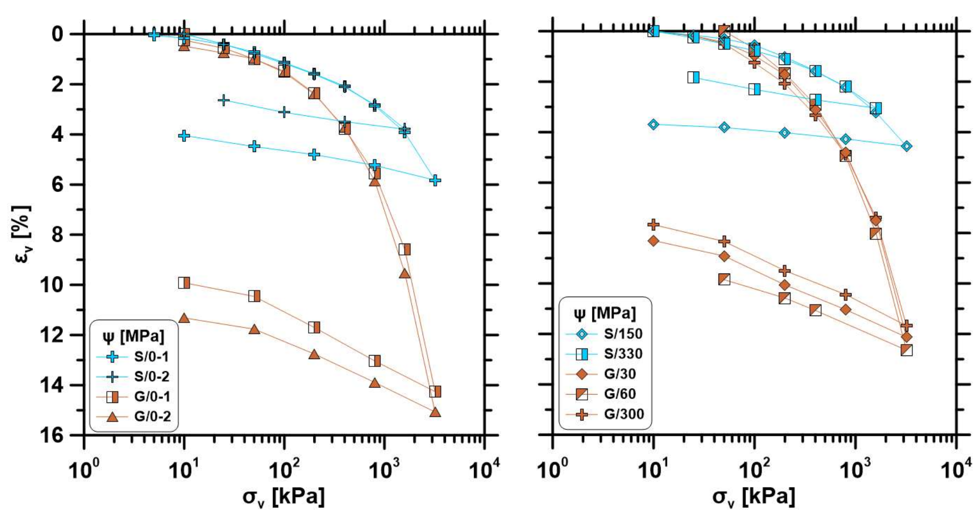

Figure 3: Compressibility curves of S and G material.

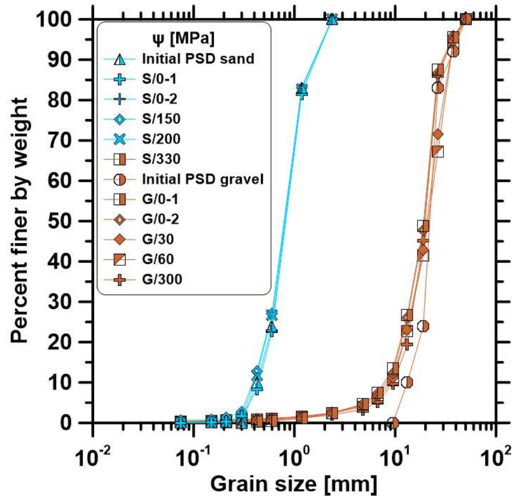

Figure 4: Grading after testing of all tests.

Figure 5 shows time-deformation during 24 hours for each stress increment on the saturated samples of S and G. For each σ_v, all cases are characterized by collapse throughout the first minute. Thereafter, deformation has a rate of evolution given by a constant creep compressibility index $C_\alpha = -\Delta e/\Delta \log t$, which strongly depends on ψ. Therefore, delayed particle fragmentation due to SCC is promoted at higher humidity. As shown in Figure 6, C_α of G material decreases from a mean value of $8x10^{-3}$ after tests at ψ= 0 MPa, to around $4x10^{-3}$ at ψ= 300 MPa. Regarding size effect, C_α values are 4 times lower in S material comparing G samples.

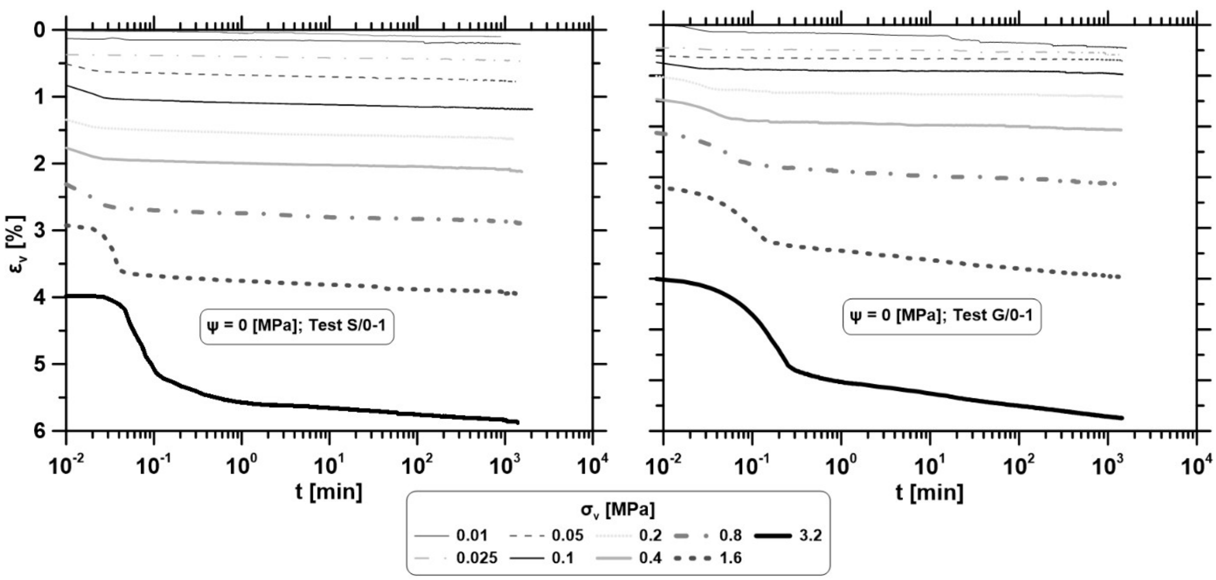

Figure 5: Time-dependent deformation in saturated samples.

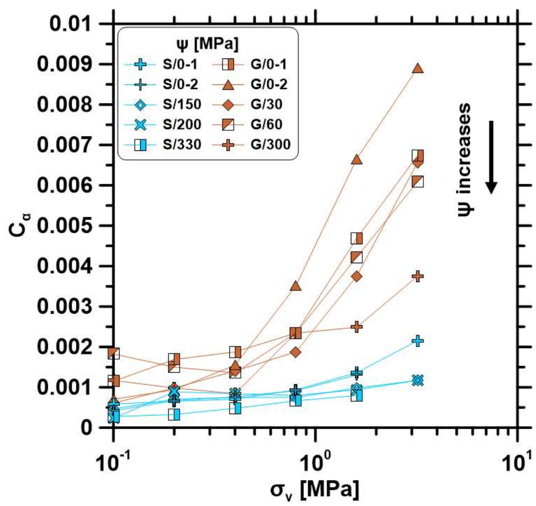

Figure 6: Creep indexes for all stress increments in each test.

Discussion

Compared with finer material (S), the increased probability of weaker flaws (or microcracks) in larger rock particles contributes to size effects in coarse material (G). Consequently, G experiences greater grain crushing than S, leading to higher compressibility. Regarding partial saturation conditions, it is well established that increased humidity accelerates time-dependent deformation due to delayed crushing events triggered by SCC. Advancing the understanding of size effects, this study reveals that coarser particles also undergo greater creep deformation, presumably since SCC has a more pronounced impact on coarser materials. This effect is linked once again to the greater incidence of weak flaws in G, which, subjected to the same conditions of stress and partial saturation, are more exposed and vulnerable to corrosion than S.

Conclusions

This paper presented experimental evidence of size effects on creep deformation of crushable saturated and unsaturated granular soils. Oedometric tests on two samples of mine waste rock materials having parallel particle size distribution were presented. The following conclusions ca be drawn from the results:

- For a given particle size distribution, total compressibility and creep deformation increased with decreasing suction, certainly due to degradation caused by Stress Corrosion Cracking (SCC).
- For a given suction, total compressibility was higher in G compared to S material, due to increasing grain breakage in coarser samples.
- For a given suction, creep deformation increases with particle size. This result contributes to a better understanding of the rarely reported phenomenon of size effect on time-dependent behavior of crushable granular materials.

In practical engineering designs, it is worth noting that testing small scale samples to capture the behavior of a coarser material in the field, might led to optimistic results regarding total compressibility and creep deformation. Therefore, given the significant particle size reduction usually used in small scale tests, in situ monitoring becomes essential to validate design criteria.

Acknowledgements

This research work benefitted from the financial support of ANID Chile [project FONDECYT 11150084] and the Natural Sciences and Engineering Research Council of Canada (NSERC) [project RGPIN-2019-06118]. Fortescue Metals Group Ltd. provided the material and supported Mr. Osses during different stages of this research; this support is greatly appreciated.

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