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Technical Note

Data Compilation from Large Drained Compression Triaxial Tests on Coarse Crushable Rockfill Materials

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Abstract: Investigating the mechanical properties of rockfills requires laborious, time-consuming, and expensive large-scale testing. Therefore, practitioners frequently adopt design parameters based on a limited number of reports with experimental results. With the aim of enlarging and consolidating the database on the mechanical behavior of coarse rockfills, this paper compiles 158 drained triaxial compression tests conducted on 33 different materials, performed on samples ∼1 m in diameter and having a maximum particle size between 100 and 200 mm. Data are analyzed in terms of particle breakage, shear strength, and stiffness. The results are compared with limits for high and low shear strength previously reported. At confining pressures lower than 0.2 MPa, rockfills consistently have a maximum internal friction angle higher than 45°; at high pressure, this value decreases to a range between 30° and 40°, mainly due to degradation caused by particle breakage. Average secant Young's moduli for all uniform and well-graded rockfills analyzed are in the typical range for loose sands, characterized by a normalized secant modulus of 100 to 200. **DOI: 10.1061/(ASCE)GT.1943-5606.0002314.** © *2020 American Society of Civil Engineers.*

Author keywords: Rockfill; Large triaxial tests; Particle crushing; Shear strength; Secant stiffness.

Introduction

Owing to their massive production potential by quarrying and their mechanical properties in the dense state, rockfills are frequently used in civil engineering works. These granular fills are mainly composed of a mix of sand and angular rock aggregates with oversized particles that are too large to be handled by standard laboratory devices for compression and shearing. Alternative laboratory and in situ large direct shear tests have been developed by others (Barton and Kjaernsli 1981; Matsuoka et al. 2001; Estaire and Olalla 2006). However, these methodologies only allow for the evaluation of the mechanical behavior at low stresses, while calibration of new constitutive models that have been specifically developed for rockfill behavior (Chávez and Alonso 2003; Varadarajan et al. 2003; Xiao and Liu 2017; Yin et al. 2017) require accurate data on stress-strain controlled response over a large range of stresses. Therefore, a common challenge that engineers face when designing rockfill structures is that published information which documents large-scale tests is very scarce.

The largest triaxial testing apparatus ever built handles specimens with a diameter of ∼1 m. While equipment of this scale has been built, there are few examples currently in use due to the high cost involved in their maintenance and operation. Pioneering development of testing on very large samples was first reported during the 1960s at the laboratories of Karlsruhe Technical University (Leussink 1960), the University of California at Berkeley (UCB) (Marachi et al. 1969), and the Federal Electricity Commission of Mexico (CFE) (Marsal et al. 1965). These groups designed and built devices that could handle samples ranging in diameter (D) from 914 to 1,130 mm, and having a maximum particle size (d_{max}) of 200 mm using the classic minimum aspect ratio $D/d_{max} =$ 5 to 6 (Holtz and Gibbs 1956). Experimental programs at CFE and UCB were carried out on several rockfill dam materials, and the results have become a reference for engineers and researchers. Part of the data produced at the CFE and UCB laboratories has been analyzed in detail and used to propose empirical correlations and ranges for mechanical parameters of coarse rockfill materials (Leps 1970; Barton and Kjaernsli 1981; Hunter and Fell 2003). Other authors have subsequently reported new results and have updated the database (Charles and Watts 1980; Al-Hussaini 1983; Matsuoka and Liu 1998; Hunter and Fell 2003; Varadarajan et al. 2003; Xiao et al. 2014a, b) using triaxial cells that can take samples of 300–500 mm in diameter. These studies have significantly advanced the understanding of the mechanical behavior of rockfills, such as the study of the effects of partial saturation (Oldecop and Alonso 2003; Alonso et al. 2016), stress path (Chávez and Alonso 2003; Xiao et al. 2015), and particle size (Verdugo and De la Hoz 2006; Hu et al. 2011; Ovalle and Dano 2020).

Due to the size limitation of testing devices, a common practice is to test small-scale samples with a parallel gradation while maintaining the particle shape, mineralogy, and sample aspect ratio.

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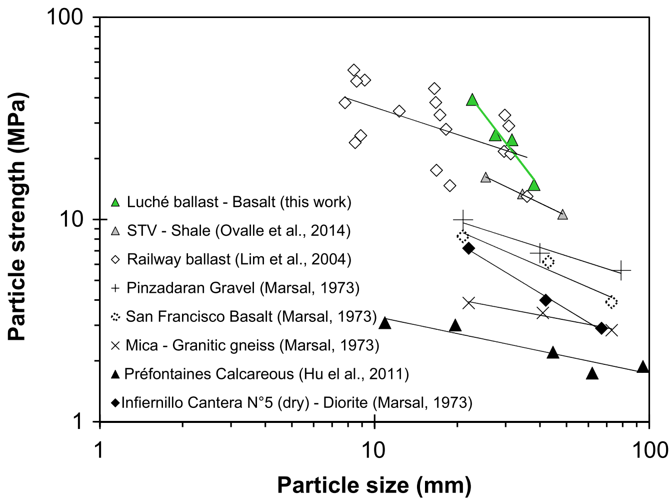

Fig. 1. Particle crushing strength of rock aggregates.

However, it has been proven that this method may be limited due to size effects on particle crushing (Marachi et al. 1969; Frossard et al. 2012; Ovalle et al. 2014). Fig. 1 presents the results of several diametral compressions of individual rock aggregates between two stiff parallel platens where crushing strength decreases when particle size increases, which is consistent with the brittle fracture mechanics theory (Weibull 1939). Therefore, the amount of particle crushing is less in small-scale (i.e., finer) granular materials than in coarser prototype materials.

Along with presenting new tests carried out in recent, very large triaxial devices, the aim of this study was to consolidate and extend the existing database through the compilation of data on large triaxial tests on coarse rockfill samples carried out between the 1960s and the 2000s. To present comparable results in terms of stress path, particle size, and particle shape, only drained compression triaxial tests on coarse rockfills samples of ~1 m in diameter, composed of angular shaped grains with d_{max} between 100 and 200 mm, have been considered. Results from 158 tests on samples from 33 rockfill materials are presented. The influence of the confining stress and the amount of particle crushing on shear strength and secant stiffness is discussed. To highlight the data on coarse crushable rockfill materials, the results were compared with published data on finer materials, such as dense uniform quartzitic sands and railway ballasts.

Recent Experimental Data Included in the Database

Recently, new large triaxial devices have been operating at École Centrale Nantes (ECN) in France and at the IDIEM laboratory in Chile. The large device at ECN can test samples that are 1,000 mm in diameter and 1,500 mm in height, at a maximum confining pressure of 1.5 MPa. The IDIEM large triaxial device can handle samples of 1,000 mm in diameter and 1,800 mm in height at confining pressures up to 3 MPa. Exhaustive descriptions and testing methodologies can be found in Hu et al. (2011) and Ovalle (2013) for ECN, and in De La Hoz (2007) for IDIEM.

Among the 158 large triaxial tests on 33 materials compiled and analyzed, 14 rockfill materials were tested at IDIEM (1 unpublished—on Pilbara rockfill), 3 at ECN (2 unpublished—on Agence Nationale de la Recherche (ANR) Pedra granite and Sainte Cécile d'Andorge dam), 4 at UCB, and 12 at CFE. Fig. 2(a) shows the grain size distribution (GSD) for each material. Descriptions of the new rockfills reported in this study are the following:

- Pilbara: Waste crushed mining rockfill from the Pilbara region in Western Australia, consisting of Neogene alluvial and colluvial sediments originated from weathering, erosion, and transportation of Precambrian banded iron formation rocks.
- ANR Pedra granite: Washed, crushed angular granite rockfill.
- Sainte Cécile d'Andorge dam: Schist and mica-schist rockfill with subangular grains.

The materials analyzed here have diverse origins, and differ in terms of relative density, mineralogy, particle shape, GSD, and water content (tests on saturated and air-dried samples). Accordingly, significant data scatter should be expected. However, due to the lack of available data to perform accurate analyses, this paper aims to present ranges of results for shear strength and secant Young's modulus to compare the results with quartzitic sands and ballasts and to provide references for engineers and researchers. The analyses presented highlight the influence of the breakage ratio (B_g), using the definition of Marsal (1967), given by the sum of positive differences between the percentage of the total sample contained in each size fraction before and after the test.

Quartzitic Sands and Ballast Data Collected

Compiled data from new tests on rockfills were compared with published data on dense uniform quartzitic sands and ballast materials, as well three new tests on Luché ballast. The results of drained triaxial compression tests with confining pressures over the same range as the database compiled for rockfill materials (e.g., from 1 to 10 MPa) were considered for the materials presented in Table 1; Fig. 2(a) presents the GSD for each quartzitic sand and ballast.

Analysis and Discussion

Shear Strength

Fig. 2(b) presents shear strength for all tests collected in terms of the maximum friction angle (ϕ_{max}) against the effective normal pressure on the failure plane (σ_n'), according to the Mohr-Coulomb failure criterion. Fig. 2(b) also includes the limits for high, average and low shear strength proposed by Leps (1970) and Indraratna et al. (1993), which can be expressed as:

$$\phi_{\max} = -2.8 \ln \sigma_n' + \phi_1 \tag{1}$$

with σ_n' in MPa and ϕ_{max} in degrees; and ϕ_1 = maximum friction angle at $\sigma_n' = 1.0$ MPa, and is 36°, 41°, and 46° for low, average, and high strength according to Leps (1970), respectively, and 33° for the low strength limit proposed by Indraratna et al. (1993).

For rockfills, ballasts, and sands, Fig. 2(b) confirms that shear strength decreases with σ_n', as a consequence of dilatancy decreasing due to particle rearrangement and crushing. At the highest stress levels presented, no constant critical friction angle could be observed, which can be attributed to significant particle crushing potential still relevant at higher strains (Coop et al. 2004), compared to limited maximum strains of 15% to 20% in triaxial testing. While common values of ϕ_{max} in dense sands at low confining pressure are typically between 40° and 45° (Bolton 1986; Biarez and Hicher 1994; Schanz and Vermeer 1996), all rockfills in Fig. 2(b) present $\phi_{max} > 45°$ at $\sigma_n' < 0.2$ MPa, due to the interlocking of highly angular grains and high friction on the rough surfaces of

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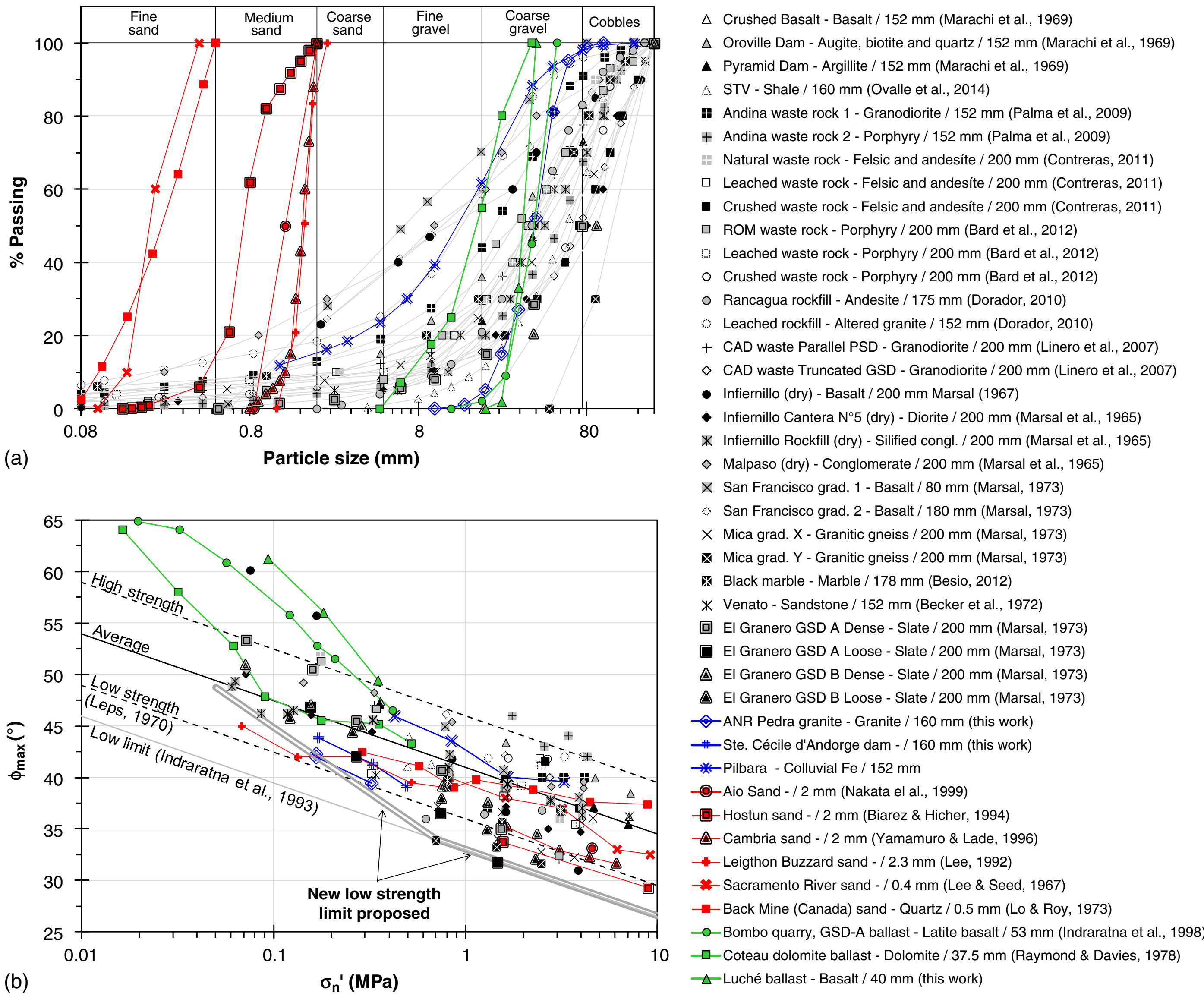

Fig. 2. Compiled sands, ballasts, and rockfills: (a) GSD; and (b) maximum internal friction angle [legend: "Material Name/d_{max} (millimeters) (Ref.)"].

Table 1. Data collected on sands and ballast

Material	Description	d_{max} (mm)	LLA (%) (for ballast only)	Relative density (for sands only)	Reference
		Quartzitic sands			
Hostun sand	98% quartz angular	2	—	1	Biarez and Hicher (1994)
Aio sand	Quartz and 30% feldspar, subrounded sand	2	—	1	Nakata et al. (1999)
Cambria sand	Subrounded sand composed by a mix of quartz and gypsum	2	—	0.9	Yamamuro and Lade (1996)
Leighton Buzzard sand	Subrounded quartz sand	2.3	—	0.8	Lee (1992)
Sacramento River sand	Subrounded quartz sand	0.4	—	1	Lee and Seed (1967)
Quartz sand	Angular, derived from crude quartz from Back mine, Canada	0.5	—	0.6	Lo and Roy (1973)
		Railway ballast materials			
Bombo ballast	Latite basalt from Bombo quarry, Australia	53	15	—	Indraratna et al. (1998)
Coteau ballast	Dolomite from Coteau, Quebec, Canada	37.5	17.6	—	Raymond and Davies (1978)
Luché ballast	Diorite ballast from Luché quarry, France	40	10	—	This work

crushed rocks. This effect is even more significant in ballast materials, where ϕ_{max} reaches values higher than 60° at low stresses. At $\sigma_n' > 0.5$ MPa, ϕ_{max} in rockfills and ballasts decreases to values between 35° and 45°, approaching the results reported in dense sands. In general, the shear strength of quartzitic sands stays below the average values for rockfills, near the low strength limit proposed by Leps (1970) (i.e., $\phi_1 = 36°$). For $\sigma_n' < 0.7$ MPa, the low shear strength limits proposed by Leps (1970) and Indraratna et al. (1993) seem conservative for rockfills and ballasts. Therefore, a new low strength limit is proposed here for low stress, given by:

$$\phi_{\max} = \begin{cases} -5.6 \ln \sigma_n' + 32; & \sigma_n' \leq 0.7 \text{ MPa} \\ -2.8 \ln \sigma_n' + 33; & \sigma_n' > 0.7 \text{ MPa} \end{cases} \quad (2)$$

To consider high shear strength at low stresses, the new limit proposal—included in Fig. 2(b)—keeps the low strength limit of Indraratna et al. (1993) for $\sigma_n' > 0.7$ MPa and adds a new expression for higher ϕ_{max} at lower stresses.

Particle Breakage

As applies to any granular material subjected to high stresses, rockfills may experience particle crushing, which leads to increasing compressibility and decreasing dilatancy and ϕ_{max} (Vesic and Clough 1968; Biarez and Hicher 1994; Lade et al. 1996; Biarez and Hicher 1997; Ovalle et al. 2015; Dano et al. 2018). For a given material, the amount of particle breakage is a function of independent variables of stress and strain, which can be expressed as plastic work input (Daouadji et al. 2001; Yin et al. 2017; Ovalle and Hicher 2020), and independent material parameters such as grading, particle size, particle shape, and water content. Breakage is more significant in coarse materials with angular particles, uniform GSD, and high water content (Hardin 1985; Ovalle et al. 2013; Ovalle 2018). It follows that rockfill materials have favorable conditions for grain breakage, since the process of blasting and grinding produces large angular aggregates.

In constitutive models, B_g can be linked with dependent mechanical variables through empirical expressions, such as friction coefficient, Young's modulus or hardening pressure (Yin et al. 2017; Ovalle and Hicher 2020). In this paper, the role of particle breakage in the degradation of the internal friction angle is highlighted to give empirical support to engineers and researchers designing and modeling rockfill structures.

Fig. 3(a) presents B_g against σ_3'. As expected, for a given stress, most rockfill materials present higher B_g values when compared to dense quartzitic sands. Particle breakage in rockfills is significant, even under very low stresses $\sigma_3' < 0.1$ MPa, whereas in sands it becomes relevant for σ_3' of about 1.0 MPa. Fig. 3(b) shows the relationship between shear strength and particle breakage, where ϕ_{max} in sands is less sensitive to B_g than rockfills and ballasts. The analysis also shows that at high stresses, when a significant amount of crushing occurs, the strengths of sands and rockfills tend to have similar values.

It is well known that B_g is expected to be inversely proportional to the initial uniformity coefficient $C_u = d_{60}/d_{10}$ (Hardin 1985; Ovalle et al. 2016). However, it is not worth proposing a relationship for the current rockfill database given the large data scatter due to other independent variables that affect the material response.

Secant Young's Modulus

Young's moduli values for rockfills have been proposed based on dam settlement analyses (Hunter and Fell 2003; Kermani et al. 2018). However, data from stress-controlled laboratory tests needed for calibration of constitutive models are scarce. Here, secant Young's moduli from drained triaxial stress paths were obtained to compare the results with typical values used for sands. To avoid experimental scatter from data recorded at small strains in triaxial tests, a convenient modulus E_{50} has been chosen, defined as the secant modulus associated with a deviatoric stress level ($q = \sigma_1' - \sigma_3'$) equal to half of the maximum strength. E_{50} is commonly fitted by the following expression:

$$E_{50} = K_{50} \cdot p_a \left(\frac{\sigma_3'}{p_a} \right)^n \quad (3)$$

where n = fitted parameter, typically from 0.4 to 0.6 in sands (Schanz and Vermeer 1998; Schanz et al. 1999); K_{50} = reference normalized modulus; and $p_a = 0.1$ MPa = reference pressure. Fig. 4 presents E_{50} for all rockfill materials compared to data of dense quartzitic sands and ballasts. In addition, Eq. (1) is plotted assuming $n = 0.5$ and typical values of K_{50} of 200 and 400 for loose and dense sands, respectively (Schanz and Vermeer 1998). The comparison indicates that most rockfills have lower moduli than loose sands. By contrast, E_{50} of ballasts at low pressure is similar to the values for dense sands, but tends to be in the range for rockfills at intermediate pressures of 100–200 kPa. As an explanation of this result, it is thought that even a small number of crushing events occurring in rockfill and ballast materials at

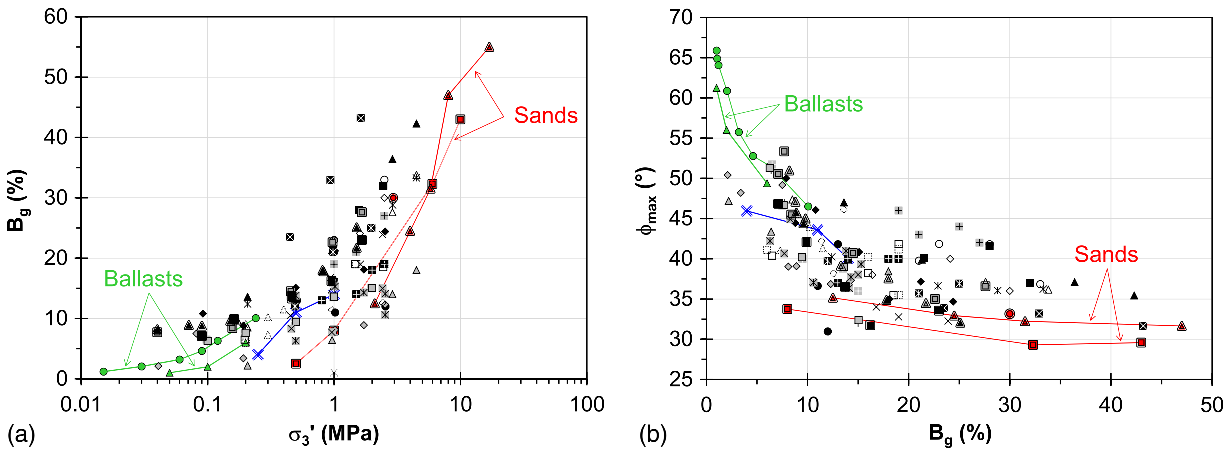

Fig. 3. Marsal's breakage ratio.

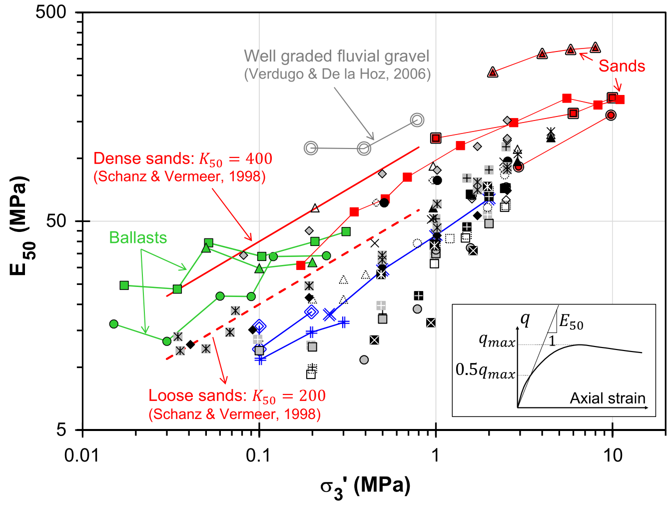

Fig. 4. Secant Young's modulus.

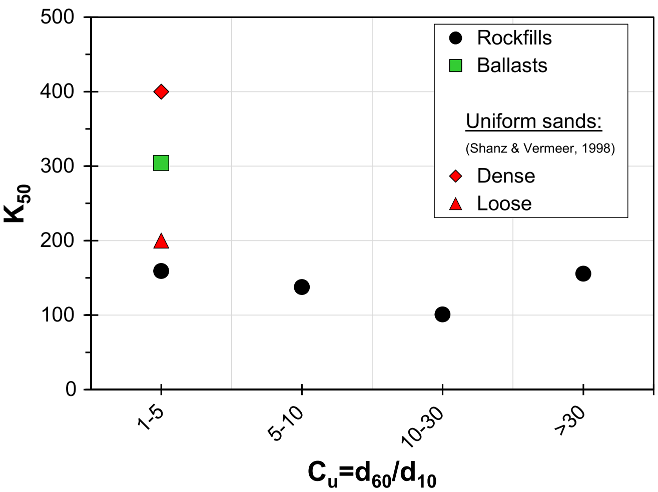

Fig. 5. Normalized secant Young's modulus.

relatively small strains (e.g., attrition process removing asperities) could result in a significant drop in material stiffness. At high stresses, crushing becomes significant in sands and the stiffness of sands and rockfills follows a similar trend.

Fig. 4 also includes values of E_{50} from drained triaxial tests on coarse, well-graded fluvial gravel composed of sound rounded clasts of $d_{max} = 200$ mm reported by De La Hoz (2007) and Verdugo and De la Hoz (2006). In this case, the amount of particle crushing is considerably lower than in rockfills due to both high C_u and highly resistant rounded gravel clasts, resulting in E_{50} being comparable to dense quartzitic sands.

For the data compiled here, K_{50} from Eq. (3) was fitted by separating and averaging the data in ranges of initial C_u. As shown in Fig. 5, regardless of the value of C_u, the data for rockfill are in a narrow band of $K_{50} = 100$–200, typically associated with loose sands.

Conclusions

The compilation of large drained triaxial tests on coarse rockfill materials presented in this article includes samples with different relative densities, mineralogies, gradings, and particle shapes, resulting in significant data scatter. However, the minimum limit imposed on d_{max} reduces the potential for size effects, allowing an appropriate comparison with data on ballast and quartzitic dense sands, which are usually taken as a reference for mechanical parameters of granular materials.

The analyses show the typical behavior of crushable granular materials previously reported, namely, shear strength decreasing due to particle crushing when pressure increases. In this study, the magnitude of this phenomenon is highlighted in coarse, angular materials. In general, data on coarse rockfill materials confirm previously reported limits for average shear strength. Dense quartzitic sands reasonably correspond to the range of average to low shear strength values for rockfills in a large range from low to high pressure. At low pressure of $\sigma_n' < 0.2$ MPa, where the amount of crushing is still not significant, rockfills and ballasts have consistently higher shear strength than dense quartzitic sands, and the maximum internal friction angle is higher than 45°. At high pressure, the amount of grain breakage increases and the maximum internal friction angle of sands and rockfills is between 30° and 40°. According to the analysis, previous limits for low shear strength proposed in the literature seem conservative at low stresses. A new expression is provided in this paper that considers higher strength at normal stress lower than 0.7 MPa.

In general, dense quartzitic sands are stiffer than rockfills at low stresses and their secant Young's moduli tends to have similar values at high stresses, probably due to the significant amount of particle crushing in both materials. Normalized Young's moduli at reference pressures for rockfills are in the same typical range for loose sands.

Data Availability Statement

Compiled and new data on rockfill materials supporting this paper are available at https://doi.org/10.5281/zenodo.3625778.

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