Role of particle characteristics on the compression behaviour of gap-graded sands

Nocilla Alessandra, PhD, Lecturer in Soil mechanics,

- Department of Ingegneria Civile, Architettura, Territorio, Ambiente e di Matematica, DICATAM, University of Brescia, Brescia, Italy
- orcid.org/0000-0003-0665-8826

Zimbardo Margherita, PhD, research assistant

- Department of Ingegneria Civile, Ambientale, Aerospaziale e dei Materiali DICAM, University of Palermo
- orcid.org/0000-0001-7279-7096

Coop Matthew, Richard, PhD, Professor of Geotechnical Engieneering,

- Department of Civil, Environ & Geomatic Eng, Faculty of Engineering Science, University College London, London, UK
- orcid.org/0000-0002-3301-552X

Full contact details of corresponding author.

Prof. Ing. Alessandra Nocilla
D.I.C.A.T.A.M.
Università di Brescia
Via Branze 43
25123 Brescia

mobile: +3903392809412

Abstract

Recent research has investigated the compression in gap graded mixtures of sands with combined mineralogy focusing on the key factors that might imply the occurrence of convergent or non-convergent paths in compression (i.e. transitional or non-transitional behaviour). From previous work, the mineralogy of the matrix composed by larger grains seems to determine the possibility of the occurrence of transitional behaviour. Hence, if there is a strong and stiff matrix made of quartz sand particles, which are either larger than or at least of similar size to the other component, then non-convergent compression paths (i.e. transitional behaviour) are likely to occur. As a further confirmation of this hypothesis, this technical note presents the results of oedometer tests on the same range of mixtures of a quartz sand and a carbonate sand as was used in previously published work, but with the larger component being of the stiffer and stronger quartz sand. In agreement with the hypothesis, transitional behaviour occurred.

Keywords

Laboratory tests; Sands; Compressibility

Introduction

In recent literature, the several papers on 'transitional' behaviour of reconstituted and natural intermediate graded soils have highlighted the occurrence of non-convergent paths in compression (e.g. Martins et al., 2001, Nocilla et al., 2006; Nocilla & Coop, 2008; Ventouras & Coop, 2009; Ponzoni et al., 2014). In gap graded soils, even if the influence of particle features has been investigated (i.e. particle nature, granulometry and mineralogy), a clear picture has not yet emerged about what causes it (e.g. Martins et al., 2001; Ferreira and Bica, 2006; Shipton et al., 2006; Carrera et al., 2011; Shipton and Coop, 2012; Shipton and Coop, 2015).

Analysing existing research on transitional behaviour in gap graded sand or sand-silt mixtures, Ponzoni et al. (2017) highlighted that non-convergent compression paths and/or non-unique Critical State Lines (CSLs) were detected for mixtures in which the matrix was made of larger particles of quartz, no matter whether other component was of the same mineralogy or not. In order to test this observations, albeit indirectly, they carried out an investigation involving a series of oedometer and triaxial tests to determine the behaviour of gap graded mixtures with larger particles of carbonate and smaller particles of quartz. In recent literature the importance has been highlighted of packing in sandy silt mixtures (e.g. Chang at al. , 2015) along with the existence of a transitional content of fines for which the mixtures pass from the coarse-grain dominant region to a fine-grain dominant region (e.g. Chang at al., 2016; Zuo and Baudet, 2015). Using high stresses in order to be sure whether the compression paths would eventually converge or not, Ponzoni et al. (2017) showed ~~**the**~~ **convergent** compression paths **for their mixtures made of larger grains of carbonate. In detail, comparing their results with non convergent compression paths of mixtures tested by Shipton & Coop (2012), which were featured by a similar binary mineralogy (i.e. quartz and carbonate) but larger particles of quartz,** ~~for all the~~ **they highlighted the convergence of the** mixtures **they** tested ~~**did converge**~~, confirming that the mineralogy of the larger grains seemed to determine the occurrence or not of the transitional mode of compression behaviour. Indeed, the convergence of the compression paths for all mixes **of Ponzoni et al. (2017)** of different proportions seemed to confirm that the presence of a fabric **made of larger particle of carbonate** that is easier to erase in mixtures in which quartz particles are always the smaller component, possibly allowing particle arrangement, hence the destructuration of the fabric and a unique Normal Compression Line (NCL) to be defined. In their investigation, as for the particle breakage, the values of the overall relative breakage (Br) for the mixes tested were quite low, even if the one-dimensional Normal Compression Lines (1D NCLs) appear to be unique, confirming that while significant breakage can occur in soils with convergent behaviour it is not a prerequisite.

As a consequence, the authors hypothesised that a much more robust fabric that would be difficult to erase should be present in a mixture with a quartz matrix when the other component of the mixture has either smaller particles or particles of similar dimension, and either of the same mineralogy or of a weaker type. In this case, the other, non-quartz component can break severely, inhibiting breakage of the larger quartz particles, which might prevent a unique 1D NCL being defined. Taking this into account, this technical note presents a new series of oedometer tests that were conducted to confirm the role of the mineralogy of the larger grains. As supposed by Ponzoni et al. (2017), transitional behaviour should be expected for gap graded mixtures of sands with larger grains of a stronger type. However, such data did not exist in their work for the same mineralogy of mixtures. Hence, in order to compare with what was previously investigated, this study used the same mineralogy as Ponzoni et al. (2017) but with the reverse composition, i.e. larger particles of the same stronger type (quartz).

2. Materials, procedures and laboratory tests

Ponzoni et al. (2017) found convergent behaviour in compression for quartz-carbonate mixtures of Leighton Buzzard sand (LBS) and Carbonate sand (CS) with a low ratio R between dmax and dmin, where the dmax is the mean value of the larger particle size distribution, and dmin is the mean value of the smaller. Their mixtures had an R value equal to 3.02 and the matrix made of larger particles of weaker carbonate grains. More often, in the literature, R is estimated as R*=

D50/d50 (e.g. Cabalar and Hasan, 2013; Zuo and Baudet, 2015) which provides a rigorous definition of this value. In Table 1, both values have been reported. The Leighton Buzzard sand (LBS) used by Ponzoni et al. (2017) consisted of strong and sub-rounded particles, characterised by high sphericity, a specific gravity Gs equal to 2.66 and grain dimensions used by them between 0.212 and 0.80mm, while the Carbonate sand (CS) had angular and weak shelly carbonate particles, with low sphericity, a specific gravity Gs equal to 2.71 and grain dimensions between 0.212 and 0.3mm (Table 1).

This research therefore focused on the reverse combination with an identical quartz-carbonate mineralogy with a low ratio R equal to 5.7 but larger particles of the stronger type (i.e. quartz). High pressure one-dimensional compression tests were performed on specimens of mixtures that were created artificially by mixing two soils of these different mineralogies. The Leighton Buzzard sand (LBS) again consists of strong and sub-rounded particles, characterised by high sphericity, a specific gravity Gs equal to 2.66 but grain dimensions between 0.85 and 2mm. The Carbonate sand (CS), obtained by crushing a weak limestone, has sub-angular and weak particles, with low sphericity, a specific gravity Gs equal to 2.72 and grain dimensions between 0.075 and 0.425mm. Single particle strengths σf have been measured (Tso and Wang, 2015) and characteristic strengths of 406 MPa and 39 MPa were found for the LBS and for CS, respectively. Before testing, the commercial granulometric distributions were confirmed with particle size analyses by means of sieving. All four sand grain characteristics for the current research and that of Ponzoni et al. (2017), are summarised for comparison in Table 1, while the particle size distributions are shown in Fig. 1.

Five “mixtures” were considered. Two of them were 100% one mineral and three were mixtures of the two soils; 80% Quartz/20% Carbonate, 50% Quartz/50% Carbonate, and 20% Quartz/80% Carbonate by dry weight. Twenty-four oedometer Tests were carried out using a conventional 38mm diameter fixed ring oedometer (up to stresses of 12.4MPa) and a 30mm diameter floating ring oedometer, used to reach higher pressures (up to 20.5MPa) while minimising wall friction. Wet compaction was used in order to create groups of samples with the same initial specific volumes and control their repeatability.

The accuracy in the measurements of the initial specific volume, vi, is of essential importance otherwise apparent non-convergence could simply arise from poor accuracy. The initial specific volumes, vi, should be calculated from different methods based on measurements as independent of each other as possible, although some inter-dependency is necessarily present (Rocchi and Coop, 2014). For the oedometer tests presented in this study, when possible, measurements were based on the initial and final dry unit weights and on the final water contents when water loss could be prevented. Discarding any clearly anomalous data, the absolute value of the maximum difference between the mean of the initial specific volumes and the single calculated values was, on average, less than 0.01. The mean standard deviation between methods was also equal to 0.01. Gs was not the same for the two sands so that the specific volumes have to be determined by means of the phase equations.

3. Results

Compression data for the five mixtures are shown in Fig. 2. The oedometer tests show that at higher stress levels it is possible to identify a unique one-dimensional normal compression line (1D-NCL) in the v-log σ'v plane for the 100% one mineral samples, as expected (Coop and Lee, 1993; Coop, 2005) and highlighted in Fig. 2a. Despite this, the remaining three mixes (20%Q, and 80%Q in Fig. 2b and 50%Q in Fig. 2c) showed a non-convergent compression behaviour. The non-convergence of the compression paths for these mixtures, including those with a large amount of weaker grains (20%Q), highlights a compression behaviour which is distinctly different from that seen by Ponzoni et al. (2017), for which unique normal compression lines occurred no matter what their proportions, as compared in Fig.2c, where compression paths of mixtures for the same mix proportions (50%Q) are shown for the two programmes.

The mixtures of Fig. 2b and 2c are therefore examples of transitional soils, despite a similar low R ratio and mineralogy as those of Ponzoni et al. (2017), in which the larger particles were of carbonate. For the single mineral samples (0%Q and 100%Q), the convergence of compression paths eventually occurs for effective vertical stresses that depend on the mineralogy and the corresponding particle strengths, which are significantly different. Hence, for mixtures with a quartz content of 100% the convergence occurs for effective vertical stresses of about 10MPa, while if the soil is made of carbonate particles only (0%Q) the convergence is reached for effective vertical stresses smaller than 8 MPa. The slope chosen for each 1D-NCL was set to a value of 0.48, since the lines appear to be parallel, similarly to Ponzoni et al. (2017).

The comparison for single mineralogy samples, given in Fig. 2a shows that the influence of the mineralogy on the location of the compression lines is that the 1D-NCL moves towards higher stresses for the quartz. The relative positions confirm what was previously observed (Ponzoni et al., 2017; Leleu and Valdes, 2007) and as observed by McDowell & Bolton (1998), for each mineral the smaller particles are stronger and give a higher 1D-NCL, resulting in the 1D-NCLs being closer to each other for the current tests than those of Ponzoni et al. (2017).

According to Ponzoni et al., 2014, the degree of convergence of the oedometer compression data can be quantified by the coefficient m which is calculated from a graph plotting the initial specific volumes against that at a common maximum stress (12,4MPa). For consistency the initial specific volume was taken in each test at 20kPa vertical stress (v20). For soils with fully convergent paths, like for example a uniform sand (e.g. Coop & Lee, 1993), the gradient of the data on this graph, defined as m, would be zero and for soils with perfectly parallel compression paths m=1. The value of m for the oedometer curves in Fig.3a is clearly increasing with the amount of quartz content up to the a maximum of 0.6 when the proportion of the two mineralogies is balanced (50%Q) and tends to decrease toward the single mineralogy specimens (100% and 0%Q) where the unique 1D-NCL can be identified again. For the convergent behaviour of the mixes of Ponzoni et al. (2017), values of m equal to 0 can be assumed. The ratio Cs/Cc between the swelling index Cs and the compression index Cc, in Fig. 3a, shows higher values the more transitional is the soil (i.e. higher m) indicating a more gradual yielding behaviour, which is another typical feature of transitional behaviour.

3.1 *Particle breakage*

Figure 3b shows an analysis of the particle breakage that was carried out on the five mixtures in terms of Hardin's (1985) relative breakage Br. The final gradings were measured by means of sieves. The convex trend of the line that interpolates the Br values seems to be the mirror image of the trend of m in Fig. 3a.

If the relative breakage is compared with the values of Ponzoni et al. (2017) in Fig. 3b, the overall breakage is similar, even when the percentage of quartz is low and even if the stress levels are not quite the same. Although this confirms that the amount of overall breakage is not a good guide as to whether transitional behaviour may occur or not, for this research, when transitional behaviour occurs the quartz content seems to be an influencing factor for Br. The amount of breakage for the larger quartz particles is low. This is probably due to the particle strength of quartz and, even if in Fig. 4 there is breakage for the 100%Q, for the 50% Q mixtures it is clear how breakage involves the carbonate particles only. However, it is possible that there is an effect of density on breakage (Altuhafi & Coop, 2011): a close inspection of the values of initial specific volume vi on Fig. 3b, indicates a general trend for which denser samples show higher breakage, in contrast to what was expected, but this may add to the scatter of values.

4. Conclusions

According to Ponzoni et al. (2017), transitional behaviour should be expected for gap graded mixtures featuring larger grains of a stronger type, no matter in which proportion. Hence, this technical note has presented a new series of oedometer tests that were carried out investigating the behaviour of gap graded mixtures with larger particles of quartz but using the same mineralogy as Ponzoni et al. (2017).

As shown in Fig.3, the non-convergence of compression paths for all the three mixtures tested, included those with a large amount of stronger grains, highlights a compression behaviour which is very different from that detected by Ponzoni et al. (2017), for which unique NCLs were encountered for all mixtures. The amount of overall breakage was found not to be a good guide as to whether transitional behaviour may occur or not. However, for these mixtures the quartz content might be an influencing factor for Br and the trend for Br is the mirror image of the trend of the of degree of convergence m.

The non-convergence of the compression paths at high stresses for the three mixes seems to confirm the presence of a fabric that is difficult to erase, in mixtures in which quartz particles are the larger component. The absence of breakage after test for the quartz component in mixtures shown in Fig. 4 can be a further confirmation of this assumption.

By comparing the behaviour of these mixtures with those previously investigated with a weaker matrix made of carbonate sand particles, that are of larger size to the other component, the mineralogy of the larger grains seemed to determine the possibility of the occurrence of the transitional mode of compression behaviour. Further research should be carried out on other binary mixtures of artificial soils investigating the relative breakage of the single components in the mixture, if possible, in order to assess any influence in determining transitional or non-transitional behaviour.

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Soil	**Sand**	**Mineralogy***	**Gs***	**Shape^{+}**	**Grading [mm]**	**R**	**d_{50}**	**R***
Ponzoni et al. (2017)	Crushed Limestone	Calcium carbonate ($CaCO_3$: 99%)	2.72	Low sphericity sub-angular	0.71-2.36	3.02	1.56	3.25
	Leighton Buzzard Sand	Quartz (SiO_2: 100%)	2.66	High sphericity sub-rounded	0.212-0.8		0.48	
This research	Crushed Limestone	Calcium carbonate ($CaCO_3$: 99%)	2.72	Low sphericity sub-angular	0.075-0,425	5,7	0,274	5.18
	Leighton Buzzard Sand	Quartz (SiO_2: 100%)	2.66	High sphericity sub-rounded	0.85-2		1,42	

$^{+}$classification based on Powers (1953). * Thermogravimetric analyses and Gs investigation carried out by Ponzoni et al. (2017).

Table 1. Mixture properties: comparison with Ponzoni et al. (2017).

Figure captions

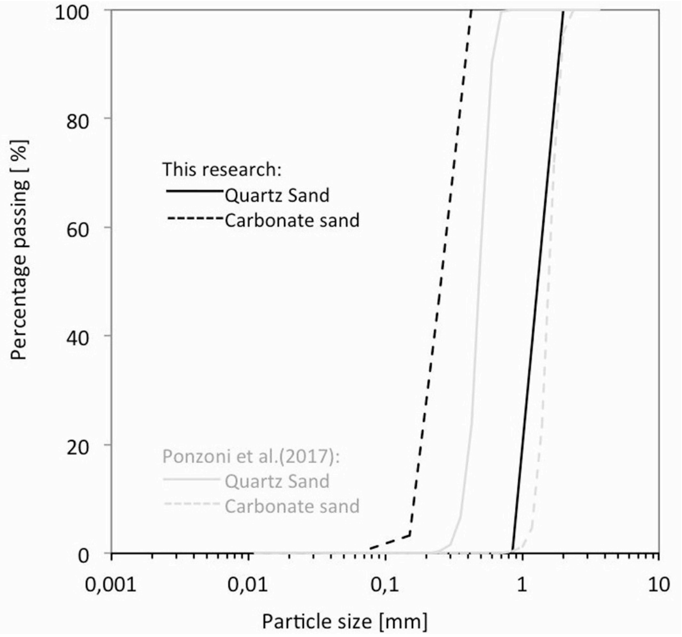
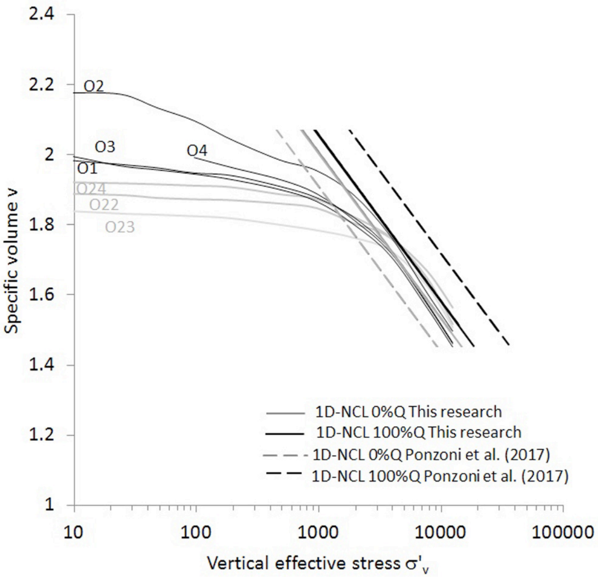


Figure 1. Particle size distributions of sands tested in this research and by Ponzoni et al. (2017).



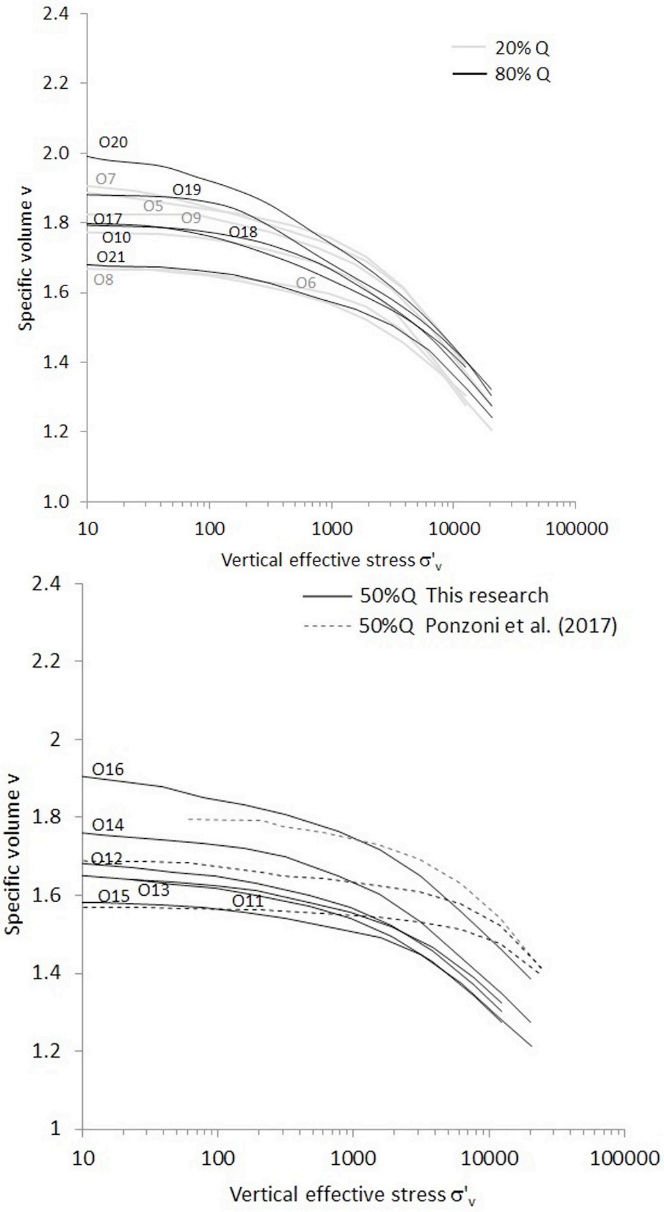
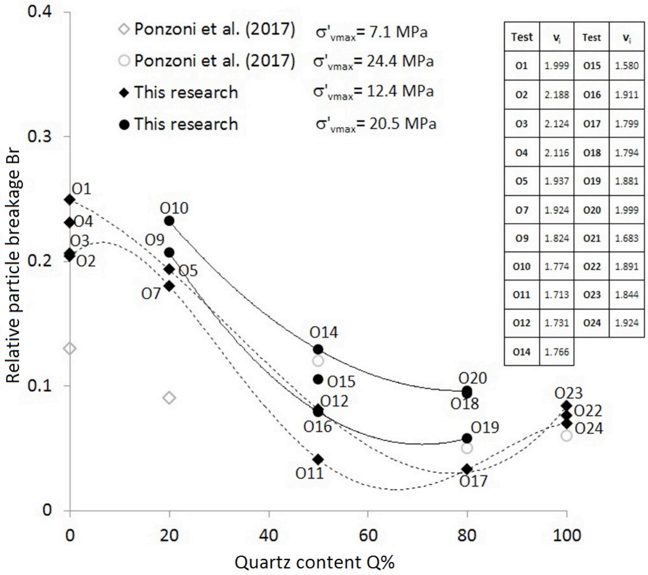


Figure 2. Oedometer compression curves for mixtures of quartz and carbonate sands: (a) 0% quartz and 100% quartz in this research and by Ponzoni et al., 2017; (b) 20% quartz and 80% quartz; (c) 50% quartz and comparison of compression behaviour between mix with 50%Q of this research and mix with 50% Q of Ponzoni et al. 2017;



Test	v_i	Test	v_i
O1	1.999	O15	1.580
O2	2.188	O16	1.911
O3	2.124	O17	1.799
O4	2.116	O18	1.794
O5	1.937	O19	1.881
O7	1.924	O20	1.999
O9	1.824	O21	1.683
O10	1.774	O22	1.891
O11	1.713	O23	1.844
O12	1.731	O24	1.924
O14	1.766		

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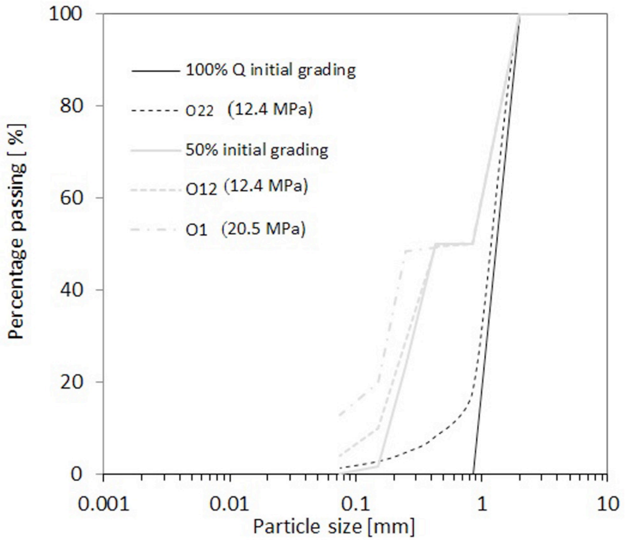
327 Figure 3. (a) Degree of convergence m and Cs/Cc ratio versus quartz content (Q%). Comparison 328 with Ponzoni et al. 2017. (b) Relative particle breakage (Br) versus quartz content (Q%) and 329 comparison with Ponzoni et al. 2017.



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331 Figure 4. Particle size distribution before and after the test for 100% Q and 50% Q.

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