Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0824

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

The role of particle mineralogy in mixtures of sands

Rôle de la minéralogie des grains dans les mélanges de sables

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ABSTRACT: Several recent studies on mixtures of sands of different granulometries and/or mineralogies have focused on the key factors that might lead the behaviour to change from transitional to not transitional, where a transitional behaviour is characterised by non-convergent compression paths and critical state lines that might be non-unique. The authors present a review of mixtures of different soils showing a complex pattern of compression and shearing behaviour in which transitional behaviour can be caused by relatively small variations to the proportion or nature of soil particles. Laboratory investigations, carried out by means of oedometer tests, have confirmed the role of the mineralogy of the matrix composed by larger grains. This determines the mode of behaviour so that, 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 are likely to occur, no matter whether particle breakage occurs or not.

RÉSUMÉ: Plusieurs études récentes sur les mélanges de sables de granulométries et/ou minéralogies différentes ont été concentrées sur les facteurs clefs qui pourraient amener le comportement à changer de « transitionnel » a « non transitionnel », où un comportement transitionnel se caractérise par une non convergence des chemins de compression et la non unicité des lignes d'états critiques. Les auteurs présentent une revue des mélanges de sables montrant un mode complexe de comportement en compression et en cisaillement, où des variations relativement petites en proportion et nature des grains provoquent un comportement transitionnel. Des programmes d'essais en laboratoire, sur appareils œdométriques, ont permis de confirmer le rôle de la minéralogie de la matrice formée des gros grains. Le mode de comportement est ainsi déterminé, que si la matrice est forte, rigide, et composée de grains de sable de quartz plus gros ou au moins de taille similaire à l'autre composante du sol, alors il est probable que les chemins de compression soient non convergeant, qu'il y ait cassure des grains ou non.

Keywords: Laboratory tests; Mixtures; Sands; Compressibility; Transitional behaviour

1 INTRODUCTION

Several recent studies on the mechanical behaviour of intermediate graded soils, either natural or reconstituted, highlighted a transitional mode of behaviour in which non-convergent paths and/or non-unique Critical State Lines occur (e.g. Nocilla et al., 2006; Ventouras & Coop, 2009; Ponzoni et al., 2014). Non-convergent compression paths and/or non-unique Critical State Lines (CSLs) were initially observed for gap graded soils (e.g. Martins et al., 2001; Ferreira & Bica, 2006). An extensive analysis of the key factors (i.e. particle nature, granulometry and mineralogy) that may have a role on the occurrence of this behaviour was then carried out, although a clear picture had not yet emerged. Analysing the previous study on sand or sand-silt mixtures, Ponzoni et al. (2017) highlighted that the transitional behaviour occurred for mixtures in which the matrix was made of larger particles of quartz, no matter whether the other component was of the same mineralogy or not.

Studies on the influence of particle breakage of gap graded soils after compression up to elevate stresses or intense shearing (e.g. Miao & Airey, 2013; Zhang & Baudet, 2015) showed that the breakage process tends to preserve features of the initial grading, so gap gradings tend to remain bi-modal. Hence, it is reasonable to imagine the influence of this feature on transitional behaviour, which is characterised by a similar difficulty of erasing the initial differences in fabric (Todisco et al., 2018). Despite that, whether particle breakage occurs or not, it was proven not to determined whether a transitional mode of behaviour is seen (e.g. Shipton & Coop, 2012).

As for the influence of mineralogy, the theory of breakage mechanics took into account the features of mixed components, highlighting that in a mixture, the stronger mineral, such as quartz, dominates the compression behaviour (Nakata et al., 2001).

Considering this, the present paper presents the essentials of two laboratory programmes consisting of oedometer tests that were conducted to confirm the role of the mineralogy of the larger grains and that were carried out by the authors on gap graded mixtures of sands using the same mineralogy but with the reverse compositions (Ponzoni et al., 2017; Nocilla et al., 2018). These results were then compared with a previous study (i.e. Shipton & Coop, 2012), with the purpose of assessing a clear role of the mineralogy of components on the occurrence of non-convergent compression paths for artificial gap graded sandy mixtures of similar mineralogy. Indeed, the authors hypothesise that a much more robust fabric is 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, leading to transitional behaviour. A further comparison with a natural gap graded soil composed of larger quartz grains of sand and kaolinite (Martins et al., 2001) seems to confirm the role of the mineralogy of the larger grains in the occurrence of transitional behaviour strengthening the hypothesis that this would not be simply an artefact of created soils with artificial fabric but can be extended to natural gradings.

2 LABORATORY TESTS

The authors' two studies summarised in this paper were carried out on quartz-carbonate mixtures of Leighton Buzzard sand (LBS) and Carbonate sand (CS) partly in response to the work of Shipton & Coop (2012) who found transitional behaviour in a mixture of quartz-carbonate mineralogy of Thames valley sand (TVS) and Dogs Bay sand (DBS). All the compared mixtures then feature similar (or identical) mineralogy and show low ratios R, where R is the ratio of large to small grain diameters which was estimated as the ratio between dmax (mean value of the larger particle size distribution) and dmin (mean value of the smaller particle size distribution). In Table 1, the three mixture properties have been summarised. According to the data estimated in the former papers, they are all composed of a low sphericity angular carbonate sand (Calcium Carbonate between the 88-99%) mixed with high sphericity sub-rounded grains of quartz sand (Silicon dioxide at 100%). Initial particle size distributions are shown in Figure 1.

Table 1. Mixture properties

Soil	Sand	Gs	Grading [mm]	R	d_{mean} [mm]
Shipton & Coop (2012)	DBS TV	2.71 2.67	0.212-0.3 0.18-0.6	1.5	0.26 0.39
Ponzoni et al. (2017)	CS LBS	2.72 2.66	0.71-2.36 0.212-0.8	3.0	1.54 0.51
Nocilla et al. (2018)	CS LBS	2.72 2.66	0.075-0.425 0.85-2	5.7	0.25 1.43

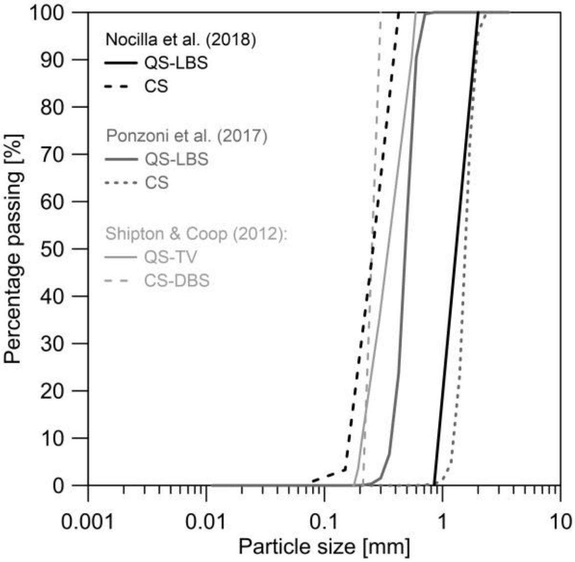

Figure 1. Particle size distribution of sands tested in the two studies of the authors and by Shipton & Coop (2012).

Larger grains of quartz feature the mixtures of Shipton & Coop (2012) and of Nocilla et al. (2018), while the reverse mineralogy of larger grains (i.e. larger grains of carbonate) characterizes the mixture of Ponzoni et al. (2017).

For both the works of the authors (Ponzoni et al., 2017; Nocilla et al., 2018) 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. Ponzoni et al. (2017) carried out twenty-one oedometer tests using a conventional 50mm diameter fixed ring oedometer. A 30mm diameter floating ring oedometer was also used in order to reach high pressures (up to 25MPa) while minimising wall friction. Subsequently, Nocilla et al. (2018) carried out twenty-four oedometer tests using a conventional 38mm diameter fixed ring oedometer (up to stresses of 12.4MPa) and a 30mm diameter floating ring oedometer (up to 20.5MPa).

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. Gs was not the same for the two sands so that the specific volumes have to be determined by means of the phase equations. The obtained data were then compared with the results of Shipton & Coop (2012).

3 DEGREE OF TRANSITIONAL BEHAVIOUR

By way of example, for the three studies, compression data for mixtures with a prevalent amount of quartz sand (80%Q-90%Q) are shown in Figure 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 Ponzoni et al. (2017) mixtures only, in which the larger particles were of carbonate. In contrast this, the other two mixes (Shipton & Coop, 2012; Nocilla et al., 2018), characterised by larger grains of quartz, showed a non-convergent compression behaviour. The non-convergence of the compression paths for these mixtures, highlights a compression behaviour, that can be defined as transitional, which is distinctly different from that seen by Ponzoni et al. (2017), for which unique normal compression lines occurred no matter what their proportions.

In the case of Ponzoni et al. (2017), effective vertical stresses at which the convergence occurs, depend on the amount of each mineral content and the corresponding particle strengths, which are significantly different so that the one dimensional normal compression lines (1D-NCLs) shown in Figure 3 vary their location according to the amounts of quartz content. The slope chosen for each 1D-NCL was constant and, since the lines appeared to be parallel, it was set to a value of 0.48.

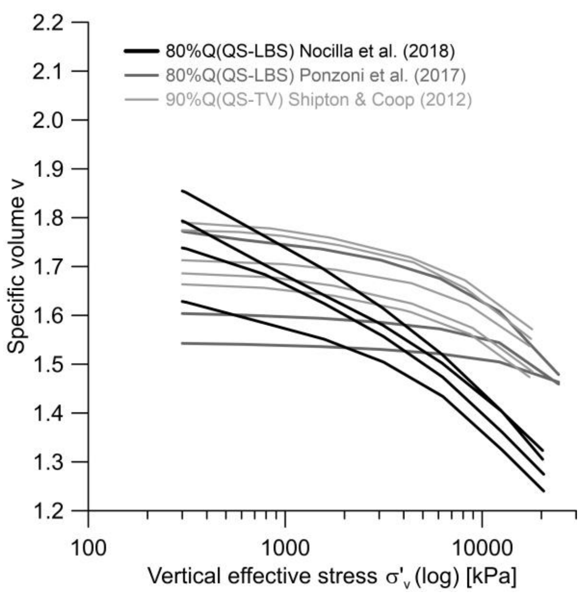

Figure 2. Oedometer compression curves for mixtures of quartz (80%Q-90%Q) and carbonate sands.

Indeed the different spacing of the 0%Q and 100%Q NCLs on Figure 3 could be influenced by the different R values of the two researches, but it does not seem likely that a relatively small R difference would have such a large effect.

In the study carried out on the identical mineralogy (i.e. Nocilla et al., 2018), only for the single mineral samples (0%Q and 100%Q), the convergence of compression paths eventually occurred, as expected (Coop & Lee, 1993; Coop, 2005), for effective vertical stresses that depend on the corresponding particle strengths. Similarly to the 1D-NCLs of Ponzoni et al. (2017), again for Nocilla et al. (2018) the slope chosen for the 1D-NCLs was fixed at the same value of 0.48. The Figure 3 indeed shows the influence of the mineralogy on the location of the compression lines for which the 1D-NCL moves towards higher stresses for the quartz. Therefore, the relative positions confirm, as observed by McDowell & Bolton (1998), that 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 Nocilla et al. (2018) than those of Ponzoni et al. (2017).

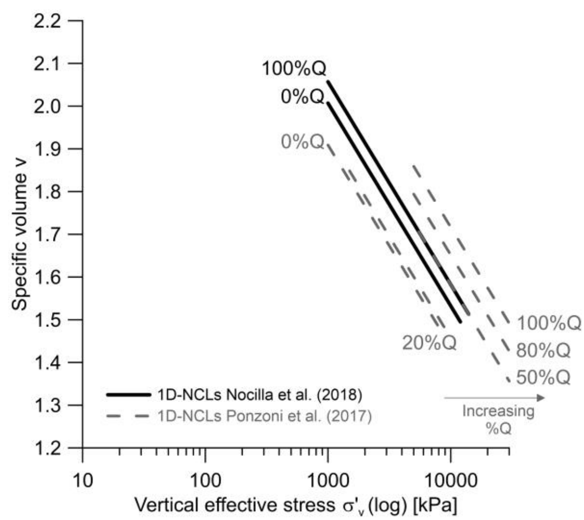

Figure 3. 1D-NCLs for the mixtures of Ponzoni et al. 2017 and Nocilla et al. 2018.

Indeed, comparing the 0%Q of the two studies, for Ponzoni et al. (2017) the 0%Q specimens are made of carbonate particles which are larger than those of Nocilla et al. (2018) and are then more prone to particle breakage so that the 1D-NCL is encountered at lower stresses. The 100%Q specimens, instead, are made of smaller quartz particles than those of Nocilla et al. (2018) and are then less prone to particle breakage so that the 1D-NCL is encountered at higher stresses.

According to the Ponzoni et al. (2014) quantification of the degree of transitional behaviour m, defined by plotting the void ratios at the highest common stress reached in the oedometer (12.4 MPa) against the initial values at 20kPa, the values of m were quantified (Figure 4). For soils with fully convergent paths, like for example the single mineralogy samples, the gradient of the data on this graph, defined as m, would be zero while for soils with perfectly parallel compression paths m=1. The value of m for the non-convergent oedometer curves of Nocilla et al. (2018) are 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 and m is then zero. For the convergent behaviour of the mixes of Ponzoni et al. (2017), values of m equal to 0 were assumed for all proportions.

Thus far, the comparison between the two mineralogically identical artificial gap graded mixes (Ponzoni et al., 2017; Nocilla et al., 2018) with the similar artificial mixture of Shipton & Coop (2012) highlights that the mineralogy of the larger grains seemed to determine the possibility of the occurrence of the transitional mode of compression behaviour. In the literature, Martins et al (2001) carried out oedometer tests on a reconstituted samples of a natural gap graded soil (70%Q), the Botucatu Residual Sandstone (BRS), made of quartz sand and kaolinite clay particles.

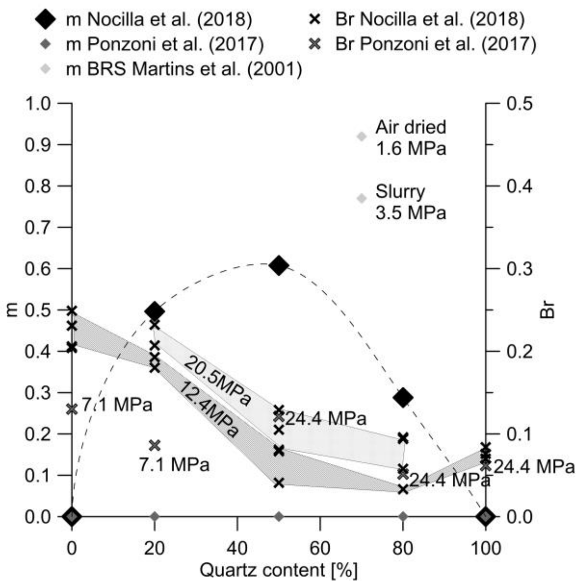

Figure 4. Degree of transitional behaviour m and Relative Breakage Br for Ponzoni et al. 2017 and Nocilla et al. 2018.

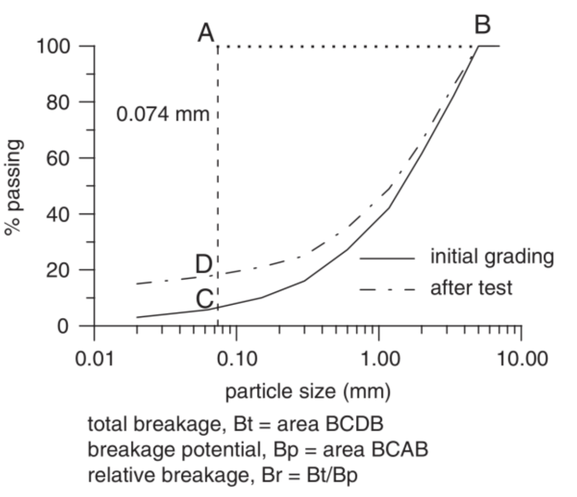

Figure 5. Definition of relative breakage, Br (Hardin, 1985).

The oedometer tests carried out on samples of BRS, with different packing methods, highlighted the typical non-convergent paths of the transitional behaviour. In the present paper, the estimation of the degree of transitional behaviour was then carried out for data of Martins et al. (2001) and values of *m* are shown on Figure 4 along with the artificial gap graded mixtures of Ponzoni et al. (2017) and Nocilla et al. (2018).

Although the quartz sand is mixed with fines and the highest stresses reached are smaller (up to 3.5MPa), the m values of the Martins et al. (2001) mixtures have been reported highlighting the transitional behaviour, which was afterwards confirmed by Ferreira and Bica (2006) who tested reconstituted samples of BRS at higher stresses (25MPa).

3.1 Particle Breakage

Figure 4 shows data of the analysis of the particle breakage in terms of Hardin's (1985) relative breakage Br (Figure 5) either for the studies of Ponzoni et al. (2017) and Nocilla et al. (2018). For the mixes of Nocilla et al. (2018) with larger grains of quartz and non-convergent paths, it is possible to observe a convex trend of the line interpreted for the Br values which seems to be the mirror image of the trend of m.

On the contrary, no particular trend results from data of Ponzoni et al. (2017) for which the overall breakage is low even with convergent paths. Although this confirms that the amount of overall breakage is not a good guide as to whether transitional behaviour may occur or not, for Nocilla et al. (2018), the quartz content seems to be an influencing factor for Br.

Relative particle breakage Br, in mixtures, depends on the relative strengths of particles according to grain dimensions and mineralogy, on maximum reached stresses and on the initial specific volume (i.e. density). Indeed, a close inspection of the values of initial specific volume for Nocilla et al. (2018), indicates a general trend for which denser samples show higher breakage, in contrast to what was expected (Altuhafi & Coop, 2011), but this may add to the scatter of values.

In Figure 6 are plotted the initial and final particle size distributions of 80%Q of Ponzoni et al. (2017). As shown, despite the high stress (about 24 MPa) and a unique 1D-NCL being reached, the gap graded features are not erased. The amount of breakage for the larger carbonate particles is low and there was no possibility of identifying the relative amount of Br for the single mineral components. The evolution of breakage in the mixture should then be measured, if possible, separating the single mineral components.

In Figure 7 are plotted the initial and final particle size distributions of 80%Q and 50%Q of Nocilla et al. (2018). Similarly to Figure 5, the gap graded features are not erased. For the 50%Q, the amount of breakage for the larger quartz particles tends to zero. This is probably due to the particle strength of quartz so that it is clear that breakage involves the carbonate particles only.

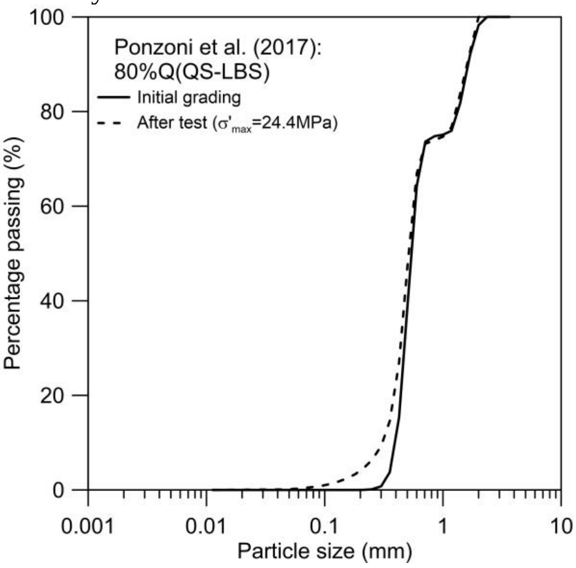

Figure 6. Initial and final particle size distribution (Ponzoni et al., 2017).

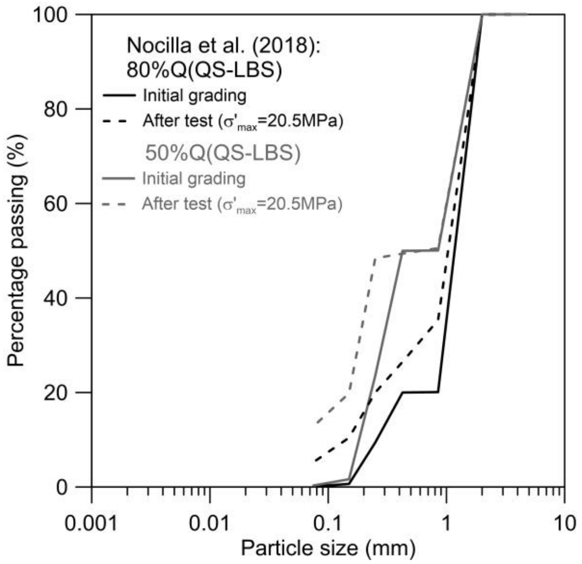

Figure 7. Initial and final particle size distribution (Nocilla et al., 2018).

On the contrary, for a mixture with higher quartz content (80%Q), as observable from Figure 7, there is no possibility of identifying the relative amount of Br for the single mineral components since also the larger quartz particles are involved in breakage so that it is impossible to assess the mineralogy which is predominantly involved in the particle breakage and a further analysis of the single mineral breakage evolution is recommended.

4 CONCLUSIONS

For artificial mixtures, for the first time, a key factor of the transitional behaviour is observable: the mineralogy of the matrix composed by larger grains seems to determine the mode of behaviour. This conclusion was achieved observing previous results obtained from oedometer tests carried out on artificial gap graded mixture of sands of similar binary mineralogy and reverse combinations of larger grain mineralogy.

The conclusions that may be drawn are as follows:

- When larger grains are made of carbonate, convergent compression paths do occur at elevated stress. In terms of structure, the initial fabric seems to be destroyed as vertical stresses increase in one dimensional conditions. It would seem that the quartz smaller particles allow the remaining particles to form a new spatial arrangement, a new fabric and the convergence to a unique 1D-NCL.

- When larger grains are made of quartz, non-convergent compression paths do occur at elevated stress. The initial fabric seems not to be completely destroyed as vertical stresses increase in one dimensional conditions, particle breakage occurs mainly in carbonate smaller particles. Hence, it can be hypothesised that larger grains of quartz preserve the original spatial arrangement and the former fabric which would be then difficult to erase, even when the quartz content increases and the breakage involves also this strongest component. Further study should be carried out on other binary mixtures of 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.

In the case of mixtures of Nocilla et al. (2018) a correlation between the occurrence of the transitional mode of behaviour and the amount of particle breakage seems to be present. Indeed, although the role of density is still unclear, 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 degree of convergence m.

- The comparison with reconstituted sample of the Botucatu Residual Sandstone (BRS), which is a natural gap graded soil composed of larger quartz grains of sand and kaolinite (Martins et al., 2001), seems to confirm the role of the mineralogy of larger grains on the occurrence of the transitional behaviour strengthening that this achievement would not be simply an artefact of created soils with artificial fabric but can be extended to natural de-structured soils too.

5 ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Prof. Beatrice Baudet for her kind advice and to Dr. Greta Tanghetti for carrying out some of the tests.

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