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The behaviour of a gap graded sand with mixed mineralogy

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Abstract

The compression and shearing behaviour in mixtures of soils of different granulometries and/or mineralogies has been researched extensively. The focus of the research has been to identify the key factors that might lead the behaviour to change from transitional to not transitional, where transitional behaviour is characterised by non-convergent compression paths and critical state lines that might be non-unique. A review of mixtures of different soils revealed a complex pattern of behaviour, in which transitional behaviour can be caused by relatively small changes in the proportion or nature of the soil particles. It was then assumed that the mineralogy of the matrix composed by larger grains determines the mode of behaviour. If there is a strong and stiff matrix made of quartz sand particles either larger than or at least of a similar size to the other component, then non-convergent compression paths and/or not unique CLSs are likely to occur. This paper presents the results of triaxial and oedometer tests on a range of mixtures of a quartz sand and a carbonate sand, but with a larger weaker carbonate sand component. As predicted, no transitional behaviour was seen in any mixture.

Keywords: Laboratory tests; Sandy mixtures; Gap graded soils; Transitional behaviour

1. Introduction

Many reconstituted and natural intermediate graded soils have been shown to have a 'transitional' behaviour for which unique Normal Compression and Critical State Lines cannot be identified (e.g. Nocilla et al., 2006; Nocilla and Coop, 2008; Ponzoni et al., 2014). The first soils described as "transitional" were gap-graded (i.e. Martins et al., 2001). Numerous gap-graded soils have since been tested to evaluate the influence of particle nature, granulometry and mineralogy (e.g. Shipton and Coop, 2012) on mixtures consisting of different grain size and/or types. However, a clear picture has not yet emerged.

In the case of sand, an apparently near-unique NCL is obtained only when grain crushing becomes prevalent. Nakata et al. (2001a) showed that as the coefficient of uniformity increases, the yield in compression becomes less distinct and the nature of crushing changes from the sudden catastrophic onset of splitting to the gradual splitting of smaller particles. By varying only the granulometry, Altuhafi and Coop (2011) found that as three sands were changed from poorly graded to fractally graded, their compression behaviour evolved from a "sand" type with a unique NCL and large amounts of crushing, to non-convergent behaviour with no breakage. McDowell and Bolton (1998) and Coop et al. (2004) identified that because the compression or shearing at high stresses tends to make the grading of a sand fractal, breakage might be quantified as a function of the final fractal grading (Einav, 2007).

For binary mixtures of single mineralogy, several complex factors may influence breakage and compressibility (e.g.: co-ordination number, grain strength, size of larger

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Nomenclature

e	void ratio	γ_i	initial bulk unit weight
D_{50}	particle size for 50% passing of larger grains	γ_f	final bulk unit weight
d_{50}	particle size for 50% passing of smaller grains	γ_{di}	initial dry unit weight
G_s	specific gravity of soil grains	γ_{df}	final dry unit weight
M	gradient of critical state line in $q{:}p'$ plane	γ_w	unit weight of water
q	deviatoric stress	ε_a	axial strain
p'	mean normal effective stress	ε_v	volumetric strain
p'_0	value of p' at start of shearing	σ'_{vmax}	maximum vertical stress
S_{ri}	initial degree of saturation	σ'_y	vertical yield stress
S_{rf}	final degree of saturation	σ_f	single particle crushing strength
v_i	initial specific volume	φ'_{cs}	critical state angle of shearing resistance
v_{20}	specific volume at 20 kPa vertical stress	ψ	state parameter
w_f	final water content		
w_i	initial water content		

particles, initial fabric, grain shape). Miao and Airey (2013) and Zhang and Baudet (2015) showed that because the breakage process tends to preserve features of the initial grading, the gap gradings tend to remain bi-modal even after compression to high stresses or intense shearing. Considering the difficulty of altering the initial bimodal grain distribution in a gap graded soil, it is reasonable to investigate the influence of this feature on transitional behaviour, since transitional behaviour also is characterised by difficulty erasing the initial differences in fabric of samples made at different initial void ratios (Todisco et al., 2017). Nevertheless, the occurrence of particle breakage does not necessarily indicate a transitional mode of behaviour (e.g. Shipton et al., 2006; Carrera et al., 2011; Shipton and Coop, 2012; Zhang and Baudet, 2013).

For binary mixtures of different mineralogies, the theory of breakage mechanics was extended to take into account their separate component features (Einav and Valdes, 2008). Nakata et al. (2001b) reported that the stronger mineral in a mixture, such as quartz, dominated the compression behaviour, and that the yield stress increases as the quartz content increases. Leleu and Valdes (2007) showed that in a specimen with a weak carbonate matrix, the quartz content does not substantially modify the compression behaviour unless the fraction of strong particles is considerable, while Evans and Valdes (2011) identified the existence of a transition fraction of weak particles that, when added to a stiff matrix, resulted in a change of regime in force transmission. The extent of the change was shown to be dependent on the relative stiffness of the particles.

2. Transitional behaviour in soil mixtures

Recent research on the transitional behaviour in gap graded sand and sand-silt mixtures by the authors and co-workers is summarised in Table 1 where the term "principal mineralogy" is the matrix mineralogy (i.e. "principal" means the larger percentage in weight). For all the gap graded mixtures the ratio of large to small grain diameters, R was estimated as the ratio between d_{max} and d_{min}, where the d_{max} is the mean value of the larger particle size distribution, and d_{min} is the mean value of the smaller particle size distribution. It should be noted that R is estimated as $R^* = D_{50}/d_{50}$ in the literature (e.g. Cabalar and Hasan, 2013; Zuo and Baudet, 2015), providing a rigorous definition of this value. Unfortunately, D_{50} and d_{50} were not always available for the gap graded soil data collected in Table 1. Nevertheless, for fairly uniform soils, the magnitude of R is reasonably similar to R^*.

In Table 1, there is one notable exception with regard to soil types. Well graded sand was not included in the table. For the varying natural fine contents, the behaviour of Thanet sand is sometimes characterised by its unique NCL, and at other times it is characterised by its non-convergent compression behaviour (Ventouras and Coop, 2009). However, the percentage of the minor constituent when a unique NCL occurred was only in the range of 5–10%.

In Table 1, for gap graded soils, non-convergent compression paths and/or non-unique CSLs were detected for mixtures with a matrix made of larger particles of quartz (the grey rows), regardless of whether the other component is of the same mineralogy or not. The only exception is the binary mixture of 60% quartz silt and 40% carbonate sand, which showed non-convergence with larger particles of another mineralogy (Shipton et al., 2006). However, in this case, the stresses applied were not as high as those reached in further tests carried out by Shipton and Coop (2012) on similar mixtures where unique NCLs were eventually encountered at extremely high stresses. This suggests that reaching high stresses is important when assessing the possibility of transitional behaviour. Regardless of whether low particle breakage is a prerequisite for transitional behaviour, Shipton and Coop (2012) reported quartz-carbonate mixtures with a quartz matrix demonstrated non-convergent behaviour with low overall breakage, and

Table 1
Summary of research carried out by the authors and co-workers on transitional behaviour in sand or sand-silt mixtures.

Soil	Reference	Origin and grading	Particle size distribution			Principal mineralogy	Mineralogy larger grains	U d_{60}/d_{10}	R=dmax/ dmin	σ'_y [MPa]	σ 'max [MPa]	Br	Observations on compression and shearing behaviour
			Clay	Silt	Sand								
Thanet sand and plastic silt	Ventouras & Coop (2009) (Reanalysed by Shipton & Coop, 2012)	Well-graded Artificial	-	15-30% Plastic	70-85% Q	Q	Q	7.7^{+}	6.98^{+}	5.5-6.0	25.0	-	Non-convergent compression paths
			-	5-10% Plastic	90-95% Q	Q	Q	2.1^{+}	6.97^{+}	-	-	-	Unique NCL
Carbonate sand and crushed quartz silt	Shipton et al. (2006)	Gap-graded Artificial	-	60% Q	40% C	Q	C	Q 9.7 C 1.44	8.10	0.4-1.0	8.0	0.20	Non-convergent compression paths (low stress level reached)
Carbonate sand and crushed quartz silt	Shipton & Coop (2012)	Gap-graded Artificial	-	40% Q	60% C	C	C	Q 9.7 C 1.2	4.66	0.2	7.0	-	Unique NCL
										0.7	11.0		
			-	60% Q	40% C	Q	C		4.66	0.8	11.0	-	
										5.0	30.0		
			-	100%Q	-	Q	Q	Q 9.7	-	1.0-7.0	7.0	-	
										7.0	30.0	-	
Carbonate sand and quartz sand	Shipton & Coop (2012)	Gap-graded Artificial	-	-	100%C	C	C	1.2	-	-	-	-	Unique NCL
			-	-	30%Q 70% C	C	Q	Q 2.2 C 1.2	1.50	0.8 - 1.1	5.0	0.22	Unique NCL
										1.5 - 3.0	15.0	0.39	
			-	-	50%Q 50% C	QC	Q		1.50	-	-	-	Unique NCL
			-	-	70%Q 30% C	Q	Q	Q 2.2 C 1.2	1.50	-	-	-	Non-convergent compression paths
			-	-	90%Q 10% C	Q	Q		1.50	-	5.0	0.04	Non-convergent compression paths
										4.5- 5.0	15.0	0.12	
			-	-	100%Q	Q	Q	2.2	-	-	-	-	Unique NCL
Quartz sand and crushed quartz silt	Shipton & Coop (2012)	Gap-graded Artificial	-	25% Q	75% Q	Q	Q	Qsilt 9.9 Q 1.4	7.95	?	7.5	negligible	Non-convergent compression paths
										?	27.7	negligible	
Quartz sand and crushed quartz silt	Shipton & Coop (2015)	Gap-graded Artificial	-	25% Q	75 Q	Q	Q	Qsilt 9.9 Q 1.4	7.95	?	7.1	negligible	Non-convergent compression paths/ No unique CSL
										?	110.1		

Q = Quartz; C = Carbonate; + calculated from 1PSD; – data missing; ? difficult interpretation. Grey rows highlight non-convergent compression paths and, eventually, no unique CSL.

that the breakage that occured was almost completely within the carbonate component.

A close examination of the data in Table 1 leads to the hypothesis that a quartz matrix includes a robust fabric which is difficult to erase. The other component of the mixture may have smaller particles or particles of a similar dimension and be either of the same mineralogy or of a weaker type. This component can break severely, inhibiting the breakage of the larger quartz particles: this would prevent a unique NCL being defined.

Examples of investigations of transitional behaviour are limited in the literature. This can be explained by the fact that a wide range of initial specific volumes is not tested in many cases. In Table 2, other more complex, gap graded mixtures of sand and finer particles are shown. Although the R values are generally much higher than those in Table 1, similar patterns are often observed and non-convergent compression behaviour and/or transitional behaviour is seen. In soils with natural mineralogies, such as some of those listed in Table 2 (e.g. Ferreira and Bica, 2006; Carrera et al., 2011), the mineral heterogeneity and the complexity of the constituents complicates the behaviour and leads to apparent inconsistencies. An investigation of the influence of particle shape might provide insight into these inconsistencies. Hence, research on artificial soils can guarantee better control.

From Table 1 and partially from Table 2, the conclusions that may be drawn are as follows:

- It is important to reach high stresses in order to assess any possible transitional behaviour during compression.
- Ideally, the relative breakage of single components in the mixture should be measured in order to assess any possible influence of crushing in determining transitional behaviour.
- The mineralogy of larger grains seems to determine the mode of compression behaviour regardless of the R value, the overall breakage (Br) value, and mineralogy of the other constituent.

With these considerations taken into account, the research described in this paper presents a new series of oedometer and triaxial tests that were conducted to investigate the role of the mineralogy of the larger grains. No transitional behaviour is expected for gap graded mixtures of sands featuring larger grains of a weaker type for any proportion, but such data do not exist. Hence, for comparison purposes with the results of previous investigations, this study focused on the mechanical behaviour of gap graded mixtures with a low ratio of large to small grain diameters R, and larger particles always of the same weaker type (i.e. carbonate).

3. Materials, procedures and laboratory tests

The research described in this paper was carried out partly in response to the work of Shipton and Coop (2012) who found transitional behaviour in the mixture of quartz-carbonate mineralogy of Thames valley sand (TVS) and Dogs Bay sand (DBS) with a low ratio R of 1.5 and a matrix and larger particles of quartz. According to descriptions of Shipton and Coop (2012), the TVS is a quartz sand that consists of strong and sub-rounded particles characterised by high sphericity, a specific gravity G_s of 2.67 and the grain dimensions of between 0.18 and 0.6 mm, whereas the DBS has angular and weak shelly carbonate particles of low sphericity, a specific gravity G_s of 2.71, and grain dimensions of between 0.212 and 0.3 mm.

In order to confirm the importance of the mineralogy of the matrix and larger grains, this research is focused on the mechanical behaviour of mixtures of a similar quartz-carbonate mineralogy with a low ratio R of 3.02 and larger particles always of the weaker type (i.e. carbonate). High pressure one-dimensional compression tests and standard drained triaxial tests were performed on specimens of mixtures that were created artificially by mixing two soils of these different mineralogies. The Leighton Buzzard sand (LBS) is a quartz sand which consists of strong and sub-rounded particles, characterised by high sphericity, a specific gravity G_s equal to 2.66 and grain dimensions between 0.212 and 0.80 mm. The crushed carbonate sand (CS), obtained by crushing a weak limestone, has sub-angular and weak particles, with low sphericity, a specific gravity G_s equal to 2.72 and grain dimensions between 0.70 and 2.36 mm. Thermogravimetric analyses were carried out in order to detect the mineral compositions of these two sands. The results are summarised in Table 3. Raman spectroscopy was carried out for the analysis of the structural characteristic of particles of LBS highlighting an alpha type of silica particles. Single particle strengths σ_f have been also measured (Tso and Wang, 2015) and characteristic strengths of 406 MPa and 39 MPa were found for the LBS and for CS, respectively. The initial commercial particle size distributions were confirmed before testing by means of a laser scanning particle analyser. All four sand grain characteristics for the current research and that of Shipton and Coop (2012) are summarised for comparison in Table 3, while the particle size distributions are shown in Fig. 1.

Five “mixtures” were considered. Two of them were comprised of one mineral only, and three were mixtures of the two soils: 80% Quartz/20% Carbonate, 50% Quartz/50% Carbonate, and 20% Quartz/80% Carbonate by dry weight. Details of these soils are provided in Table 4. Tenty one oedometer tests were carried out using a conventional 50 mm diameter fixed ring oedometer and a 30 mm diameter floating ring oedometer, used to reach high pressures (up to 25 MPa) while minimising wall friction. In order to create groups of samples with the same initial specific volumes and to control their repeatability, wet compaction was used.

To ensure apparent non-convergence does not arise from inaccurate data, it is crucial that the measurements of the initial specific volume, v_i, are taken carefully. Rocchi and Coop (2014) showed that the initial specific

Table 2
Summary of literature on transitional behaviour for more complex gap graded soils.

Soil	Reference	Origin and grading	Particle size distribution			Principal mineralogy	Mineralogy larger grains	U d_{60}/d_{10}	R=dmax/dmin	σ'_y [MPa]	σ'_{max} [MPa]	Br	Observations on compression and shearing behaviour
			Clay	Silt	Sand								
Residual Botucatu Sandstone	Martins et al. (2001)	Gap-graded Reconstituted	30% F	7%	63% Q	Q	Q	28.7^{+}	503.61^{+}	0.03-0.1	3.5	-	Non-convergent compression paths
Sand Kaolin mixture		Gap-graded Reconstituted	20%K	5%	75%Q	Q	Q	153.0^{+}	281.82^{+}	0.06-0.4	3.5	-	
Residual Botucatu Sandstone	Ferreira & Bica (2006)	Gap-graded Natural	10%K	20%	70%Q	Q	Q	64.0^{+}	1515.35^{+}	1.1-3.0	24.0	-	Unique NCL and CSL
		Gap-graded Reconstituted Remoulded	10%K	20%	70%Q	Q	Q	64.0^{+}	302.54^{+}	1.2	22.0	-	Non-convergent compression paths/ No unique CSL
Carbonate sand and kaolin	Shipton et al. (2006)	Gap-graded Artificial	60%K	-	40%C	K	C	1.4C 1312.2K	1.30	-	0.1	0.08	Non-convergent compression paths
										0.4	3.0	0.28	
										0.5	28.6	0.46	
Carbonate sand and kaolin	Shipton & Coop (2012)	Gap-graded Artificial	95%K	-	5%C	K	C	1.2C 4.7K	35.01	?	8.0	0.04	Non-convergent compression paths
								1.4C 4.7K	85.95	?	0.1	-	
										?	30.0	-	
			90%K	-	10%C	K	C	1.2C 4.7K	35.01	?	8.0	0.03	
								1.4C 4.7K	85.95	?	0.8	-	
										?	15.0	-	
								1.2C 4.7K	95.61	?	0.05	0	
										?	14.0	0.14	
			60%K	-	40%C	K	C	1.4C 4.7K	85.95	?	0.1	0.08	
										0.1-0.2	30.0	0.53	
			30%K	-	70%C	C	C	1.2C 4.7K	35.01	0.4	8.0	0.19	Unique NCL
									49.49	0.25	30.0	-	
Quartz sand and kaolin	Shipton & Coop (2012)	Gap-graded Artificial	100%K	-	0%Q	K	K	4.7K	-	?	1.1	-	Unique NCL
										?	8.0	-	
			75% K	-	25% Q	K	Q	1.9Q 4.7K	36.47	?	0.7	-	
										?	8.0	-	
			50%K	-	50%Q	K Q	Q			?	3.0	-	
										?	8.0	-	
			25%K	-	75%Q	Q	Q	1.9Q 4.7K	36.47	1.5	0.7	-	Non-convergent compression paths
										3.0	30.0		
			10%K	-	90%Q	Q	Q			0.9-1.2	8.0	-	
			0%	-	100%Q	Q	Q	1.9Q	-	5.0-11.0	30.0	-	Unique NCL
Quartz sand and kaolin	Shipton & Coop (2015)	Gap-graded Artificial	25%K	-	75%Q	Q	Q	1.9 Q 4.7 K	36.47	0.8	8.0	negligible	Non-convergent compression paths/ No unique CSL
										4.5	28.4		
Stava Tailings	Carrera et al. (2011)	Gap graded Reconstituted	-	0%	100%Q	Q	Q	Q 2.4	-	2.0-3.0	14.0	negligible	Unique NCL
			-	10%Q	90%Q	Q	Q	Qsilt 8.6 Q 2.4	25.76	1.2-2.0			
			-	30%Q	70%Q	Q	Q		25.76	3.0-6.5			
			-	50%Q	50%Q	Q	Q		25.76	1.5			
			-	70%Q	30%Q	Q	Q		25.76	1.5			
			-	100%Q	0%	Q	Q	Qsilt 8.6	-	1.5			

Q = Quartz; C = Carbonate; F = Feldspar; K = Kaolin; $^{+}$ calculated from 1PSD; – data missing; ? difficult interpretation. Grey rows highlight non-convergent compression paths and, eventually, no unique CSL.

Table 3
Mixture properties: comparison with Shipton and Coop (2012).

Soil	Sand	Mineralogy	Gs	Shape[+]	Grading [mm]	R	d_{50}	R*	Note	σ'_{sf} [MPa]
Shipton and Coop (2012)	Dogs Bay Sand	Calcium carbonate ($CaCO_3$: 88–94%)[1]	2.71	Low sphericity angular[3]	0.212–0.3	1.5	0.25	1.2	Sieving	25[5]
	Thames Valley	Flint (SiO_2: ~100%)[2]	2.67	High sphericity sub-rounded[4]	0.18–0.6		0.30		Natural grading	–
This research	Crushed Limestone	Calcium carbonate ($CaCO_3$: 99%)	2.72	Low sphericity sub-angular	0.71–2.36	3.02	1.56	3.25	Sieving	39
	Leighton Buzzard Sand	Quartz (SiO_2: 100%)	2.66	High sphericity sub-rounded	0.212–0.8		0.48		Sieving	406

[1] Data from Houlsby et al. (1988).
[2] Data from Hughes (1973).
[3] Data from Yasufuku and Hyde (1995).
[4] Data from Takahashi and Jardine (2007).
[5] Data from Yasufuku et al. (2006).
[+] Classification based on Powers (1953).

volumes, v_i, can be calculated from different methods using measurements as independent of each other as possible, although some inter-dependency is necessarily present.

The measurements taken in the oedometer tests presented in this study were based on the initial and final dry unit weight, on the initial and final water content and on the final bulk unit weight. After discarding clearly anomalous data, the absolute value of the maximum difference between the mean of the initial specific volumes and the single calculated values was 0.02 as an average. The mean standard deviation between the methods was also equal to 0.02.

Twenty-five consolidated drained triaxial tests on 50 mm diameter samples (Table 5) were carried out in a conventional triaxial apparatus. During isotropic compression, samples reached mean effective stresses of up to 600 kPa. Reconstituted samples were created by wet compaction, wet pluviation or wet pluviation plus tamping in order to achieve as wide a range of initial specific volumes as possible. Unfortunately, the wet pluviation method of preparation, used to reach the highest possible saturations of the mixture, made it impossible to take measurements of the initial bulk unit weight and initial water content of the sample. Hence, in order to estimate the initial specific volume, measurements were based on the initial and final dry unit weight, on the final water content and on the final bulk unit weight. The average accuracy for the initial specific volumes, discarding any anomalous data, was ± 0.007 while the absolute value of the maximum difference between the average and single calculated values was, on average, 0.03. The mean standard deviation between methods was equal to 0.006. For both types of tests, a weighted value of G_s was used for all mixtures.

4. Compression behaviour in oedometer tests

Compression data for the five mixtures are shown in Fig. 2. The oedometer tests show that it is possible to identify a unique one-dimensional normal compression line (1D-NCL) in the v-log σ'_v plane at higher stress levels for each soil or mixture. The convergence of the compression paths for all the five mixtures tested, including those with a large amount of stronger grains, highlights, as shown in Fig. 3, a compression behaviour which is distinctly different from that seen by Shipton and Coop (2012) for which transitional behaviour (i.e. non-convergence of compression paths) occurred if the mixtures were composed of a matrix of stronger larger particles of quartz with a quartz content between 70% and 90%.

The mixtures of Fig. 2 are therefore not examples of transitional soils, despite a similar low R ratio and a mineralogy similar to those of Shipton and Coop (2012) except that the larger particles were of quartz in Shipton and Coop's study. The convergence of compression paths eventually occurs for effective vertical stresses that depend on the amount of each mineral content and the corresponding particle strengths, which differ significantly. Hence, for

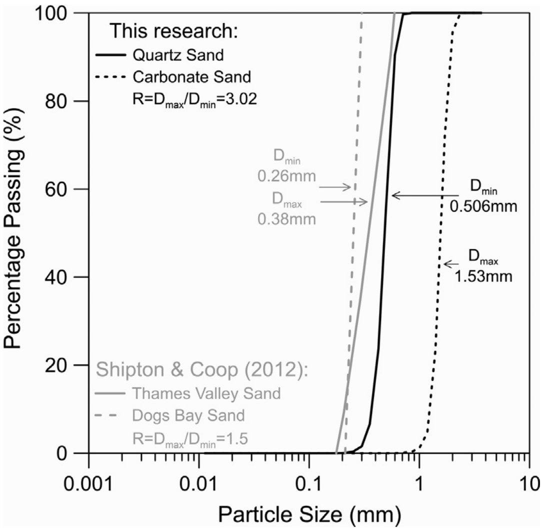


Fig. 1. Particle size distribution of sands tested in this research and by Shipton and Coop (2012).

Table 4
Details of oedometer tests.

Test	Mix of Sand (%)		Ring	σ'max [kPa]	v_i
	Quartz	Carbonate			
O1	0	100	FX	7145	2.202
O2	0	100	FX	7145	2.123
O3	0	100	FX	7145	1.890
O4	20	80	FX	7145	1.856
O5	20	80	FX	7145	2.197
O6	20	80	FX	7145	1.902
O7	50	50	FX	7145	1.671
O8	50	50	FX	7145	1.712
O9	50	50	FX	7145	2.003
O10	50	50	FL	24425	1.971
O11	50	50	FL	24425	1.712
O12	50	50	FL	24425	1.570
O13	80	20	FX	7145	1.723
O14	80	20	FX	7145	2.671
O15	80	20	FX	7145	1.703
O16	80	20	FL	24425	2.030
O17	80	20	FL	24425	1.616
O18	80	20	FL	24425	1.546
O19	100	0	FL	24425	2.276
O20	100	0	FL	24425	1.725
O21	100	0	FL	24425	1.712

FL = floating ring; FX = fixed ring.

Table 5
Details of drained triaxial tests.

Test	Mix of Sand (%)		Method	p'_0 [kPa]	v_i
	Quartz	Carbonate			
T1	20	80	WP	600	1.702
T2	20	80	WP + T	600	1.589
T3	20	80	WP	300	1.723
T4	20	80	WP + T	300	1.575
T5	50	50	WP	400	1.646
T6	50	50	WP	600	1.619
T7	50	50	WP	100	1.628
T8	50	50	WP + T	400	1.483
T9	50	50	WP + T	600	1.456
T10	80	20	WP	120	1.636
T11	80	20	WP	600	1.627
T12	80	20	WP + T	100	1.505
T13	80	20	WP + T	300	1.495
T14	80	20	WP + T	400	1.470
T15	80	20	WC	100	1.814
T16	80	20	WC	450	1.619
T17	80	20	WC	450	1.740
T18	80	20	WC	370	1.780
T19	100	0	WP	100	1.655
T20	100	0	WP	600	1.668
T21	100	0	WP + T	600	1.526
T22	100	0	WP + T	100	1.540
T23	100	0	WP	300	1.675
T24	100	0	WP + T	300	1.522
T25	100	0	WP + T	600	1.530

WC = Wet compaction; WP = Wet Pluviation; WP + T = Wet Pluviation + Tamping.

mixtures with a quartz content of between 50% and 100%, convergence occurs at effective vertical stresses of about 20 MPa, while convergence is reached for effective vertical stresses smaller than 7 MPa when the quartz content is between 20% and 0%. Because the lines appear to be parallel, the slope chosen for each 1D-NCL was constant and set to a value of 0.48. Data and observations from the oedometer tests are summarised in Table 6, which can be compared to the values from the literature listed in Table 1.

The influence of the quartz content on the location of the compression lines is that the 1D-NCL moves towards higher stresses as the quartz content (percentage of dry mass) increases (Fig. 4a). The relative positions confirm what was previously observed by Leleu and Valdes (2007): it is necessary to add a relative large amount of stronger particles (i.e. more than 20% quartz – percentage in terms of volume) in order to see a significant effect on the position of the 1D-NCL in mixtures made predominantly of weaker particles such as carbonate grains (Fig. 4b). In Fig. 4a, the proximity of the 1D-NCLs for 0%Q, 10%Q and 30%Q highlights that, for mixtures in which the matrix is mainly of carbonate, small changes in the constituent proportions do not have a significant effect on the mechanical behaviour. On the other hand, the 1D-NCL locations for 70%Q, 90%Q and 100%Q are strongly influenced by small changes in the carbonate content.

4.1. Particle breakage

As shown in Fig. 5 for 100%Q and 100C% samples, among other parameters such as stress level and particle dimensions, particle breakage depends on grain mineralogy. Fig. 6 shows an analysis of the particle breakage carried out on the five mixtures in terms of Hardin's (1985) relative breakage B_r, using the final particle size distributions from the oedometer tests of Fig. 6a. The final gradings were measured by means of a laser scanning particle analyser capable of highlighting even small changes in distributions (Altuhafi and Coop, 2011). In Fig. 6b the yield stress σ'_y was determined at the point of maximum curva-

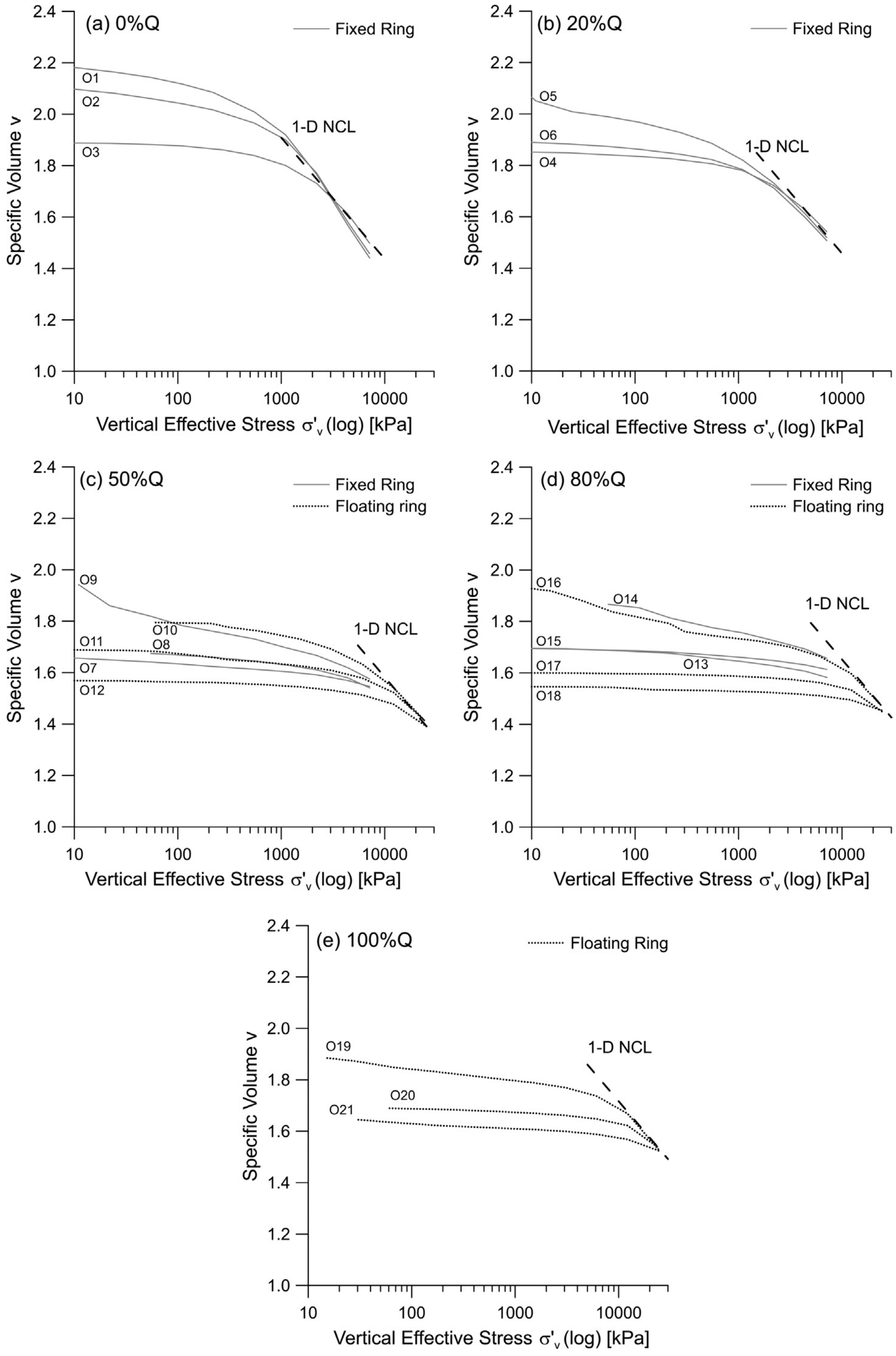


Fig. 2. Oedometer compression curves for mixtures of quartz and carbonate sands: (a) 0% quartz; (b) 20% quartz; (c) 50% quartz; (d) 80% quartz; (e) 100% quartz.

ture, assuming an average value between estimations using the methods of Becker et al. (1987) and Butterfield (1979). The values are plotted against the quartz content, showing that there is a sudden change of yield stress between 20 and 50% quartz content. Quartz content is not the only influencing factor: for example, values of the yield stress also depend on the initial specific volumes.

As shown in Fig. 6c, if compared with the *Br* values of Shipton and Coop (2012), the overall breakage is lower even when higher maximum stresses were reached. This confirms that the amount of overall breakage is not a good guide to whether transitional behaviour will occur or not.

From Fig.6c it is possible to observe that, with a little scatter, B_r slightly decreases with the increase in quartz content. A more complete correlation, also accounting for the initial specific volume, is however not yet possible. Further research should identify relative breakage, Br of the mixture components considered separately. Although

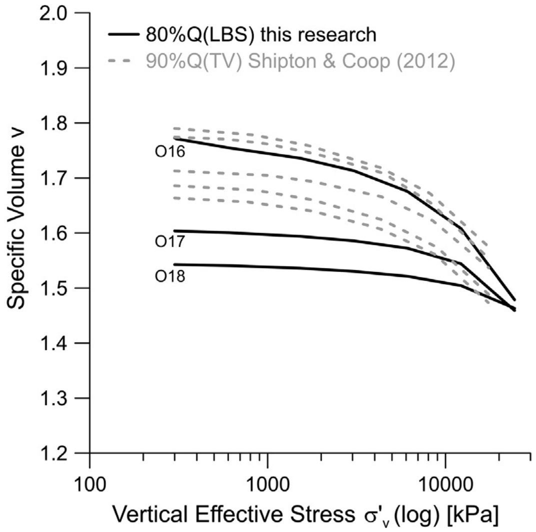


Fig. 3. Comparison of compression behaviour between mix with 80% quartz of this research and mix with 90% quartz of Shipton and Coop (2012).

it is acknowledged that there may be no direct link since some soils that experience no breakage are transitional, a study of the relative breakage of the mixture components should be useful to reveal the role of particle breakage in mixtures.

As suggested by Valdes and Koprulu (2008), in Fig. 6d the value of B_r has been plotted as a function of the ratio β, defined as the applied maximum vertical stress σ'_{vmax} normalised by the yield stress σ'_y. As was expected, B_r increases with the increase of the carbonate content and the extent to which the stress passed the yield stress, although the two effects cannot be separated. In Fig. 7, an example of mass density function for the mixture 50% Q is given. Despite reaching a high stress and a unique NCL, the bimodal distribution was not erased.

5. Shearing behaviour in triaxial tests

Each triaxial sample in Table 5 was isotropically compressed and then sheared in drained conditions. Tests were carried out on four mixtures (labelled as '20%Q'; '50%Q'; '80%Q'; '100%Q'). Examples of stress-strain curves for the triaxial tests carried out are given in Fig. 8 together with the corresponding volumetric strains ε_v, for the 50% Q and the 80%Q samples. The critical states, i.e. states of constant deviatoric stress and constant volume with continued shearing, were generally simple to identify, with the exception of a few tests (T12, T14, T17) which were still dilating or contracting at large strains or tests T2, T13 and T21 for which the critical state was not reached because of the premature termination of the tests, due to the breakage of the membrane, for example. Regardless of whether the behaviour was contractive or dilative, the samples generally had a typical barrelled shape at failure, with the exception of test T25 for which a barrelled shape

Table 6
Summary of observations and test results.

Soil	Origin and grading	Sand	Principal mineralogy	Mineralogy larger grains	U d_{60}/d_{10}	R	Data from oedometer tests			Data from triaxial tests			Observations on compression and shearing behaviour
							σ'$_y$ [kPa]	σ'$_{max}$ [kPa]	Br	p'$_0$ [kPa]	p'$_{peak}$ [kPa]	Br	
Carbonate sand and quartz sand	Gap-graded Artificial	100%C	C	C	1.31 C	–	1050–1100	7145	0.13	–	–	–	Unique NCL and CSL
		20%Q 80%C	C	C	1.38 Q 1.31 C	3.02	1100	7145	0.09	300–600	640–1175	–	
										600	1150	0.10	
		50%Q 50%C	QC	C	1.38 Q 1.31 C	3.02	?	7145	–	100–600	200–1400	–	
							4500–6000	24425	0.12	600	1200	0.12	
		80%Q 20%C	Q	C	1.38 Q 1.31 C	3.02	?	7145	–	100–450	180–930	–	
							5750–9000	24425	0.05	600	1100	0	
		100%Q	Q	Q	1.38 Q	–	6500–9500	24425	0.06	100–600	190–1300	–	
										600	1060	0	

? difficult interpretation; underline refers to related values.

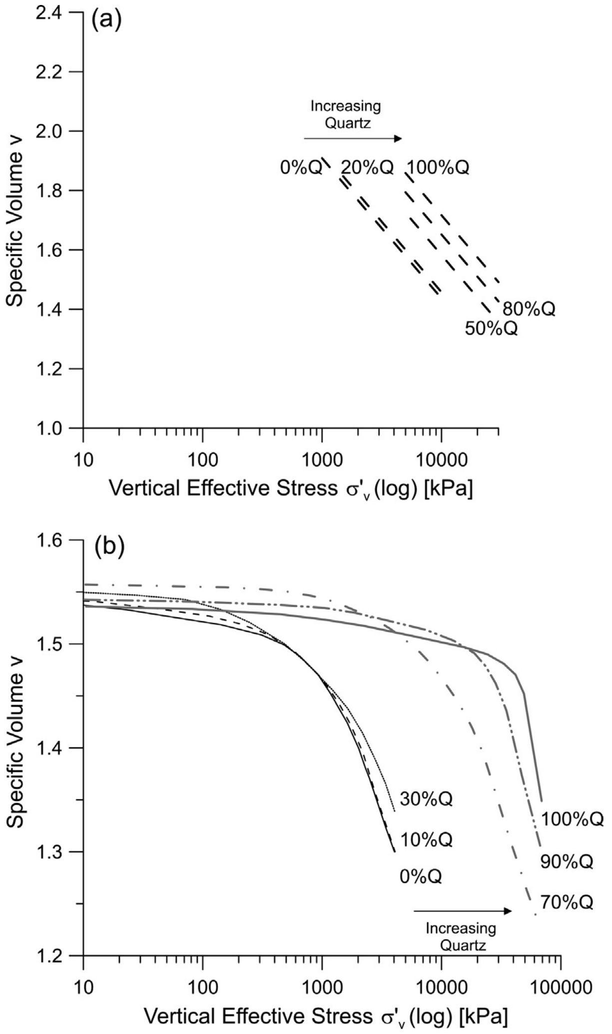


Fig. 4. Influence of the quartz content on the location of the NCL: (a) this research; (b) Leleu and Valdes (2007).

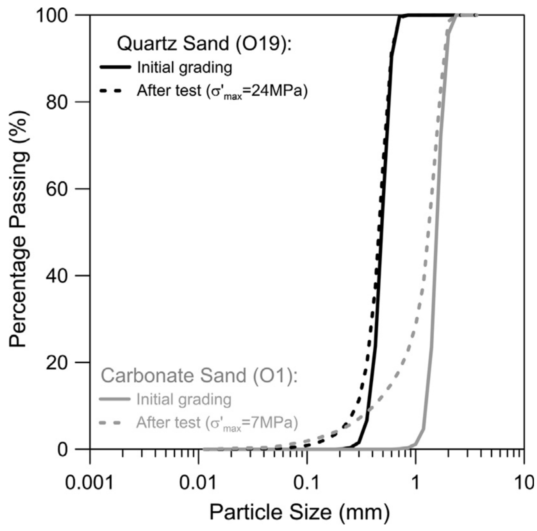


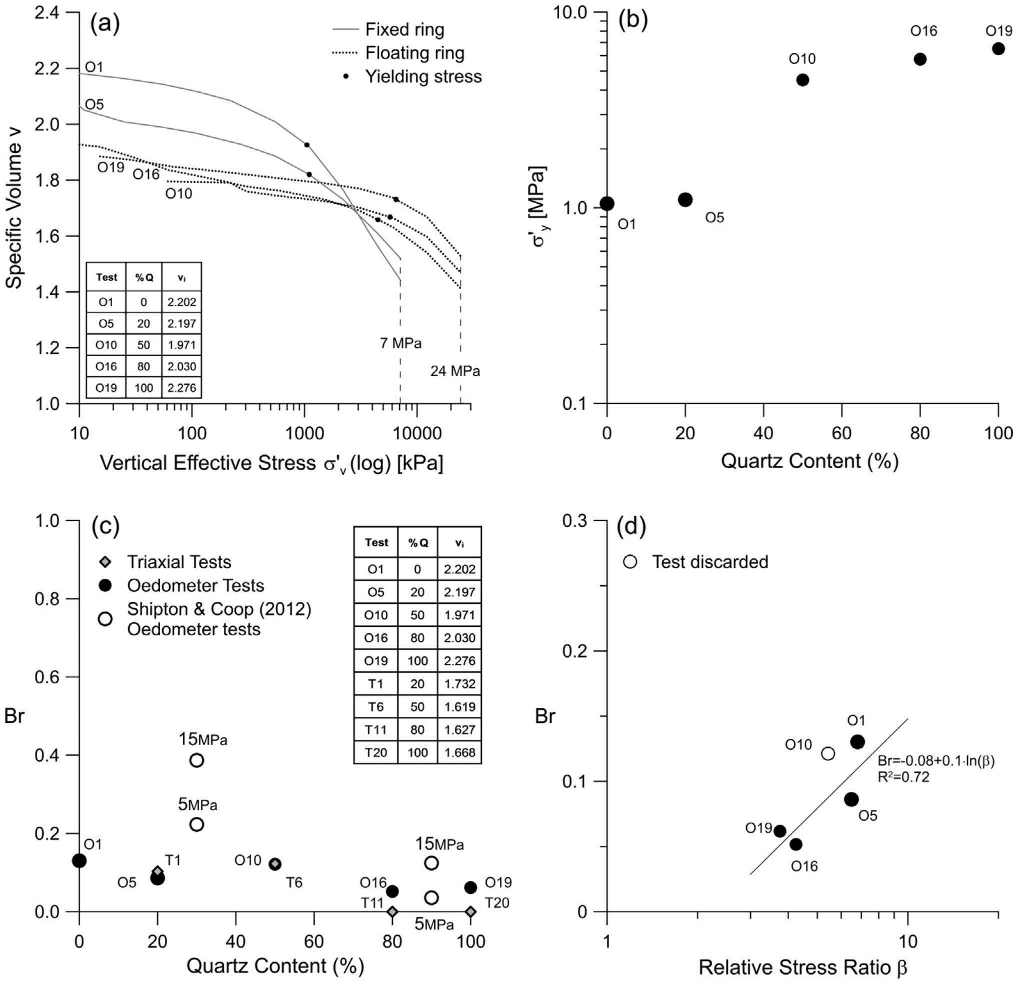
Fig. 5. Example of particle size distributions before and after the test for 100%Q (O19) and 0%Q (O1).

with also a shear plane occurred. The particle breakage measurements are summarised in Table 6 and in Fig. 6c. Very low values of relative breakage B_r, were obtained, smaller than or similar to those obtained after the oedometer tests.

An example of the stress paths in the q:p′ plane is given in Fig. 9. For each mixture, a unique critical state line was identified, with gradients varying between $M = 1.50$ and $M = 1.27$ (Fig. 10), corresponding to critical state angles of shearing resistance φ'_{cs} between 36.9° and 31.6°. The critical state strength (M and φ'_{cs}) appears to stabilize when higher amounts of quartz are reached.

The shearing paths and end of test states are plotted in the *v:lnp'* plane in Fig. 11. Despite the incompleteness of some tests, as shown in Fig. 8, the stability of the final states for most of the tests which started from a wide range of initial values of v_i, allowed the unique critical state lines to be identified. These CSLs are curved, as seen for many sands (e.g. Verdugo and Ishihara, 1996) and mixtures (e.g. Carrera et al., 2011). In Fig. 11, a question mark was used to indicate doubt about their correct locations at higher stresses. Unfortunately, the stress levels available in the apparatus were insufficient to reach the higher pressure straight part of the CSLs. For 100%Q, the CSL might be considered the upper bound to the data, as it is most likely that incompleteness (i.e samples are still dilating) and/or localisation, affects the data even if not visible. In Fig. 11c, where some points do not reach the unique CSL that has been chosen, it should be noted that a unique 1D- NCL was however reached for the 80%Q mixtures (see Fig. 2d). In Fig. 8, it can be seen that at the maximum axial strains of around 30% both the stresses and the strains are less stable for 80%Q than for 50%Q. While this is not really well-defined transitional behaviour, it does mean that larger strains are required to reach a unique volume for this mixture. Also, the contrast with the compression behaviour may indicate that the fabric is more easily rearranged by compressive strains than shear strains, as reported for several transitional soils and slowly convergent soils. However, in general, the uniqueness of the critical state lines, for each mix, indicates that it is likely that the initial specific volume does not control the location of the current critical state line, and any difference in the initial fabric must have been erased during the compression, although no fabric studies were undertaken here. In Fig. 12 the 1D-NCLs are compared with the locations of the CSLs. The same tendency towards parallel lines is seen for each, as also seen by Leleu and Valdes (2007), who showed that the compression lines move parallel and upwards as the quartz content increases.

A normalisation for state in the v:lnp’ plane was carried out in terms of the state parameter, ψ, (Wroth and Bassett, 1965; Been and Jefferies, 1985) defined as the vertical distance in specific volume to the critical state line at the current p’ ($\psi = v - v_{cs}$). The data are further normalised by M for each mixture allowing a unique State Boundary Surface (SBS) to be identified for all the mixtures, as indicated in



Test	%Q	v_i
O1	0	2.202
O5	20	2.197
O10	50	1.971
O16	80	2.030
O19	100	2.276

Test	%Q	v_i
O1	0	2.202
O5	20	2.197
O10	50	1.971
O16	80	2.030
O19	100	2.276
T1	20	1.732
T6	50	1.619
T11	80	1.627
T20	100	1.668

Fig. 6. (a) Oedometer curves of selected samples; influence of quartz content on: (b) yield stresses and (c) relative particle breakage; (d) relative particle breakage against relative stress ratio.

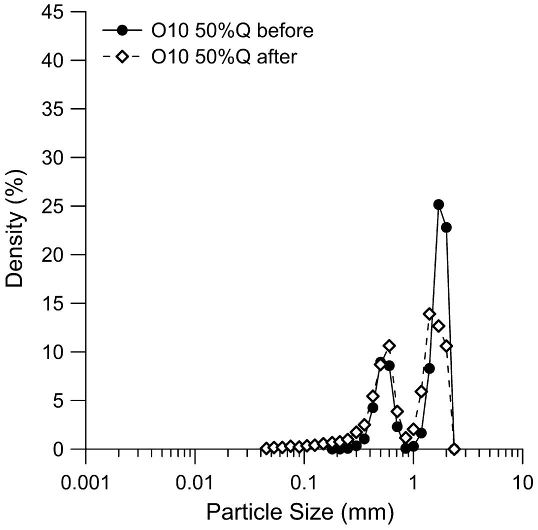


Fig. 7. Example of mass density function before and after the test (mixture 50%Q).

Fig.13. Not much of the wet side ($\psi > 0$) of the SBS can be defined. From the oedometer data, and accounting for fact that the isotropic NCL should lie above the 1D-NCL, it can be estimated that it would take triaxial tests at 10 s of MPa to completely define the wet side.

The stress-dilatancy relationships in Fig.14 also indicated that once the data had been normalised for the different M values, the relationships were practically the same for all the mixtures at different stresses and densities, as highlighted by the presence of a unique line. The only difference is that the low quartz content samples tend not to dilate as much, and therefore have lower peak stress ratios.

6. Conclusions

An analysis of the existing research on transitional behaviour in mixtures of sands carried out by the authors and co-workers, suggested no transitional behaviour was to be expected for gap graded mixtures featuring larger grains of a weaker type, no matter their proportions. Hence, for comparison purposes with data in the literature, and in particular with the mixtures with larger grains of the stronger type (quartz) studied by Shipton and Coop (2012), an investigation was carried out involving a new series of

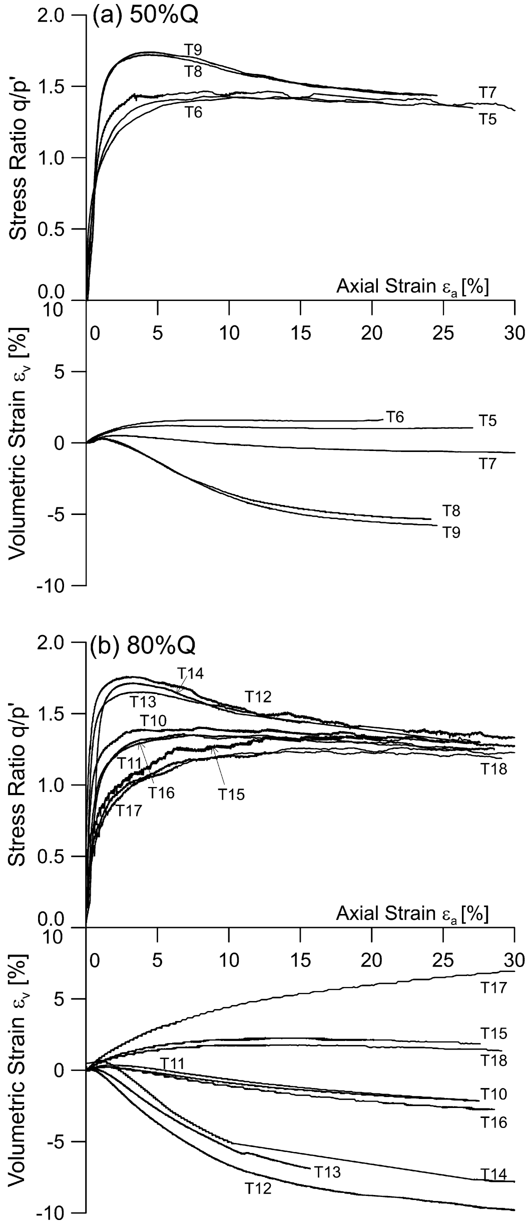


Fig. 8. Examples of stress–strain and volume change data for shearing of quartz and carbonate sand mixtures: (a) 50% quartz; (b) 80% quartz.

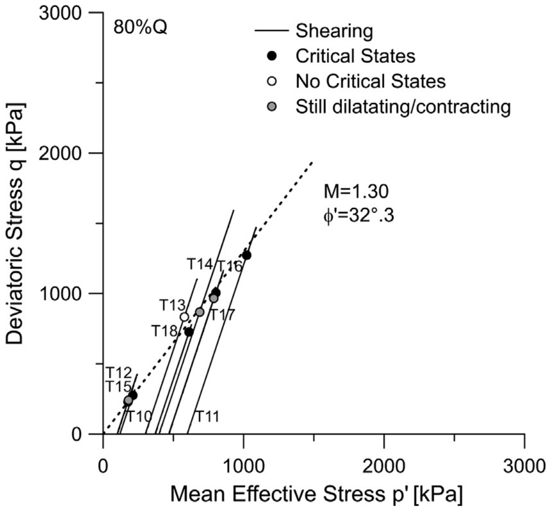


Fig. 9. An example of stress paths for mixtures with 80% quartz content.

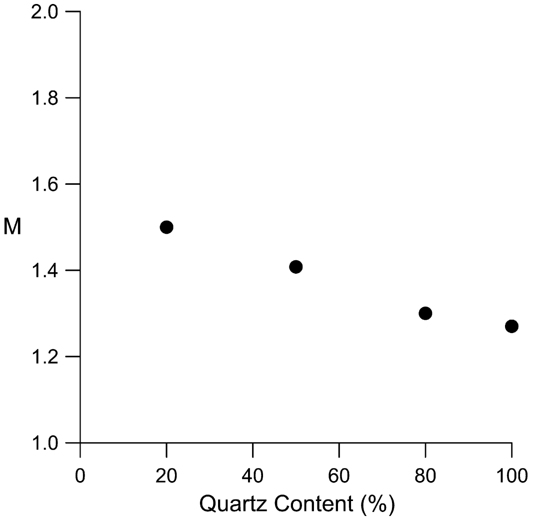


Fig. 10. Critical stress ratio M against quartz content.

oedometer and triaxial tests to determine the behaviour of gap graded mixtures with larger particles of carbonate.

The convergence of compression paths for all the mixtures tested, including those with a large amount of stronger grains, highlights compression behaviour different from that detected by Shipton and Coop (2012). Shipton & Coop reported that transitional behaviour occurred if in the mixtures the quartz content was between the 90% and 70%, and the weaker carbonate between 10% and 30%. The values of B_r for the mixtures tested is quite low, even when the 1D NCLs appear to be unique, confirming that while overall particle breakage can occur in soils with transitional behaviour, it is not a prerequisite or vice versa. Therefore, even when a unique NCL was encountered, the bimodal particle size distribution was preserved despite compression to high stresses. This is confirmation of the absence of a direct link between the presence of peaks in the mass density function and the certainty of the transitional behaviour occurring. Further research is needed to identify the evolution of B_r for each of the mixture components, considered separately.

The convergence of the compression paths at high stresses for all mixes seems to confirm that the presence of a fabric easier to erase in mixtures in which quartz particles are always the smaller component. This allows a new arrangement and a unique NCL to be defined.

In the triaxial tests, very little or negligible particle breakage after shearing occured and, for each mixture, a unique critical state line, although curved, was identified. For the 80%Q, larger shear strains were required to reach unique critical states than for the other mixtures, leading to more scatter of the end of test data. While this is not strictly transitional behaviour, it does perhaps indicate a

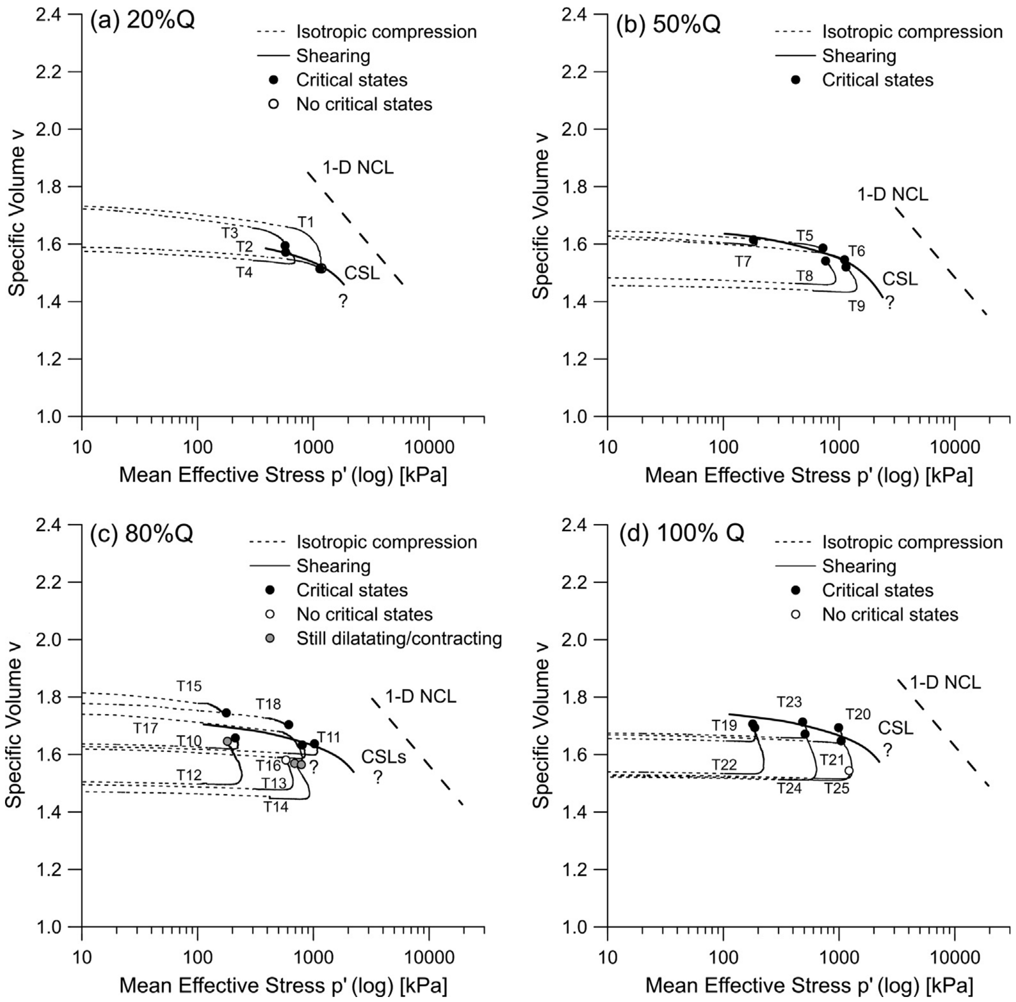


Fig. 11. Isotropic compression and shear paths: (a) 20% Quartz; (b) 50% Quartz; (c) 80% Quartz; (d) 100% Quartz.

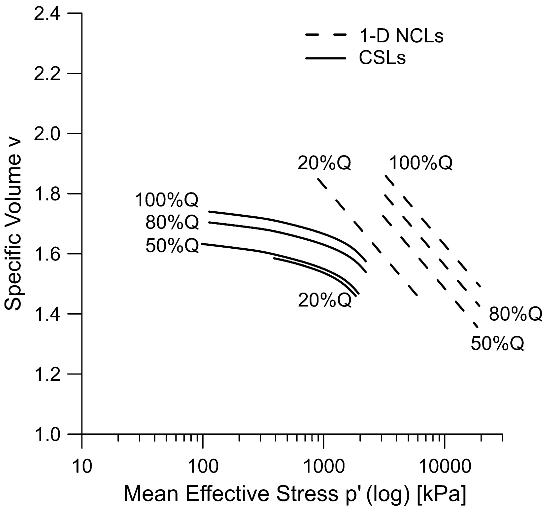


Fig. 12. Influence of quartz content on the location of 1-D NCL and CSL.

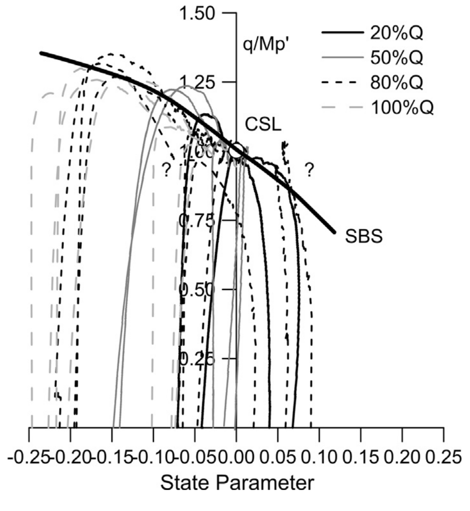


Fig. 13. Normalisation using state parameter.

more robust fabric more difficult to break down in shear than in compression, for which a unique NCL was more easily defined.

It is possible to conclude that, for mixtures where the larger grains are the weaker particles (i.e. carbonate), a unique 1D-NCL and a unique CSL is reached. The influence of the quartz content of smaller grains on the

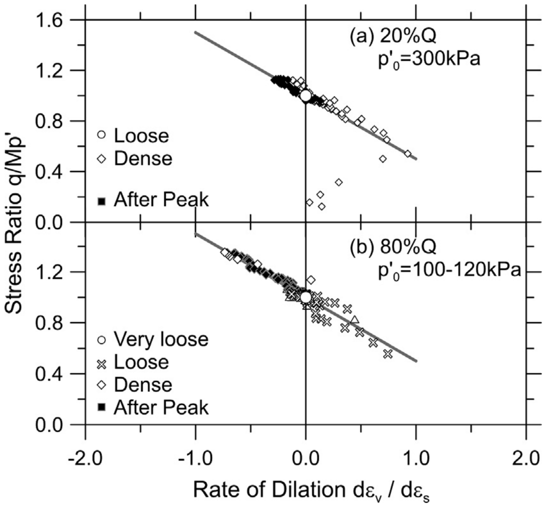


Fig. 14. Examples of stress-dilatancy data for triaxial tests: (a) 20% Quartz and $p'_0 = 300\text{kPa}$; (b) 80% Quartz and $p'_0 = 100\text{–}120$ kPa.

locations of the 1D-NCLs and CSLs was to move them upwards as the quartz content increased. Hence, by comparing the behaviour of this mixture with the data in the literature for mixtures with a strong matrix made of quartz sand particles either larger or at least of similar size to the other component, it was concluded that the mineralogy of the larger grains plays a clear role in determining the mode of behaviour. In order to confirm the results of the present work, further research should be carried out on several binary mixtures of artificial soils. Among these, the relative breakage of the single components in the mixture should be measured, if possible, in order to assess any possible influence in determining transitional or non-transitional behaviour.

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Further reading

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