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Technical Paper

On the mechanical behaviour of a bonding-dominated soft rock

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Abstract

The role of bonding intensity in controlling the mechanical evolution of cemented carbonate formations towards an intrinsic reference state remains an open issue. This study investigates the behaviour of strongly cemented Palermo Calcarenite through drained triaxial and high-pressure oedometer tests on intact and reconstituted specimens, and compares the results with those previously obtained for the weakly bonded Marsala Calcarenite. Palermo Calcarenite undergoes progressive destructuration and approaches a well-defined reference state, with intact and reconstituted specimens converging in both one-dimensional compression and triaxial shearing. In contrast, the previously investigated Marsala Calcarenite shows no convergence between intact and reconstituted states under one-dimensional compression. The contrasting responses are associated with marked differences in the degree and distribution of cementation and in the resulting structure. These results show that the response to reconstitution is not unique among calcarenites with different structural characteristics and that a reference state cannot be assumed a priori for this class of geomaterials.
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Keywords: Critical State; Bonded soils; Structure; Reference material; Destructuration

1. Introduction

The mechanical behaviour of natural geomaterials is profoundly influenced by their structure, which encompasses both fabric — defined by the size, shape, packing, and orientation of particles — and bonding, representing interparticle cementation developed during diagenetic processes (Mitchell, 1976). In cemented soils and weak rocks, this structure produces a metastable fabric whose response evolves during loading as bonds degrade and the granular skeleton rearranges. Understanding destructuration is therefore fundamental to interpreting the transition from structured, rock-like behaviour to intrinsic frictional behaviour, and to establishing whether a unique reference state can be defined.

Within the framework of Critical State Soil Mechanics, the reconstituted condition is commonly adopted as a reference, representing the intrinsic response once structure is erased. For many natural clays and structured sands, destructuration leads to convergence towards a unique Normal Compression Line (NCL) and Critical State Line (CSL), allowing the reconstituted material to serve as a reliable reference (Leroueil and Vaughan, 1990; Baudet and Stallebrass, 2004). However, this convergence is not universal. Coop and Atkinson (1993) showed that cemented carbonate sands can reach states well outside the NCL of the uncemented material, and that even after bond breakage their specific volume may remain higher within the explored stress range. Cotecchia and Chandler (1997, 2000) showed that structural effects may persist even at

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List of symbols

CT	Computer Tomography
G.C.	Grain Contact
M	Gradient of CSL in q:p′ space
n	Porosity
P.D.	Packing Density
p′, q	Mean effective stress and generalised shear stress
v_0	Initial specific volume
v	Specific volume
Γ	Intercept of CSL in v:lnp′ plane at p′=1 kPa
ε_a	Axial strain
ε_v	Volumetric strain
λ	Gradient of CSL in v:lnp' plane
σ'c	Confining stress
σ'_{vmax}	Maximum vertical stress
Φ'_{cs}	Critical state angle of shearing resistance

large strains, whereas Cuccovillo and Coop (1999) observed coincident CSLs for intact and reconstituted sandy soils in the q–p′ plane, suggesting that structure does not always control the ultimate state. Similarly, Burland (1990) noted that triaxial shearing may not induce sufficient destructuration to reach intrinsic conditions, so that convergence towards an intrinsic reference state cannot always be assumed.

For granular soils, a unique NCL is typically observed even in the presence of particle crushing (McDowell et al., 2013), with the compression behaviour converging towards a limiting response at high stress levels (Pestana and Whittle, 1999), and the CSL approximately parallel to it at high stresses (Coop and Lee, 1993). The location of these lines depends on mineralogy and particle breakage (Coop and Jovićič, 1999; Bandini and Coop, 2011). After destructuration, cemented soils may develop an interlocked granular fabric that continues to influence the mechanical response, particularly at large strains (Dusseault and Morgenstern, 1979; Barton, 1993; Fonseca et al., 2013).

A substantial body of research has investigated bonded geomaterials, including both natural and artificially cemented soils. Although artificial cementation differs from diagenetic bonding, the governing mechanical mechanisms are comparable. Experimental studies show that increasing cementation enhances strength and stiffness, promotes strain-softening, and can shift the CSL (Cruz et al., 2011; Li et al., 2015; Rahman et al., 2018; Gajo et al., 2019). In some cases, the CSL of bonded materials lies above that of reconstituted soils and gradually approaches it as bonding degrades (Rahman et al., 2018). The ultimate stress ratio, however, appears largely intrinsic and insensitive to cementation level (Le and Airey, 2023; Landivar Macias and Rotta Loria, 2023). Constitutive models reflect this behaviour by introducing bonding variables that degrade with strain, progressively approaching the critical state response (Lee et al., 2004; Landivar Macias and Rotta Loria, 2023). Recent micromechanical studies further highlight that convergence towards intrinsic states depends not only on density and stress level but also on bond-scale variability (Farhat et al., 2024), and that extending the critical state framework to cemented soils remains a challenging issue (Khan et al., 2025), particularly when considering the combined effects of fines content and cementation.

From a compression standpoint, yielding in bonded soils marks the onset of bond degradation, after which compression behaviour depends on the degree of cementation (Rotta et al., 2003), as also reflected in constitutive modelling approaches (Rahimi et al., 2016). The initial specific volume also plays a key role: for the same bond strength, denser materials may exhibit behaviour similar to weakly cemented soils (Cuccovillo and Coop, 1997; Rotta et al., 2003). Although differences between bonded and reconstituted states are commonly used to assess the effects of structure (Burland, 1990; Leroueil and Vaughan, 1990), this relationship is not always consistent in natural calcarenites, where fabric heterogeneity and cement distribution play an important role.

Calcarenites from southwestern Sicily provide a suitable natural framework to investigate these issues. These bioclastic carbonate rocks, deposited in shallow-marine Quaternary environments (Agate et al., 2017), share similar mineralogical composition but exhibit markedly different bonding intensity and pore structure depending on diagenesis (Longman, 1980). Their destructuration mechanisms are particularly relevant, as structural evolution controls their response under loading (Kavvadas, 2000), with bond collapse occurring progressively through cracking within force chains (Khoshini et al., 2019). Previous investigations on Palermo Calcarenite (Zimbardo, 2016) have shown that this lithotype exhibits a strongly cemented, low-porosity fabric, with CT-based analyses indicating that the specific volume can be considered a representative quantitative parameter of the degree of cementation. Microstructural characterisation (Zimbardo et al., 2011) revealed high packing density and low grain contact extent, consistent with pervasive interstitial cementation that reduces direct grain-to-grain contacts. Under triaxial compression, intact specimens exhibited a transition from brittle to ductile behaviour depending on initial specific volume and confining pressure, with critical state conditions approached at high stress levels. However, the behaviour of reconstituted Palermo specimens had not been previously investigated, and it therefore remained unclear whether intact and

reconstituted materials would converge towards a unique intrinsic mechanical response, and whether the reconstituted condition could be considered a reliable reference state for this lithotype. Furthermore, previous studies investigated each lithotype separately, so that the contrasting behaviour of calcarenites characterised by different degrees and distributions of cementation and the resulting different structure had not been directly compared.

The present study addresses this gap by investigating the mechanical behaviour of the strongly bonded Palermo Calcarenite and directly comparing it with the weakly bonded Marsala Calcarenite — two lithotypes from the same regional carbonate succession but markedly different cementation degree. The objectives are:

- to investigate the shear and compression behaviour of Palermo Calcarenite through drained triaxial and high-stress oedometer tests on intact and reconstituted specimens;
- to determine whether intact and reconstituted Palermo materials converge towards common intrinsic compression and critical state conditions;
- to compare Palermo Calcarenite's behaviour with that of Marsala Calcarenite and investigate how differences in cementation characteristics and the resulting structure are associated with different post-destructuration responses.

By addressing these objectives, the present study provides an experimental basis for assessing the post-destructuration behaviour of calcarenites with markedly different bonded structures. The novelty lies in the new experimental characterisation of reconstituted Palermo Calcarenite, which provides a contrasting case to the behaviour previously observed for Marsala Calcarenite. While the previous study established the lack of convergence for that calcarenite, the present comparison demonstrates that such behaviour is not a general consequence of reconstitution in calcarenites, since Palermo exhibits convergence between intact and reconstituted states. The contrasting responses further suggest that differences in cementation characteristics and the resulting structure play an important role in their post-destructuration evolution.

2. Materials and methods

Calcarenites belong to the class of hard soils-soft rocks, representing transitional geomaterials between soils and lithified rocks. These materials typically exhibit relatively high deformability and moderate strength, and their mechanical behaviour is strongly influenced by their internal structure. In structured geomaterials, the microstructure results from both fabric, defined as the arrangement and packing of particles, and bonding, representing the interparticle cementation that develops during diagenetic processes such as compaction and calcite precipitation. As a consequence, their mechanical behaviour may vary significantly depending on the degree of cementation and the stress conditions, showing either brittle or ductile responses.

The laboratory tests were carried out on Palermo Calcarenite (lithotype CL2), and the results were compared with those of lithotype B2 Marsala Calcarenite (Zimbardo et al., 2022). Petrographic and textural analyses were performed on thin sections under transmitted light microscopy (XPL: cross-polarised light). Palermo Calcarenite consists of carbonate (calcite) and siliceous rock fragments, monocrystalline quartz, sparitic grains, and small amounts of bioclasts. The grain size varies from 0.025 mm to 1 mm, with a mode of approximately 0.035 mm. The specific gravity Gs was measured using a Thermo helium pycnometer (Pycnomatic) and is 2.76 for Palermo Calcarenite and 2.74 for Marsala lithotype.

The highly spherical and rounded granules show high-angle grain boundaries. Only a few macropores are present, and they are much less frequent than mesopores. Intergranular interstices and intragranular voids are almost obstructed by carbonate cement, with a few scattered mesopores. As shown in Fig. 1a, the calcite cement forms a thin microsparitic rim that bonds the grains together at the contact points (Zimbardo, 2016). Marsala Calcarenite is a biocalcarenite (bioclasts 96.4%) where lithoclasts were rare. In decreasing order of quantity, the bioclasts are made of rhodolites, fragments of mollusc shells, foraminifera, a few briozoa, entrocha, an-ellids; the lithoclasts are mainly made of carbonate rock fragments and monocrystalline and, more rarely, polycrystalline grains of quartz silt. The shape and size of the clasts vary greatly (100 μm to 8 mm) with no preferential grain orientation (Zimbardo et al., 2022). Macropores are slightly more abundant than mesopores. The widespread occurrence of mesopores is attributed to the partial infilling of intergranular spaces by the cement patina that envelops the grains. As shown in Fig. 1b, intragranular voids appear open, partially filled, or locally occluded.

Grain packing (Packing Density, PD) – defined as the ratio between the total length of grains (Σgi) intercepted by a scan line across the thin section and the total line length (t) – and grain contact extent (Grain Contact, GC) – defined as the percentage ratio between the total length of grain-to-grain contact zones and the grain perimeter (Kahn, 1956) – were quantified from photomicrographs of thin sections taken under an optical microscope. Fig. 2 displays the measured values of Packing Density (PD) and Grain Contact (GC) for the Palermo and Marsala lithotypes. These materials show a correlation between packing density and porosity (n) that is consistent with the trend identified by Dobereiner and De Freitas (1985) for sandstones.

Representative photographs of intact Palermo and Marsala calcarenite specimens together with the corresponding optical micrographs, are shown in Table 1. The images highlight differences in texture and degree of cementation

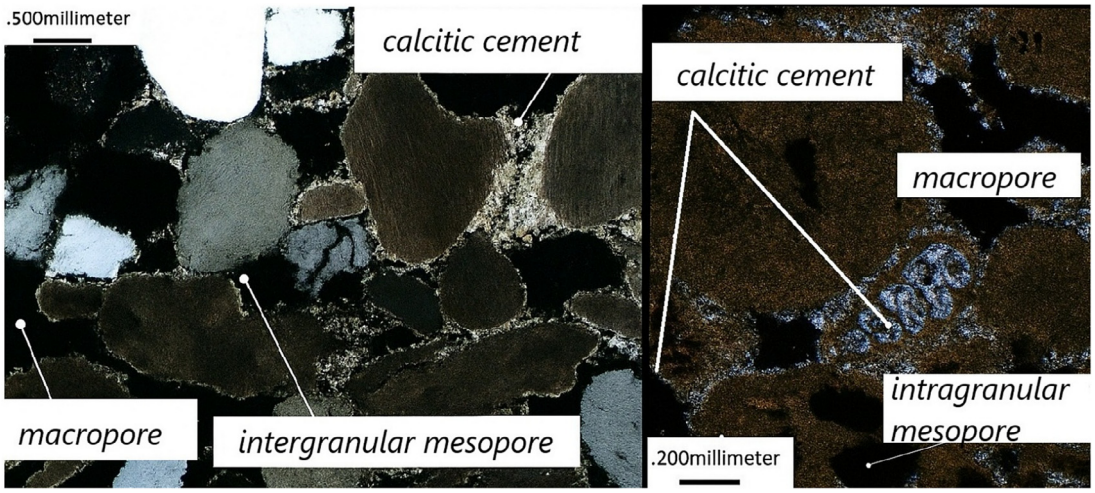


Fig. 1. Thin sections of calcarenite: a) lithotype Palermo CL2, b) lithotype Marsala B2.

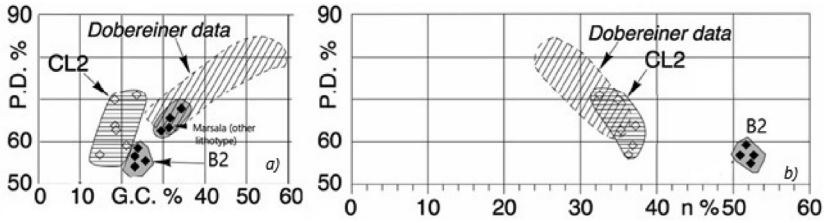


Fig. 2. a) grain contact versus packing density, b) porosity versus packing density (fromZimbardo et al., 2011).

between the strongly bonded Palermo calcarenite and the weakly bonded Marsala calcarenite.

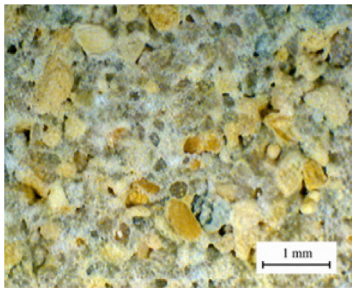
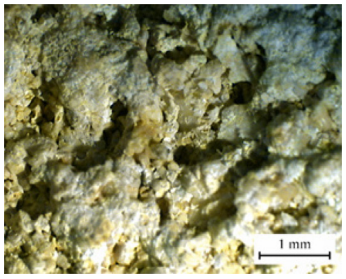
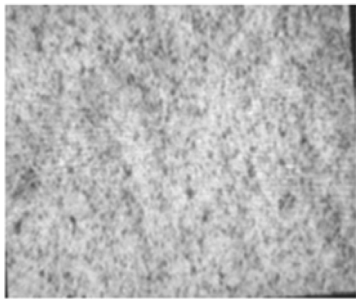
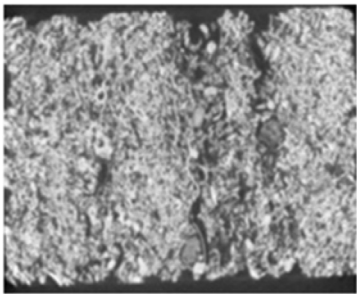
In X-ray Computed Tomography, the CT number, also referred to as Hounsfield Units (HU), is a parameter used to quantify the relative X-ray attenuation of a material with respect to water. According to Ren and Ge (2004), X-ray Computed Tomography (CT) enables a quantitative evaluation of density, fabric, and degree of cementation, as well as the transitions between different density states. In this context, CT-based analyses suggest that the specific volume can be considered a representative and quantitative parameter of the degree of cementation (Zimbardo, 2016). Thus, the difference in cementation degree between the two lithotypes was assessed through CT number analysis. Palermo Calcarenite exhibits CT values in the range 1437–1767, while Marsala Calcarenite shows CT values of 1148–1261, indicating that the degree of cementation of Marsala Calcarenite is approximately 25% lower than that of Palermo Calcarenite. As shown in the X-ray computed tomography images reported in Table 1, Palermo Calcarenite displays a homogeneous, dense texture with cement pervasively distributed throughout the matrix, whereas Marsala Calcarenite exhibits a markedly heterogeneous structure, with dark intergranular voids clearly visible. This structural contrast is further reflected in the fabric indicators: Palermo Calcarenite exhibits higher packing density (PD: 55–70%) and lower grain contact extent (GC: 12–22%) compared to Marsala Calcarenite (PD: 53–60%; GC: 22–25%). This apparently counterintuitive combination, denser packing yet fewer direct grain-to-grain contacts in the Palermo material, is explained by the pervasive cementation filling the intergranular spaces and acting as an intermediary between grains, reducing direct contact. In contrast, the higher GC of Marsala Calcarenite reflects a more granular structure in which grains are in direct contact, with cement present only locally and discontinuously.

It should be emphasised that porosity, fabric and cement distribution are not independent of one another in these natural materials, but are interrelated features of the bonded structure developed during diagenesis, since cement precipitation and its spatial distribution directly affect pore space and grain-to-grain contact conditions.

Taken together, these indicators — CT values, CT images, PD, GC, UCS (6–12 MPa vs 1.4–3.5 MPa) and tensile strength (0.25–0.76 MPa vs 0.30 MPa) — provide a consistent and quantitative structural characterisation of the two lithotypes, confirming that they differ substantially in their initial bonded fabric (Table 2).

To assess the influence of structure on the mechanical behaviour of the intact Palermo Calcarenite, reconstituted samples were prepared. The reconstituted state was studied as a reference representing the destructured condition, in order to highlight the effects of structure in the intact material, despite differences in macroporosity, bonding degree, and strength. Reconstituted material was obtained by

Table 1
Representative photographs, optical micrographs and CT images of Palermo and Marsala Calcarenite.

Lithotype	Palermo Calcarenite	Marsala Calcarenite
Intact cylindrical self-standing specimens prior to testing (diameter D = 3.8 cm, height H = 7.6 cm)		
Reflected light optical micrographs		
Images from X-ray computed tomography		

crushing intact samples through tamping and light hand-hammering, applying small compressive forces between the grains, to produce a homogeneous granular material, which was subsequently oven-dried at 80°C. Specimens were prepared by placing the material in three compacted layers within a split mould using a 1 kg pestle (Zimbardo et al., 2022). Suction was applied to stabilise the sample before installation in the triaxial cell.

However, it was not possible to achieve initial specific volume values comparable to those of the intact samples.

Table 2
Range of initial specific volume (v_0), CT number, unconfined compressive strength (UCS), and tensile strength for the calcarenite lithotypes.

Lithotype	V_0	CT number	UCS [MPa]	Tensile strength [MPa]
Palermo Calcarenite	1.29–1.45	1437–1767	6–12	0.25–0.76
Marsala Calcarenite	1.98–2.16	1148–1261	1.4–3.5	0.30

Table 3
Palermo Calcarenite (CL2): details of drained triaxial tests on a) Intact samples (test data from Zimbardo 2016) and b) Reconstituted samples.

	Test	v_0	σ'_c [MPa]
Intact (from Zimbardo,2016)	TCL2	1.41	5
	TCL4	1.45	2
	TCL5	1.38	4
	TCL6	1.47	6
	TCL7	1.32	10
	TCL8	1.29	4
	TCL4a	1.32	7
	TCL5L	1.48	2.5
	TCL11	1.29	4.5

a)

	Test	v_0	σ'_c [MPa]
Reconstituted	Txr1	1.67	0.70
	Txr2	1.65	0.35
	Txr3	1.87	0.45
	Txr4	1.78	0.20
	Txr5	1.63	0.45
	Txr6	1.58	0.20
	Txr7	1.53	0.48
	Txr8	1.61	0.30
	Txr9	1.40	0.35
	Txr10	1.53	0.39
	Txr11	1.55	3.00

b)

The reconstituted samples exhibit a higher initial specific volume due to the formation of macropores after destructuration and remoulding. Some broken grains and cement fragments did not compact efficiently during reconstitution, leaving part of the macroporosity unfilled.

To investigate the mechanical behaviour of Palermo Calcarenite, triaxial and oedometer tests were carried out. A series of consolidated isotropically drained triaxial compression tests was conducted on reconstituted samples (11 tests) and compared with tests (9 tests) on intact samples reported in a previous paper (Zimbardo, 2016), which featured a homogeneous cementation pattern and high specific volume. The tests are presented in Table 3. The triaxial samples were consolidated under drained conditions before shearing. The cell pressure, σ'_c, was set between 0.2 MPa and 10 MPa. Tests on intact material were performed using a computer-controlled stress path apparatus with a capacity of 10 MPa. The axial load was measured using a 50kN capacity internal submersible load cell, and the back and cell pressures were measured using 100 bar Keller pressure transducers. Local axial and radial strain measurements were obtained using linearly variable differential transformers (Zimbardo, 2016). The triaxial tests on reconstituted samples were carried out in a Bishop & Wesley triaxial cell equipped with local instrumentation for accurate strain measurements.

A test on the reconstituted sample, Txr11, was also performed in the high-pressure triaxial cell. The initial specific volume v_0, of samples (Table 3) was estimated as the average of the values obtained from the initial dry unit weight, the initial bulk unit weight after saturation, and the final water content. Table 4 presents the triaxial tests conducted on the B2 lithotype (Zimbardo, 2016) of intact Marsala Calcarenite, which are used in this study to compare the behaviour of strongly bonded and weakly bonded materials. It should be noted that triaxial tests on reconstituted Marsala samples were not carried out for this study. Therefore, comparison between intact and reconstituted Marsala Calcarenite is restricted to the one-dimensional compression behaviour, and no conclusion is drawn here regarding convergence of the two states under triaxial shearing.

The saturation of intact specimens was performed following the technique proposed by Rad and Clough (1984). This method involves applying a vacuum to partially saturated samples, followed by the use of the back-pressure technique to complete the saturation process. For this purpose, the samples were placed in an airtight Plexiglas cylinder filled with water, inside which a vacuum of approximately 80%–90% was applied. This procedure initially yielded Skempton's B values of roughly 0.6. Subsequently, a back-pressure saturation of approximately 0.2 MPa was applied for 24–48 h, resulting in B values exceeding 0.97. The reconstituted specimens were directly saturated in the cell.

Oedometer tests on intact and reconstituted Palermo Calcarenite samples (Table 5) were performed using a non-standard apparatus capable of reaching high stress levels (Zimbardo, 2016), under continuous vertical displacement control.

Table 6 summarises the details of the oedometer tests performed on Marsala Calcarenite. The reconstituted Marsala samples, unlike those of Palermo Calcarenite, exhibit an initial specific volume equal to or even lower than that

Table 4
Details of drained triaxial tests on Intact Marsala Calcarenite (B2) (Zimbardo,2016).

	Test	v_0	σ'_c [MPa]
Intact Marsala Calcarenite	**TMA1**	2.14	0.1
	TMA2	2	2
	TMA4	2	0.5
	TMA7	2.11	0.2
	TMA11	2	4

Table 5
Details of oedometer tests on Palermo Calcarenite: Intact samples (Zimbardo,2016) and Reconstituted samples.

	Test	v_0	σ'_{max} [MPa]
Intact	**CLP2-1D**	1.41	84
	CLP4-1D	1.41	157
	CLP6-1D	1.45	80
	CLP7-1D	1.42	80
	CLP8-1D	1.41	80
	CLP9-1D	1.35	80
Reconstituted	**CLP-R2-1D**	1.55	223
	CLP-R3-1D	1.53	224

Table 6
Details of oedometer tests on Marsala Calcarenite B2: Intact samples and Reconstituted samples (Zimbardo et al., 2022).

	Test	v_0	σ'_{max} [MPa]
Intact	**ON1**	2.05	210
	ON2	1.98	210
	ON3	1.99	206
	ON4	2.16	24
Reconstituted	**OD5**	1.95	270
	OD6	1.85	270
	OD9	2.01	24

of the intact material. The comparatively high specific volume of intact Marsala Calcarenite should therefore be regarded as a feature of its natural structure. The natural bonded fabric sustains an open pore structure, whereas reconstitution modifies this arrangement and allows the resulting granular material to rearrange into a denser configuration.

3. Stress-strain behaviour during shearing: critical state

Fig. 3 shows the drained stress–strain and volumetric strain curves for both intact (Fig. 3a) and reconstituted Palermo Calcarenite samples (Fig. 3b). In this figure, a unique q/p' ratio at the critical state M (equal to 1.50, corresponding to $\varphi'_{cs} = 36°$) is estimated for almost all the samples, except for intact samples 5 L and 11, in which a distinct shear plane developed during shearing. A dashed line has been drawn in Fig. 3a and in Fig. 3b to represent this trend. Reconstituted samples are less stiff and do not exhibit a bond yield point, whereas curves for intact samples show that the bonds enhance the initial stiffness. Notably, the intact samples with the lowest porosity (TCL2, TCL4a, and TCL7) display a response similar to that of reconstituted materials, even at low stress levels.

Typically, denser samples that exhibit a higher degree of cementation would be expected to show a more brittle response. However, the experimental results show a more ductile behaviour in these specimens. This apparent contradiction can be explained by the progressive nature of bond degradation. Cementation bonds do not fail simultaneously but break gradually with increasing strain, leading to a partial and spatially distributed destructuration. In denser samples, the limited initial void space restricts sudden structural collapse and promotes a more diffuse deformation mechanism. As bonds progressively degrade, the load is redistributed between remaining bonded contacts and frictional interactions, allowing the granular skeleton to rearrange incrementally rather than undergoing abrupt failure. This results in a smoother stress–strain response and delays the formation of a well-defined shear plane. Therefore, the observed less brittle response is interpreted as the consequence of progressive bond breakage combined with constrained fabric rearrangement, which favours distributed deformation over localized brittle collapse.

The transition from strain-softening to strain-hardening in intact calcarenite samples with a higher degree of cementation depends mainly on the initial specific volume and, to a lesser extent, on the confining pressure. Conversely, samples with higher specific volumes show a mechanical response mainly controlled by the applied confining pressure, exhibiting brittle behaviour at lower stresses and ductile behaviour at higher stresses.

As discussed above, samples with low initial specific volume exhibit a less brittle response despite their higher cementation, owing to the metastable structure that redistributes the load through both intact bonds and interparticle friction and the consequent delay in the formation of a macroscopic shear plane, regardless of the applied confining pressure.

Conversely, samples with higher initial specific volume are more sensitive to the applied confining pressure, as the initial void space allows sudden structural collapse. These samples typically exhibit brittle behaviour at lower stress levels, with ductile behaviour emerging only at higher stresses when frictional contacts dominate. Therefore, the observed trend, whereby strongly bonded samples exhibit a seemingly less brittle response, is consistent with the non-simultaneous destructuration mechanism and does not contradict classical expectations. Rather, it highlights the role of the metastable structure generated by progressively destructured cementation bonds, which governs the ductility of dense samples.

Most tests reached constant stress-ratio and constant-volume conditions at large strains. A small residual volumetric strain rate remained at the end of shearing for TCL5, Txr4 and Txr8. Txr10 reached an end state consistent with the critical-state locus; however, the available strain range was insufficient to verify the persistence of this asymptotic condition at larger strains. Therefore, TCL5,

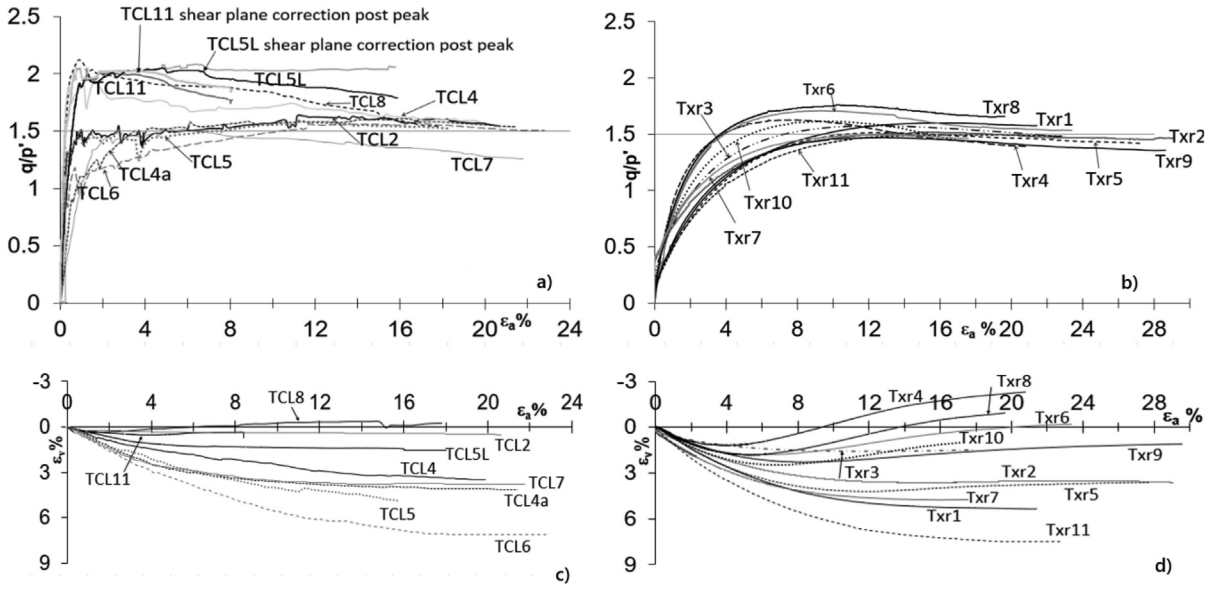


Fig. 3. Stress–strain curves for shearing stages of intact (a,c) and reconstituted (b,d) Palermo Calcarenite (CL2).

Txr4, Txr8 and Txr10 were not classified as well-defined critical states.

The cross-sectional area during shearing was calculated assuming the specimen remained a right cylinder. In the intact samples, barrel-shaped failure modes were observed at higher confining stresses, while at lower confining stresses, brittle failure accompanied by shear banding was clearly evident. For the strain-softening samples (11, 5 L), the shear plane develops at the peak deviatoric stress. For these samples, as suggested by Chandler (1966), a different post-peak area correction is required (samples "TCL11 shear plane" and "TCL5L shear plane" in Fig. 3a), assuming that after the shear plane forms, the sample divides into two sliding blocks. The sliding block area correction yields a curve with increasing deviatoric stress, indicating a reduction in effective area as the sliding progresses. Strain-softening materials may not reach, even at large strains, a stress ratio equal to that at the critical state because strain localization occurs when a shear plane forms, causing the critical state to be reached only locally on the shear plane.

For tests TCL11 and TCL5L – the only specimens showing a shear plane – a distinct CSL was obtained from the stresses acting along the shear plane, taking strain localization into account (Burland, 1990). The corresponding stress ratios at the critical state were also evaluated. In detail, the angle of friction on the shear plane was obtained from an analysis of Mohr's circle at failure and a measurement of the shear plane angle. A friction angle φ'_{cs} of 38°, corresponding to a q/p' ratio of 1.55, was obtained, which is higher than the value of 36° estimated in the samples where no strain localization occurred. After shearing, both reconstituted and intact samples converged towards a unique CSL (Fig. 4).

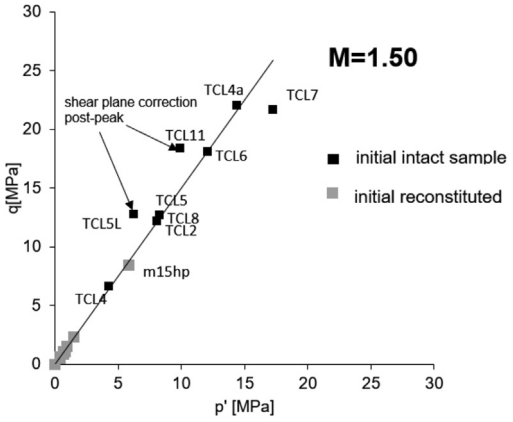


Fig. 4. Palermo Calcarenite (CL2): CSL on q-p'plane.

Fig. 5 shows the stress–strain curves and the volumetric strain curves for the drained shearing stages of the intact Marsala Calcarenite (B2).

A unique q/p' ratio at the critical state M (equal to 1.25) can be highlighted for almost all the samples (Fig. 6).

Fig. 7 shows the relationship between the specific volume at the critical state and the mean effective stress. The CSL was determined from the well-defined critical states identified in the individual tests shown in Fig. 3. Only these well-defined critical states were used to determine the CSL parameters reported below, highlighting the uniqueness of the CSL for both intact and reconstituted Palermo Calcarenite. Despite the differences in fabric, the reconstituted samples proved to be a valid reference state, as both the intact and reconstituted materials converged towards a unique Critical State Line, indicating a common asymptotic mechanical behaviour irrespective of the initial structure. In the same figure, the critical state parameters

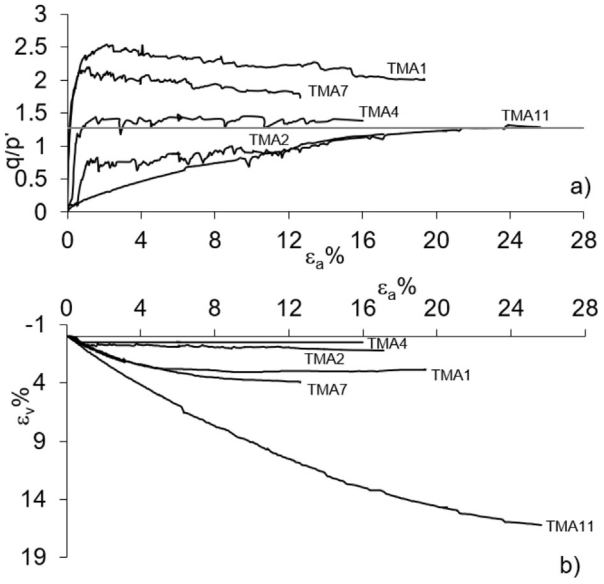


Fig. 5. Intact Marsala Calcarenite shearing stages: a) stress–strain curves, b) volumetric strain curves.

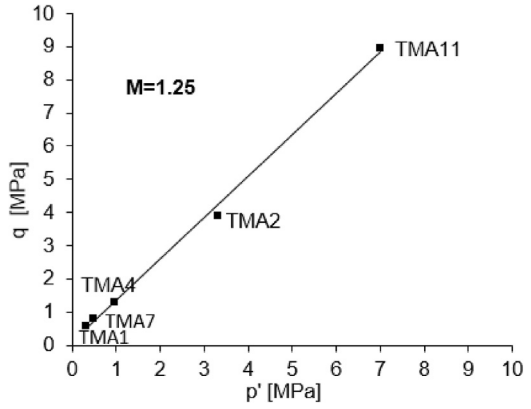


Fig. 6. Intact Marsala Calcarenite (B2): CSL on *q-p'*plane.

obtained for the Palermo and Marsala calcarenites are reported.

The critical state parameters of the two lithotypes differ substantially. Marsala Calcarenite exhibits a steeper CSL slope ($\lambda = 0.183$ vs $\lambda = 0.122$) and a higher intercept ($\Gamma = 3.126$ vs $\Gamma = 2.402$), confirming that its CSL is shifted upward and to the right in the v–ln p′ plane relative to Palermo Calcarenite. The lower critical state friction angle of the Marsala material ($\varphi'_{cs} = 31°$ vs $\varphi'_{cs} = 36°$) is consistent with a more granular, fabric-controlled response. These quantitative differences confirm that the two lithotypes occupy distinct regions of the v–ln p′ plane and exhibit different critical-state characteristics.

4. Effect of cementing

The results of the oedometer tests on Palermo and Marsala calcarenites are presented in Fig. 8. A significant difference in compressibility is evident between the reconstituted and intact materials, reflecting their distinct initial structures.

For Palermo Calcarenite, the intact material exhibits elastic behaviour up to yield. Once yield occurs (at the knee of the curve), the destructuration process begins. Interparticle bonds begin to weaken, resulting in progressive deformations. The yield stress increases as the initial specific volume decreases (Fig. 8a). At the end of the yielding phase, at a very high level of stress ($\sigma'_v > 200$ MPa), the oedometer compression path of the intact soil converges with that of the reconstituted soil. This behaviour becomes more pronounced as the initial specific volume of the intact samples increases. This suggests that, at high stress levels, the fabric has no residual structure effects. Thus, the 1D-NCL of the intact Palermo Calcarenite converges to the 1D-NCL of the reconstituted calcarenite (Fig. 8b). This convergence highlights the absence of structural components capable of resisting compression. A similar convergence was observed under shearing, as shown by the triaxial test results discussed above.

For Marsala Calcarenite, the intact samples exhibit a conventional yielding behaviour. In contrast, the compression behaviour of the reconstituted samples is characterised by gently curved compression paths and the absence of sudden stress drops. Throughout the loading process, the reconstituted samples show increased stiffness at higher stress levels. The compressive behaviour of the reconstituted sample is thus represented by curves consistently positioned to the right of those of the intact soil (Fig. 8a). Although the mineralogical composition is comparable between intact and reconstituted samples, no unique 1D-NCL can be identified at high stresses (Fig. 8b). This divergence indicates the development of distinct final soil fabrics.

For Palermo Calcarenite, regarding the difference in compression behaviour between intact samples with high and low initial specific volumes (Fig. 8), it can be observed that the compression paths of high-porosity intact samples occupy a region in the v vs p' plane that is inaccessible to the reconstituted material, whereas those of low-porosity samples do not.

Samples with a greater degree of cementation and a lower initial specific volume show a quicker convergence with the reconstituted material curve than samples with higher initial specific volumes. However, the interpretation of Fig. 8 is not straightforward. In particular, for intact samples characterised by lower initial specific volumes, the transition from the structured compression path to the destructured behaviour occurs more gradually, with a smoother curvature of the compression curve. As a consequence, identifying the yield stress for each compression curve becomes less clear and less rigorous than for the higher-porosity samples, where the yield point is more distinct.

This suggests that, for Palermo Calcarenite, the initial specific volume plays a more crucial role than the cementation amount. Hence, a material's ability to follow a com-

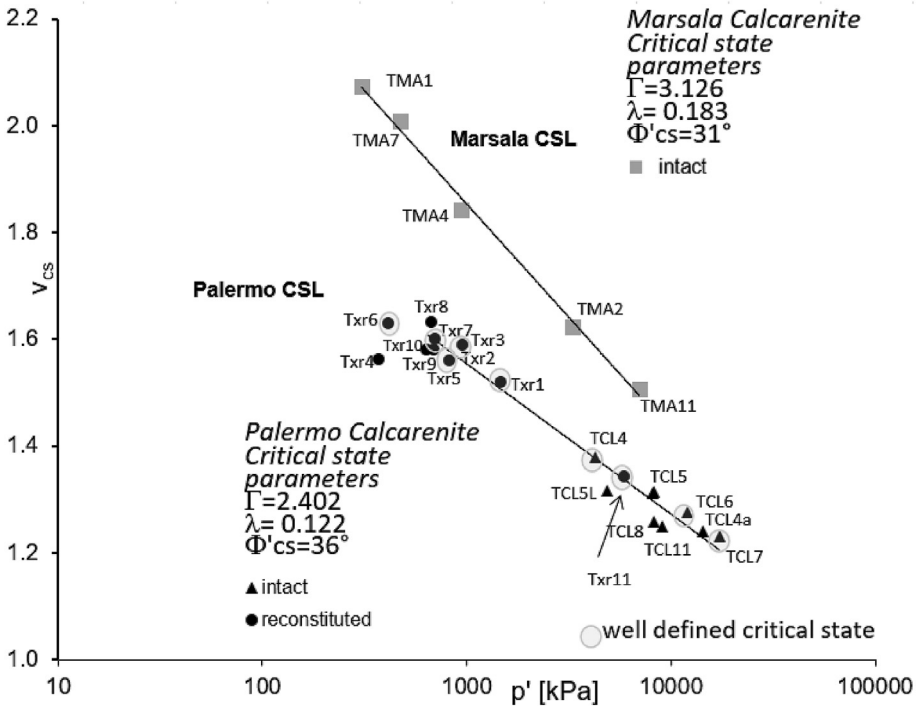


Fig. 7. Triaxial test on Palermo and Marsala calcarenites: specific volume at the critical state.

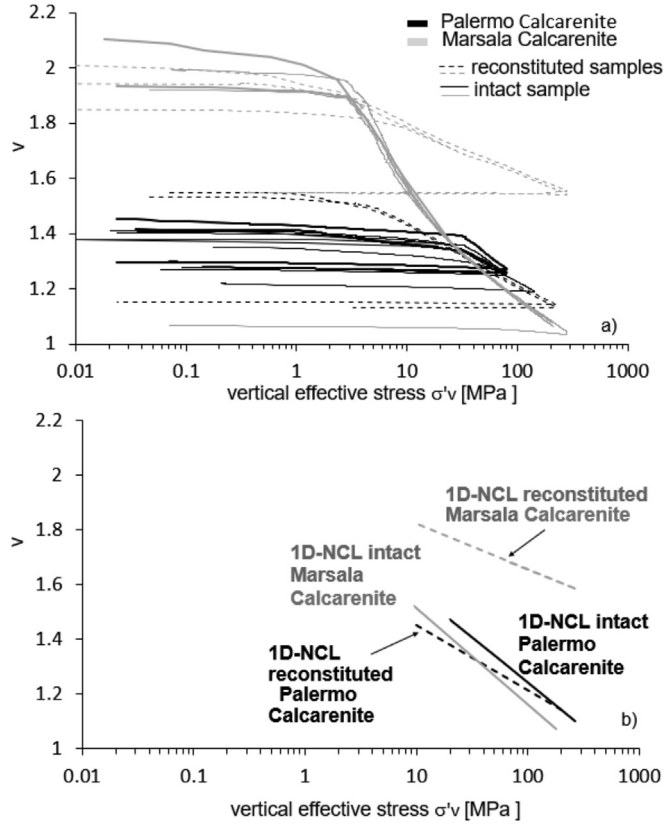


Fig. 8. Intact and reconstituted samples of lithotype Palermo Calcarenite (strong bonding) and Marsala B2 Calcarenite (weak bonding), a)1-D compression curves, b) 1D-NCL.

pression path that reaches the inaccessible area of the v vs. p' plane cannot be considered a valid parameter for quantifying the amount of structure.

From Fig. 9, it can be observed that the compression paths of Palermo Calcarenite in the v vs p' plane converge. The Palermo intrinsic NCL represents the compression paths of the reconstituted samples and the intact samples with a low initial specific volume. The post-yield compression line instead highlights the compression paths of intact samples with a high initial specific volume, where the effect of structure (i.e., bonding) is more pronounced. These two lines (intrinsic NCL and post-yield compression lines) are not parallel; the distance between them decreases as the specific volume decreases, and eventually the two lines converge at a point on the v vs. p' plane corresponding to a specific volume of about 1.16, a value that is very difficult to achieve in nature and rarely reached even under high applied compression stresses. These stress levels are therefore assumed to represent the lower limit of specific volume and NCL slope. This limit appears common to both initial states—whether intact or reconstituted—under high stress and very low specific volume conditions.

In the same figure, the CSL is also reported. It is observed that the CSL is not perfectly parallel to the intrinsic NCL but is more nearly parallel to the post-yield compression line, even at low stresses, which is the destructuration phase of the intact material.

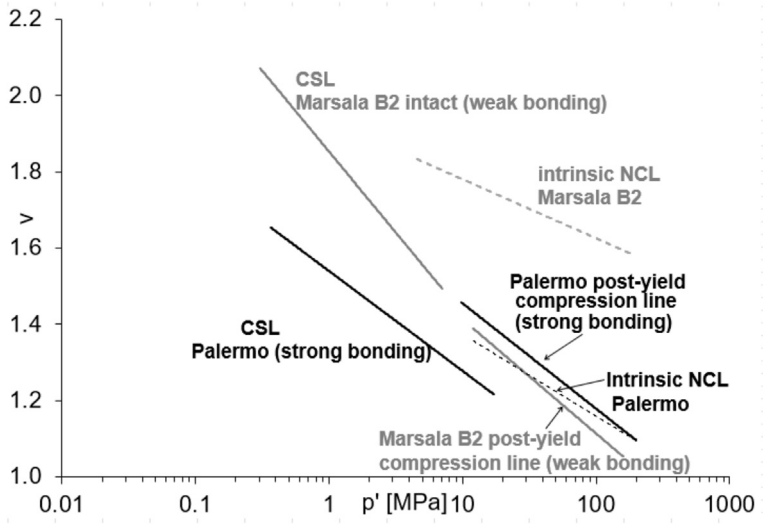


Fig. 9. CSL and NCL of intact (post-yield compression line) and reconstituted samples (intrinsic NCL): comparison between Palermo Calcarenite (strong bonding) and Marsala Calcarenite (weak bonding).

The tests conducted on the reconstituted material (Palermo Calcarenite), characterised by λ values (intrinsic NCL gradient) lower than those observed in the partially cemented material (post-yielding line), indicate a lower deformability. Regarding the compression paths of intact samples, following the destructuration process—which involves structural changes due to bond fragmentation and particle reorganization—it is likely that a new structure forms in which the particles resulting from broken bonds and the grains remain strongly interconnected.

Fig. 9 also presents data for the lithotype B2 of Marsala Calcarenite. The intrinsic NCL and the post-yield compression line, obtained from oedometer tests on reconstituted and intact specimens, respectively, are shown together with the CSL obtained from triaxial tests on intact specimens. These data, together with those for Palermo Calcarenite, enable a direct comparison between the two Sicilian calcarenites, characterised by different bonding strengths – strong in Palermo and weak in Marsala. For Marsala Calcarenite, the post-yield compression line of the intact material lies to the left of the intrinsic NCL of the reconstituted material. The intrinsic NCL and post-yield compression lines of the reconstituted and intact states, respectively, do not converge.

Zimbardo et al. (2022) showed that intact and reconstituted Marsala Calcarenite do not converge towards a unique reference compression line. The present study provides a contrasting case through the new experimental investigation of reconstituted Palermo Calcarenite, for which convergence between intact and reconstituted behaviour is observed. The comparison therefore shows that the response previously observed for Marsala Calcarenite cannot be generalised to calcarenites as a material class. The two lithotypes differ markedly in their degree and distribution of cementation and in the resulting porosity and bonded fabric, suggesting an important role of these inter-related structural characteristics in the different mechanical behaviour. However, because the comparison involves two natural lithotypes rather than a controlled variation of cementation, the individual contribution of cementation cannot be quantitatively isolated from differences in inherent particle characteristics.

A material can be considered a valid reference state when, regardless of its initial cementation or destructuration level, it tends toward a unique, regular compression line in which the initial fabric no longer influences its mechanical and deformational behaviour. Palermo Calcarenite meets this condition: intact and reconstituted specimens converge towards a unique one-dimensional compression line in oedometer tests and towards a unique Critical State Line in triaxial tests, irrespective of their initial structure. Marsala Calcarenite does not: its intact material is more compressible than the reconstituted material, the initial fabric remains robust, and the two compression curves diverge rather than converge, so that the reconstituted material cannot be considered a reference for one-dimensional compression.

This contrast is supported by qualitative microstructural observations. A higher amount of macropores was evident in the reconstituted Marsala material, suggesting a *meso*-structure composed of distinct types of interparticle contacts, which may be either the cause or the consequence of incomplete destructuration and is likely difficult to erase even under high stress. This differs from the typical response of structured soils, where reconstitution generally leads to convergence towards a unique reference line (e.g., Coop and Atkinson, 1993), and suggests that Marsala Calcarenite retains persistent heterogeneities in bonding or particle contacts not entirely erased during reconstitution. Consistent with this, de Bono and McDowell (2018) note that, for reconstituted sands, the void space after initial deformation depends mainly on the cumulative volume

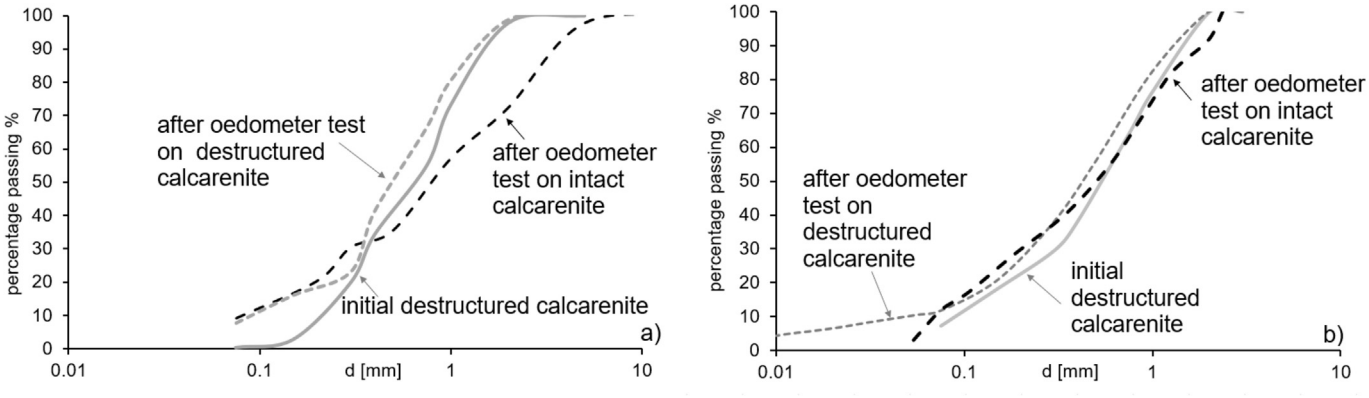


Fig. 10. Particle size distribution: a) Palermo lithotype b) Marsala lithotype.

and arrangement of the smallest particles, quantifiable through the coordination number (the number of contacts each particle has with its neighbours) — a mechanism that could plausibly sustain the fabric-dependent behaviour observed here.

Fig. 10 presents the grain-size distributions for Marsala and Palermo samples before and after the oedometer tests on the reconstituted material, and after testing only for the intact material. For Marsala Calcarenite, no significant amount of fines is generated despite the very high vertical stresses applied, consistent with the sieve analysis in Fig. 10b. In contrast, the Palermo sample shows a more pronounced increase in the fine fraction after testing, indicating more extensive bond breakage. Microscopic observations (Fig. 11) confirm that this degradation primarily affects the cementing matrix rather than the carbonate grains: the calcitic cement shows clear signs of fragmentation and debonding, while the grains remain largely intact and simply rearrange once bonding has failed. The greater breakage observed in Palermo therefore reflects the collapse of cementation rather than grain crushing, promoting thorough destructuration and the formation of a stable, interlocked granular fabric consistent with a true reference state.

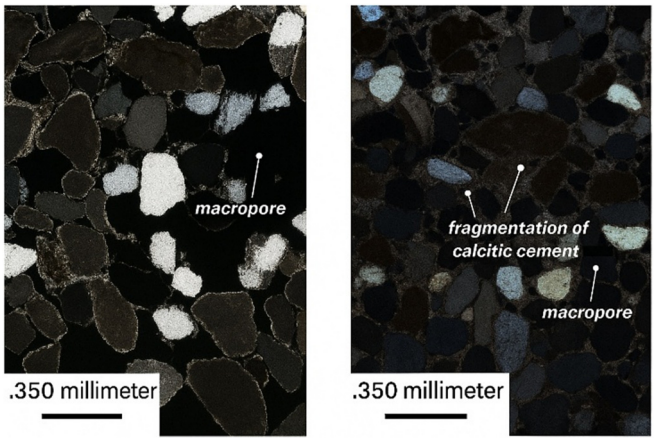


Fig. 11. Microphoto of lithotype Palermo CL2 intact sample: left: before oedometer test, right: after the oedometer test.

Marsala Calcarenite, with its much weaker and more fragile cementation, does not undergo comparable bond breakage and instead retains a residual mesostructure dominated by the original fabric — consistent with the fabric-dependent compression response and lack of convergence discussed above.

The effects of destructuration processes in the Palermo CL2 lithotype were investigated using transmitted light microscopy (XPL: cross-polarised light) on thin sections (Fig. 11). In this lithotype, oedometric compression at the stress levels reached did not induce substantial changes in the original texture: the size, shape, and contours of the clasts remain unaltered, i.e., the grains are entirely intact. Mesopores remain open, and the observed volume changes are mainly due to debonding processes, resulting in a reduction of macropores.

Regarding the Marsala intact initial sample (Fig. 12), the destructuration process is attributed to the breakdown of intergranular cement. While the grains themselves remain intact, significant textural changes are evident. Specifically, although macropores and intragranular mesopores persist, more than 90% of the intergranular mesopores are eliminated. No evidence of grain crushing is observed. This observation is fully consistent with the results of the sieve analysis (Fig. 10b), which show an almost unchanged grain-size distribution after the oedometer test.

The applied stresses were insufficient to induce either grain breakage or significant cement degradation in Marsala Calcarenite. Irregular microcracks merely developed at grain contacts, and the grain boundaries became noticeably sharper.

The intergranular cement appears less transparent (e.g. turbid) and exhibits the typical birefringence characteristics of a carbonate-silt aggregate. Additionally, microcracks originating at the grain contacts extend to lengths exceeding 50 times the grain diameter, further indicating the progressive failure of the cementing matrix rather than the grains themselves.

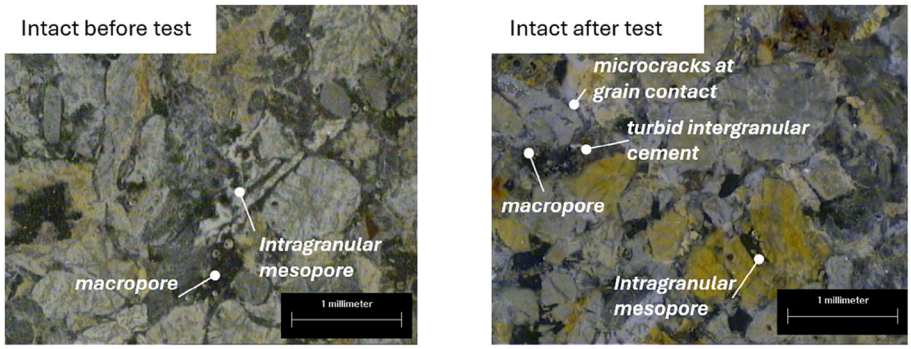


Fig. 12. Microphoto of lithotype Marsala intact sample: left: before oedometer test right: after the oedometer test.

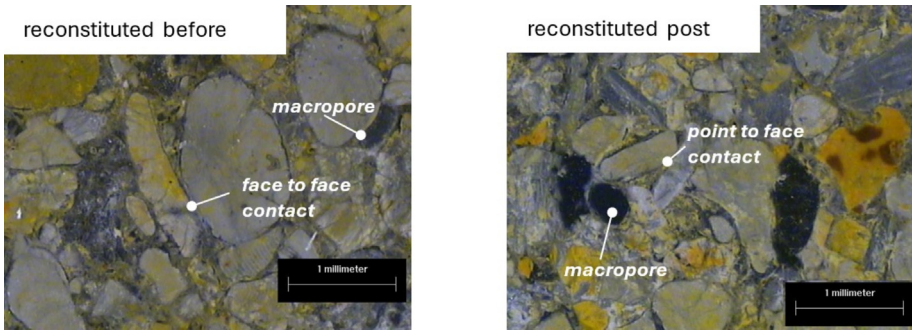


Fig. 13. Microphoto of lithotype Marsala reconstituted sample: left before the oedometer test, right after the oedometer test.

For the reconstituted Marsala sample (Fig. 13), image observations clearly reveal a different nature of the contact between the grains. The final fabric observed after testing differs between the reconstituted and intact samples. Comparison of the two indicates that the reconstituted material exhibits a more dispersed fabric than the intact one. Analysis of thin sections following the oedometer tests revealed that the intact specimen contains fewer macropores. It can be inferred that face-to-face grain contacts are more common in the intact sample, whereas point-to-face contacts prevail in the reconstituted one, contributing to the observed differences in fabric. Furthermore, the presence of a mesostructure within the reconstituted sample—difficult to alter even under high stress—may explain its distinct mechanical behaviour.

5. Conclusions

The mechanical behaviour of the strongly bonded Palermo Calcarenite was investigated through an extensive experimental programme comprising drained triaxial tests on isotropically compressed specimens and oedometer tests on both intact and reconstituted samples. The results were interpreted within the framework of Critical State Soil Mechanics and compared with those previously obtained for the weakly bonded Marsala Calcarenite, both lithotypes originating from Sicily.

Palermo Calcarenite behaves as a metastable soil whose mechanical properties are influenced by both fabric and bonding. The influence of bonding on shear behaviour becomes more pronounced as the initial specific volume decreases. Upon shearing, intact and reconstituted specimens converge towards a unique Critical State Line, with a unique stress ratio M identified. The specific volumes at critical states, plotted against ln p', align with a line parallel to the post-yield compression line even at low mean effective pressures, reflecting the influence of cementation in sustaining the applied stresses. This suggests that, at critical state conditions, the mechanical behaviour may still reflect the characteristics of the cemented structure particularly through the cement fragments and the interlocked fabric formed after bond breakage.

The oedometer tests showed that intact samples with low initial specific volume exhibit lower deformability and behave similarly to the reconstituted material. The absence of macropores reduces compressibility, and no distinct yield stress can be identified as the onset of debonding. Throughout the entire loading path, the behaviour of the intact material is influenced by the presence and strength of cementation: the strength of cement fragments, generated during structural breakdown, may contribute to the slope of both the CSL and the post-yield compression line. At high stresses, the NCL of the reconstituted material and the post-yield compression line of the intact material converge, marking the end of the destructuration process.

A key finding of this study is that intact and reconstituted Palermo Calcarenite approach a common reference response, whereas the one-dimensional compression paths

of intact and reconstituted Marsala Calcarenite, characterised in its intact state by a more open, high-specific-volume fabric and weaker cementation, do not converge.

The destructuration of Marsala Calcarenite produces a fabric that is difficult to erase and is not representative of the intact soil — a 'negative' effect of structure reflected in a progressive decrease in the inclination of the NCL and an increasing deviation from the post-yield compression line. For this lithotype, destructuration should not be understood as a simple degradation of mechanical properties but as a transformation leading to new and distinct mechanical behaviour, likely similar to that of a locked sand. The comparison shows that weaker cementation does not necessarily correspond to a closer agreement between intact and reconstituted compression behaviour.

These findings indicate that the response to reconstitution is not unique among the investigated calcarenites and is associated with differences in their initial bonded structures, including the degree and distribution of cementation and the resulting porosity and fabric.

Since the comparison involves two natural lithotypes, the individual effects of cementation and inherent particle characteristics cannot be quantitatively separated. Moreover, in the absence of triaxial tests on reconstituted Marsala Calcarenite, the lack of convergence demonstrated for Marsala is restricted here to one-dimensional compression behaviour.

The results of this study have direct practical implications for geotechnical design in areas where calcarenites constitute foundation soils or are present as building materials. These lithotypes are widespread across large areas of central and southern Italy where they underlie many urban settlements and have been extensively used in the construction of civil, monumental, and archaeological buildings due to their workability and favourable strength-to-weight ratio. A significant consequence of their widespread use is the presence of numerous underground quarries, which frequently extend beneath urban centres and may be subject to subsidence and collapse. The identification of a reliable intrinsic reference state for strongly bonded calcarenites, such as Palermo Calcarenite, provides a practical framework for characterising the post-destructuration mechanical response of these materials, which is relevant for the assessment of foundation settlements, tunnel stability and the long-term behaviour of underground cavities in cemented carbonate formations. For Marsala Calcarenite, the absence of a unique reference compression line indicates that fabric-dependent behaviour must be explicitly accounted for in geotechnical design, and that standard reconstitution procedures may not provide a reliable reference for weakly bonded calcarenites of similar depositional origin and mineralogical composition.

CRediT authorship contribution statement

Margherita Zimbardo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Alessandra Nocilla:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Matthew Richard Coop:** Writing – review & editing, Methodology, Conceptualization.

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