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Mechanical behaviour of granular materials undergoing grain dissolution

Taeheon Kim [1,2✉], Alessio Ferrari[1] & Lyesse Laloui[1]

Geotechnical engineering projects are often at risk from threats related to mineral dissolution and loss of particles that constitute the matrix of the geomaterial. Moreover, the impact of climate change can exacerbate these risks by accelerating the physical processes. To address such challenges, it is a pre-requisite to understand and quantify the effect of mineral dissolution on geomechanical behaviour. A general theoretical approach to mechanical consequences of geomaterials experiencing mineral dissolution was first proposed. Following, a series of oedometer tests were conducted using mixtures of salt and sand with various salt contents to observe and characterise the effect of dissolution on the mechanical behaviour of granular materials. The dissolution of salt crystals was performed in three different stress states to observe the stress-dependent response of the material. The effect of dissolution was dependent both on the amount of dissolved salt particles and the applied stress state. The laboratory experiments and the discussion followed shares insights into the effect of grain dissolution on the mechanical behaviour of granular materials and proved the potential of the framework presented in this paper. Finally, the paper ends by discussing the engineering implications bearing in mind the climate change we are facing today.

Keywords Dissolution, Degradation of geomaterials, Geomechanics, Granular soils, Critical state soil mechanics

List of symbols

C_c	Slope of LCC (oedometric condition)
C_e	Slope of URL (oedometric condition)
c_0, c	Initial and current salt content
e_0, e	Initial and current void ratio
N_{oed}	Intercept of LCC at 1 MPa under oedometric condition
$N_{oed,0}$	Reference N_{oed} value
V_{sd}	Soluble solid volume
V_{si}	Insoluble solid volume
V_v, V_v'	Void volume before and after dissolution
V_t, V_t'	Total volume before and after dissolution
α_{oed}	Slope of N_{oed} value with respect to salt content
σ_c	Yield vertical stress

Loss of solid grains from unbonded geomaterials is a common phenomenon encountered in geotechnical engineering, and it contributes to situations such as dam failure due to suffusion or dissolution[1–3], landfill settlement due to subsurface degradation[4], weathering of superficial sediments[5] and some cases of extraction of gas hydrates from seabed[6,7]. Loss of grains from within soil structure can be caused by transport of loose particles by fluids or dissolution of particles by chemical reactions. Regardless of the cause, the loss of grains can lead to looser internal structure in the material, which may result in significant deformation of the ground[4]. Moreover, climate change, through effects such as intensified precipitation, alterations in the biosphere and shifts in groundwater level can accelerate these processes. This can even destabilise initially secure ground and geotechnical structures without being noticed[8–10].

To understand the effects of grain loss from soils, laboratory studies were conducted using salt crystals as removable grains in the soil matrix. The results consistently showed an increase in the void ratio, volumetric

[1]Laboratory of Soil Mechanics, Swiss Federal Institute of Technology, Lausanne, Switzerland. [2]Sandakerveien 140, Oslo 0484, Norway. ✉email: Taeheon.kim@ngi.no

compaction and decreases in stiffness and strength[11–16]. Despite this evidence few studies have theorized the changes in mechanical behaviour related to the effects of grain dissolution in unbonded soils.

Fam et al.[12] performed triaxial tests on salt-sand mixtures and reported interesting behaviour. The authors induced dissolution of 10% of the grains by mass, which led to a 25% reduction in shear wave velocity at an axial strain of only 0.05%. This evidence showed that the effect of grain dissolution on unbonded granular soils did not necessarily manifest immediately through relevant volumetric compaction. McDougall et al.[4] investigated the effect of dissolution using similar mixtures in an oedometer apparatus. The authors observed a bilinear response for vertical settlement with respect to the amount of dissolved mass: with minor amount of dissolution, the settlement was relatively small; however, beyond certain amount of dissolution, the vertical settlement increased rapidly. Similar trends were reproduced with discrete element analyses[4,13,15]. While the effects of salt content on the mechanical response of soils were reported, only a handful of experimental studies have applied varying stresses and salt contents for granular materials.

From a constitutive modelling and theoretical perspective, most of the propositions account for the contribution of interparticle bonding induced by dissolution and/or precipitation[17–21]. These models are extended versions of the Cam Clay model that is rooted in earlier theoretical studies of weak sedimentary rocks or structured soils[22–24] : the preconsolidation stress evolves with density and bonding due to environmental factors including dissolution and precipitation. These constitutive models attribute changes in mechanical behaviour to the evolution of bonding alone. For instance, the yield surface would be expanded based on the degree of interparticle bonding (or structure), and it contracts correspondingly when dissolution takes place. However, these models do not account for changes in density or porosity that inevitably occurs from mineral dissolution. Thus, while the existing models were somewhat successful in incorporating the effect of intergranular bonding (i.e., soil structure), they are not appropriate for unbonded geomaterials, as they do not explicitly consider the effect of densification.

A general account on mineral dissolution of geomaterials

Chemically induced mineral dissolution and internal erosion represent geological processes that exert significant effects on geomaterials, manifesting changes across three categories: material properties, bonding characteristics, and density dynamics.

The alteration in mineralogy is a fundamental facet of material change. Here, chemical dissolution acts as a force to selectively removing soluble minerals from the solid matrix. This not only impacts the mineral composition but also modifies the mechanical and physical properties of the geomaterial. Simultaneously, changes in grain size distribution represent another dimension of material alteration. This shift in soil type alters the micromechanical interaction between neighbouring particles and therefore the overall bulk mechanical behaviour. The nature of material change is further accentuated by modifications in particle shape and morphology. The reshaping of particle structure is a consequence of the chemical interactions and erosive processes, influencing the overall morphology of the particles. These changes collectively redefine the intrinsic behaviour of the material, introducing variations in its response to external forces and environmental conditions.

The second essential aspect of this process is the impact on bonding characteristics within the geomaterial. Chemical dissolution, by removing soluble minerals, can cause the bridges between particles to disappear or weaken. This weakening of bonds facilitates easier relative movement of particles, altering the overall behaviour of the geomaterials.

Lastly, the density dynamics represent the third category of the changes induced by these geological processes. The loss of solid phases due to dissolution and erosion results in a decrease in material density. This reduction creates an open structure within the geomaterial, further deteriorating its mechanical integrity influences the stress-strain response. According to the Critical State Soil Mechanics framework, the yield surface, based on the preconsolidation stress, undergoes exponential changes with void ratio. This makes the density changes due to environmental impact crucial for properly characterizing the mechanical behaviour of geomaterials.

Assume a hypothetical scenario where a bonded geomaterial, such as carbonate-cemented sand, undergoes mineral dissolution due to the continuous supply of acidic water[25], the process is conceptually illustrated within the framework of Critical State Soil Mechanics (Fig. 1). The initial composition consists of quartz sand and carbonate minerals, with carbonate minerals existing in various states: individual particles, patching or coating quartz particles, and forming bridges between particles.

The removal of carbonate minerals contributes to three distinct processes. Firstly, material change involves the loss of carbonate minerals, leaving behind quartz particles, thereby altering the Virgin Compression Line (VCL) and Unloading Reloading Line (URL), which are characteristics of the material (Fig. 1 (a)). Secondly, the dissolution weakens interparticle bonds or cementation, leading to a reduction in the yield surface. This is depicted in Fig. 1 (b) as the translation of the VCL to the left-hand side, resulting in a decrease in material strength. The decrease in density due to dissolution signifies a change in state to a higher void ratio, illustrated in Fig. 1 (c). According to critical state soil mechanics, the yield surface is characterized by the current state and the VCL, and thus it is logical to expect that increase in void ratio systematically lowers the strength. The mechanical consequence of mineral dissolution encompasses a combination of these effects. The dissolved state, as conceptually shown in Fig. 1, provides insights into what can be expected in terms of Critical State Soil Mechanics.

Motivation of the study

Historically, the impact of density changes resulting from dissolution processes was not the primarytopics in geomechanics. While a few existing publications present intriguing findings, systematic frameworks for describing the effects of mineral dissolution on unbonded soils are scarce. This study sought to bridge this
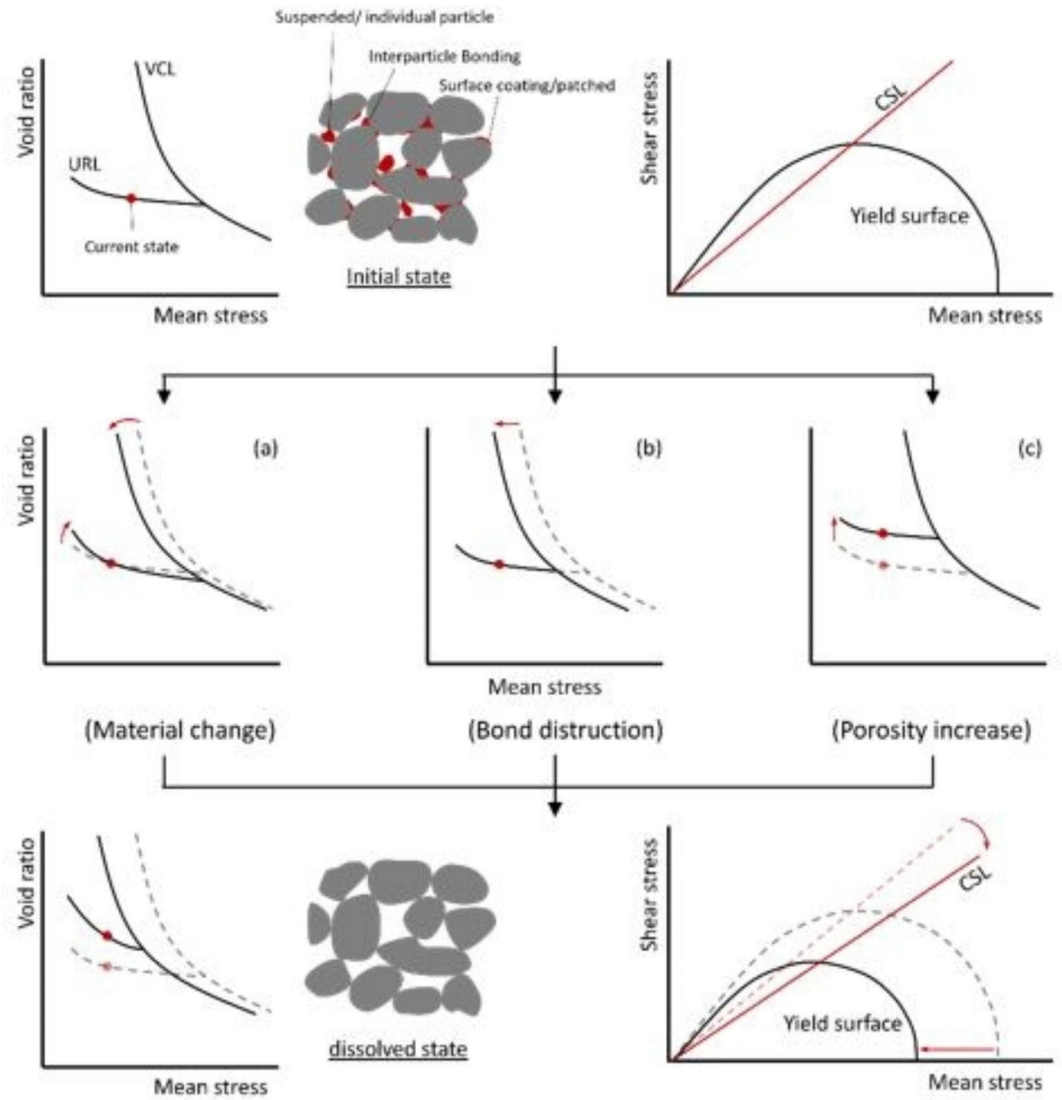
Fig. 1. Illustration of dissolution process interpreted based on critical state soil mechanics.

knowledge gap by conducting a comprehensive campaign of experiments focused on investigating the effects of densification due to dissolution in unbonded granular materials under oedometric conditions. The experimental study systematically varies the vertical stress and the amount of dissolved volume and observes the correlation between the two variables. Through the experimental findings, a novel theoretical framework based on Critical State Soil Mechanics was presented.

Experimental study

In this study, dry mixtures of sand and salt were compressed under oedometric conditions. At a later stage, each sample was saturated and flushed with water to remove the salt to mimic grain dissolution. The use of salt grains to simulate mass removal was successfully applied in previous studies[12,15,16,26], as salt dissolves quickly in water provided there is sufficient flow.

Figure 2 depicts phase diagrams of the relative composition of a test specimen before and after complete dissolution. The volume of the soluble mass (salt) is V_{sd}; the volume of the insoluble solid (sand) is V_{si} and remains unchanged in the two states. The change in volume of voids (from V_v to V'_v) is the result of the change in bulk volume (from V_t to V'_t) and the disappearance of V_{sd} due to dissolution.

The salt content to be dissolved, c, is defined as the ratio:

$$c = \frac{V_{sd}}{V_{si}} \qquad (1)$$

Materials and apparatus

Tests were conducted using a mixture of table salt and Itterbeck quartz sand grains. The densities of the solids were 2.17 g/cm^3 and 2.65 g/cm^3 for salt and sand, respectively.
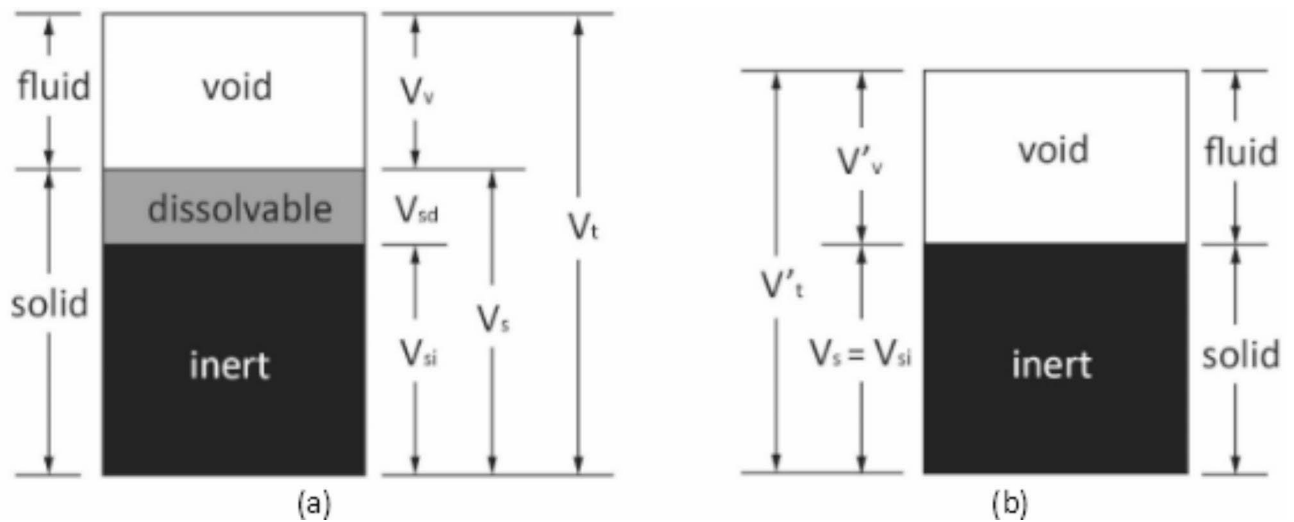
Fig. 2. Phase diagrams of the relative composition of a test specimen in the initial state (**a**) and after dissolution (**b**).

Initial target values of *c* were 0%, 5%, 11%, and 18%, and they were obtained by mixing different quantities of dry salt and sand. The salt grains had diameters between 0.125 and 0.25 mm. Sand-salt mixtures were made by thoroughly blending the two with a thin spatula. During the mixing process, noticeable colour changes were observed. Once the mixture showed uniform colour despite continued mixing, it was inferred that a homogenous mixture was created. The volumetric grain size distributions of the mixtures are shown in Fig. 3 for the various salt contents; the measured volumetric grain size distributions were very similar.

Oedometric tests were performed in a high-pressure oedometer with a maximum vertical stress of 100 MPa[27]. Vertical displacements were monitored with 3 LVDTs with a resolution of 0.2 μm. The experiments were conducted at a controlled temperature of 25 ± 1 °C. Quantities of salt and sand corresponding to the target values of *c* were mixed slowly poured into the oedometer ring, which had a diameter of 35.0 mm. A layer of filter paper was placed on both sides of the sample. Samples were statically compacted directly inside the oedometric apparatus to a target void ratio of 0.60; the resulting heights of the specimens were in the range from 12.3 to 12.6 mm.

Experimental procedure

Prior to conducting the core experiments, oedometric tests were conducted to observe the possible dependency of the results on the loading rate and any possible discrepancy between dry and saturated conditions for the pure sand. Figure 4 depicts the results of the oedometric tests under dry conditions on the pure sand (c = 0%) and on the sample with the maximum salt content (18%) for vertical strain rates of 0.001%/s and 0.01%/s. Similar to what was observed in other studies[28,29], the change in strain rate had a marginal impact on the compression curve; in this way, a strain rate of 0.01%/s was set for all the experiments.

It was important to identifyi possible differences between the behaviours of dry and saturated specimens, as in most of the experiments, the samples were loaded in a dry state prior to salt dissolution and in a saturated state after dissolution. Figure 5 shows a set of three oedometric tests on the pure sand in dry and saturated states. All tests showed repeatable trends, confirming that possible changes in the compression behaviour would be the consequence of grain dissolution alone and not of saturation.

Four test series were conducted in terms of salt content and applied vertical stress as shown in Fig. 6. The codes for the test series included the salt content as a percentage. For example, T2-11 is the second series of tests on samples with 11% salt content.

The first series of tests (T1) was focused on observing the oedometric response of samples prepared at different salt contents. An initial axial stress of approximately 300 kPa was applied and maintained until the strain stabilizes (recorded strain less than 1×10^{-5}%/h). The axial load was then increased to 80 MPa to observe the limit compression curve (LCC) defined by Pestana and Whittle[30], i.e., the final portion where the log σ_v - e plot was nearly linear (σ_v is the axial stress).

The second (T2), third (T3) and fourth (T4) series of tests were conducted to observe the effect of dissolution at different stresses (32 MPa, 10 MPa, and 4 MPa). Each experiment was composed of three stages: (i) loading and/or unloading prior to dissolution, (ii) dissolution at constant vertical stress, and (iii) final post-dissolution loading/unloading cycles. In stage (i), conventional oedometric loading/unloading was performed on dry samples to the target axial stresses at the selected constant strain rate; the samples were kept under constant stress for a minimum of 12 h or until the strain rate was below 0.01%/h. This phase allowed the time-dependent response to develop sufficiently so that the related deformation would not affect settlement caused by dissolution.

The dissolution stage (ii) was performed by allowing deionized water to flow through the dry sample. Water was introduced from the lower base by applying water at a pressure of a few kPa and maintaining the upper base at zero pore water pressure. To completely remove all the salt from the soil, the minimum volume of water
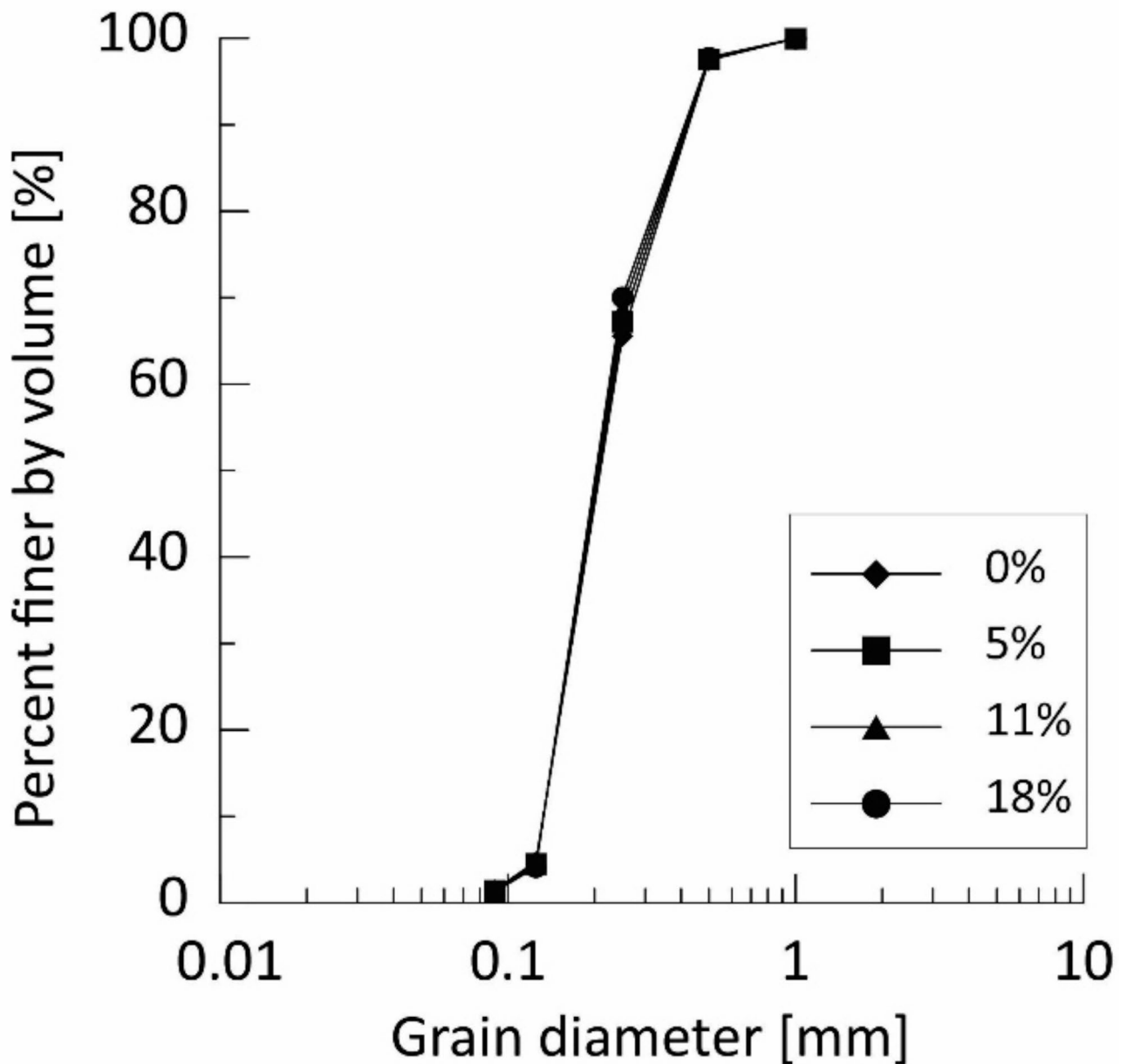
Fig. 3. Grain size distributions for various salt contents.

required to dissolve the salt was calculated based on a solubility chart of NaCl[31], and a total amount of water equal to a minimum of 5 times this quantity was flushed through the sample. Settlement was recorded for a minimum of 12 h.

In the post-dissolution stage (iii), the samples were loaded in a saturated state to higher stresses to observe possible changes in the yield stress as the consequence of salt dissolution.

After the tests were terminated, the samples were retrieved, oven dried for 24 h and weighed with a high-precision balance. The exact initial salt content was then checked using the initial mass of the salt-sand mixture and the final mass of sand remaining after the experiment.

The void ratio in the post-dissolution stage was calculated by using the volume at the end of stage (ii) and the final sand volume.

Experimental results

Figure 7 shows the results of test series T1. The results showed systematic variation in oedometric behaviour with salt content. A clear LCC was observed for each mixture, confirming that the salt crystals actively contributed to force transmission within the skeleton. The LCCs were characteristic of each mixture, as reported by other authors for various sand types[32–36], and they shifted towards the left-hand side of the graph with increasing salt content.
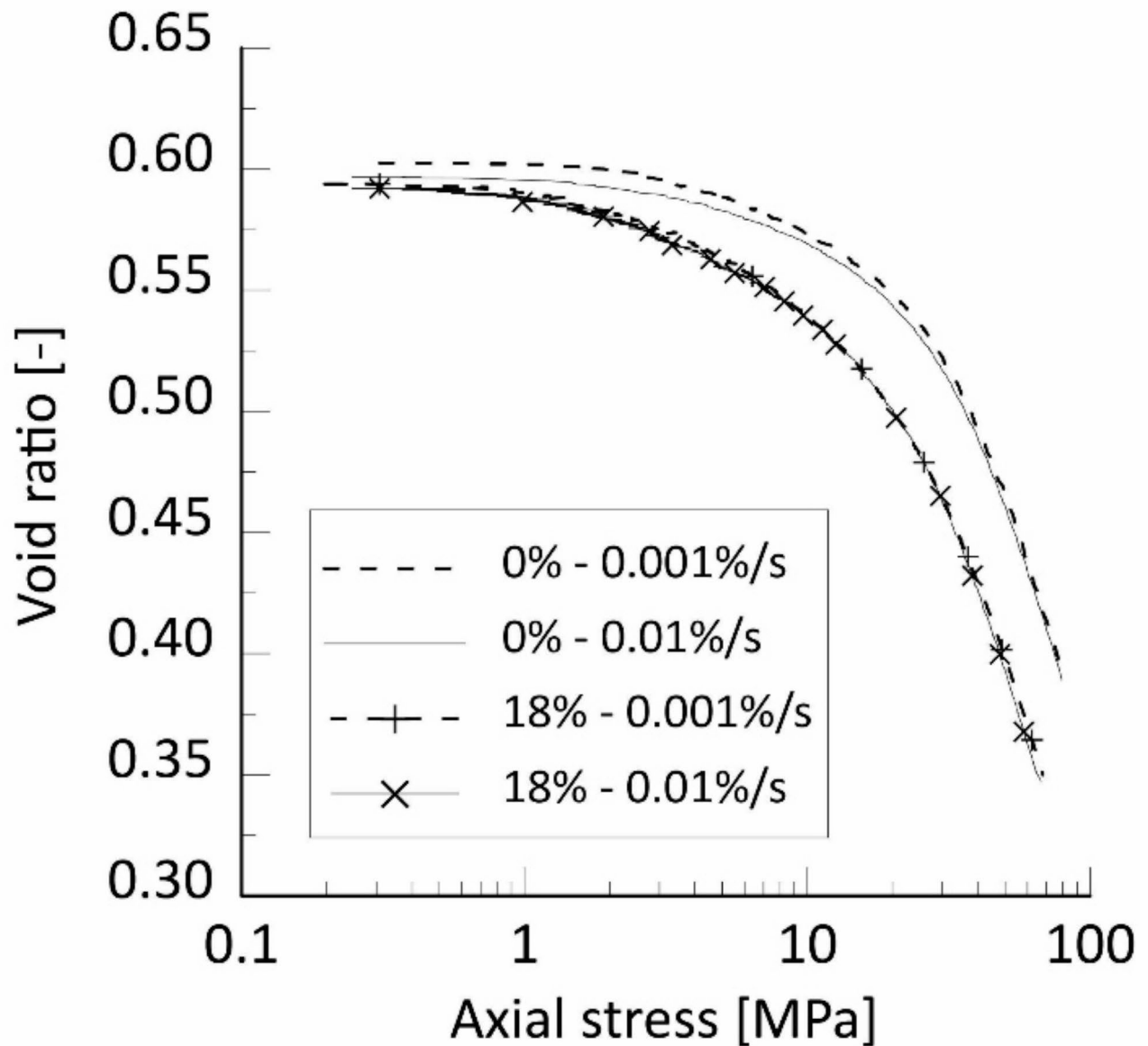
Fig. 4. Effect of the strain rate on the compression behaviour of dry samples prepared at two different salt contents.

For all the samples, the slopes of the LCCs were practically the same; the different LCCs were then expressed by:

$$e_{lcc} = N_{oed} - C_c \log \sigma_c \tag{2}$$

where e_{lcc} is the void ratio along the LCC, N_{oed} is the intercept of the LCC for an effective vertical stress of 1 MPa, C_c is the slope of the LCC and σ_c is the yield vertical stress in MPa. The average C_c was 0.338 (all values were in the range of 0.334 to 0.341); N_{oed} depended on the salt content (Fig. 8). For the explored range of salt contents, data were fitted with the following linear expression:

$$N_{oed} = \alpha_{oed} c + N_{oed,0} \tag{3}$$

with the fitting parameters $N_{oed,0}$ equal to 1.034 and α_{oed} equal to -0.318

Figure 9 depicts the results of test series 2, for which the dissolution stage was performed under a constant vertical stress of 32 MPa, in terms of the void ratio and axial strain. In the same figure, the LCC for the pure sand is also drawn (from test T1-0) for reference.

There was no dissolution in test T2-0 as there was initially zero salt content. The difference between the pre-dissolution and post-dissolution phases was marginal, as the compression behaviour of the saturated sample quickly converged to the LCC of the pure sand.
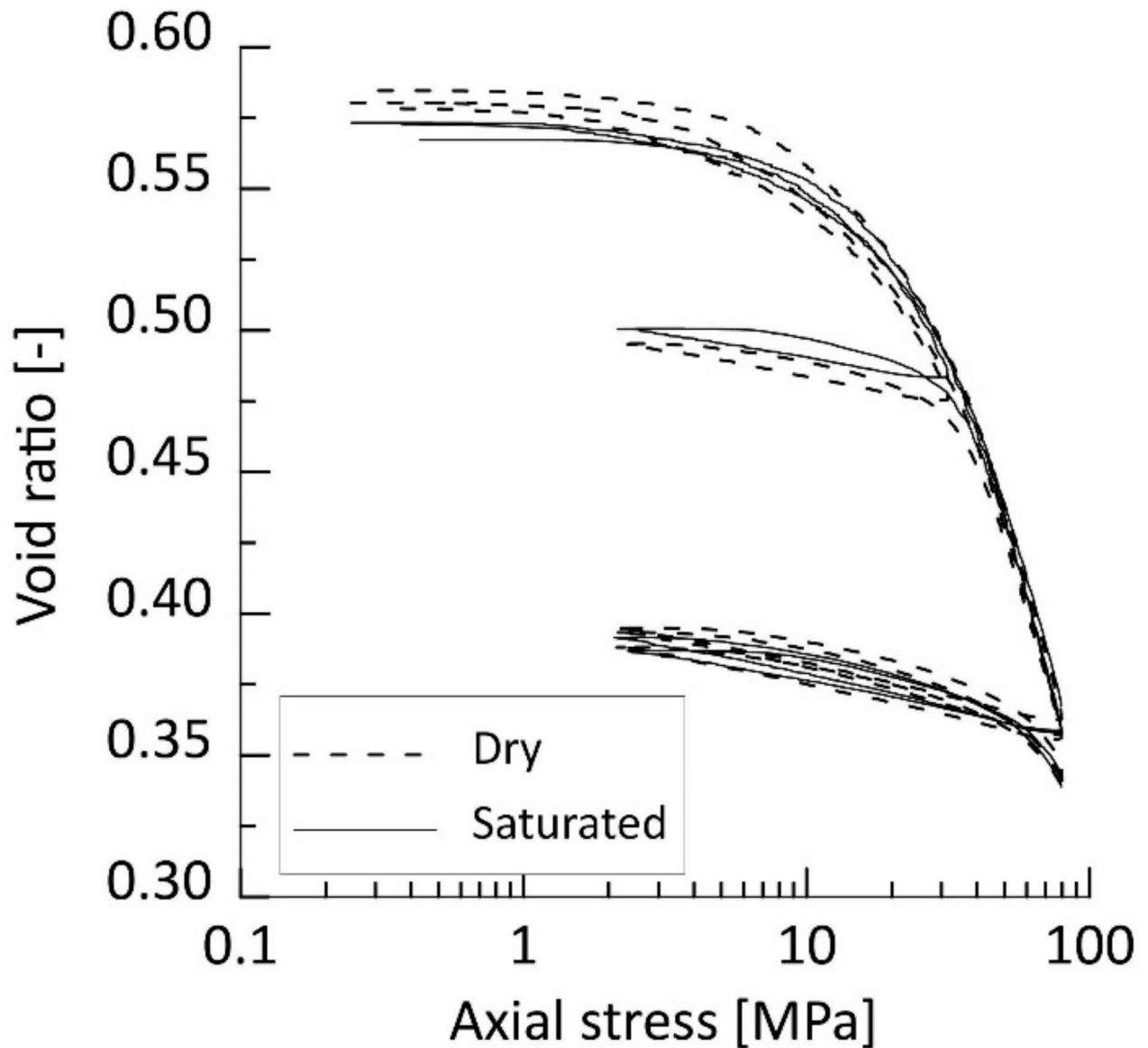
Fig. 5. Oedometer curves of dry and saturated samples of pure sand.

For tests T2-5, T2-11 and T2-18, a larger axial deformation was measured with increasing salt content. Interestingly, the combination of the compaction (increase in axial strain) and the dissolution of salt crystals (removal of V_{sd}) always resulted in an increase in the void ratio, which was very close to the corresponding value on the LCC for pure sand in every case. As the load continued to increase, the oedometric behaviour was perfectly aligned with this LCC.

Figure 10 shows the response measured in tests in which dissolution occurred at a vertical stress of 10 MPa after preloading to 32 MPa. The test on pure sand (T3-0) showed the typical oedometric response of sand in loading–unloading cycles. In particular, upon reloading, the yield stress was always clearly coincident with the maximum applied vertical stress. This was notable because the behaviour was different when dissolution occurred. Also, the saturation of the sample did not have any impact on the response. Similar to the previous test series, the axial strain induced by dissolution increased with increasing initial salt content. Additionally, in this series, the void ratio value corresponding to the LCC was always approached as a result of dissolution; interestingly, with respect to the previous series T2, the change in void ratio was larger for the same salt content. The LCC was then fully reached as the loading continued. In general, the yield stress that could be obtained with Casagrande's construction was always less than the maximum applied stress.

The results of the fourth series of tests are depicted in Fig. 11. In this series, dissolution was applied at a vertical stress of 4 MPa after unloading from the maximum stress to 32 MPa. Axial strains upon dissolution were smaller with respect to series 3 for the same salt content, while increases in void ratio were larger. This feature is analysed below.

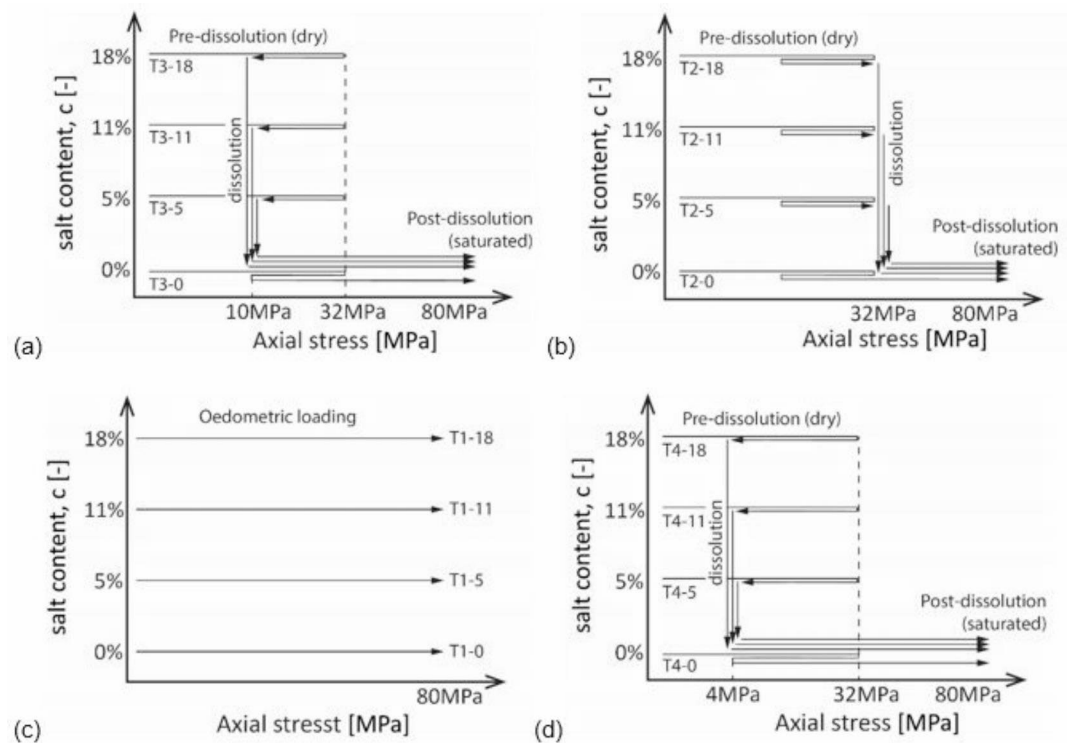The experimental results for salt sand mixtures undergoing grain dissolution showed some notable results:

Fig. 6. Salt content vs. applied stress in test series T1 (**a**), T2 (**b**), T3 (**c**) and T4 (**d**).

i.   The oedometric curve upon compression systematically depended on the salt content; in particular, samples with higher salt content showed smaller values of N_{oed}, while the slopes of the LCCs were practically unchanged.

ii. Salt dissolution induced volumetric compaction, which was greater at higher salt content and larger applied stress (Fig. 12). The combination of axial strain and salt removal resulted in an increased void ratio; this increase was larger at higher salt content and at smaller applied stresses (Fig. 12). The salt crystals contributed to the transmission of intergranular force for all the salt contents investigated in this study. Although a portion of solid grains that supported the externally applied stresses was always removed, compaction was more evident only for the higher salt contents. Thus, the experimental evidence confirmed that the specimens maintained their physical integrity under moderate dissolution.

iii. After dissolution, the samples showed lower yield stresses compared to the maximum vertical stress applied in the pre-dissolution stage (32 MPa).

iv. For the samples that underwent large compaction (i.e., those with higher salt content, see Fig. 12), the state of each specimen was close to the LCC in the $e - \log \sigma_v$ space.

Discussions and insights

A series of experiments performed in the current study showed that the vertical compaction was greater for higher salt content and stress conditions, while the increase in void ratio was larger for smaller vertical stress and higher salt content. The effect of grain dissolution on granular materials was investigated experimentally and numerically[15] using oedometer tests and discrete element analyses. The authors suggested an initial formula for volumetric compaction with grain dissolution where the equation was developed based on the premise that dissolution did not contribute to void ratio increase but solely induced volumetric compression. However, in the present study, changes in void ratio and volumetric compaction both occured and was significant. Moreover, changes in void ratio and volumetric compaction were dependent on the salt content and applied axial stresses.

   All tests from series 2, 3 and 4 suggests that the consequence of mass removal could be seen as a shift of the state of the material towards a new URL (unloading reloading line). Figure 13 conceptually summarizes this behaviour by depicting different stages of a dissolution process in which the salt content progressively decreased from the initial value (c_0) to 0. For each decrement of c, a new URL was reached. In the first stages of dissolution (from c_0 to c_1), the void ratio increased essentially as a consequence of the reduction of the salt as the overall deformation is minimal (see the minor change in axial strains recorded in test series 3 and 4). At the same time, the LCC moves towards the right, proportionally to the reduction of c, as suggested by test series 1 (see Fig. 7). As the dissolution continued, if the moving URL met the corresponding LCC for the applied vertical stress (stage c_2 in the figure), then the soil was prone to undergo relevant compressive axial strains, and thus that the increment in the void ratio was partially compensated by the volumetric compaction (from c_2 to c_3). Therefore, the LCC could be seen as the threshold to trigger dissolution-induced large volumetric compactions similar to those observed in earlier studies[4,13,15].
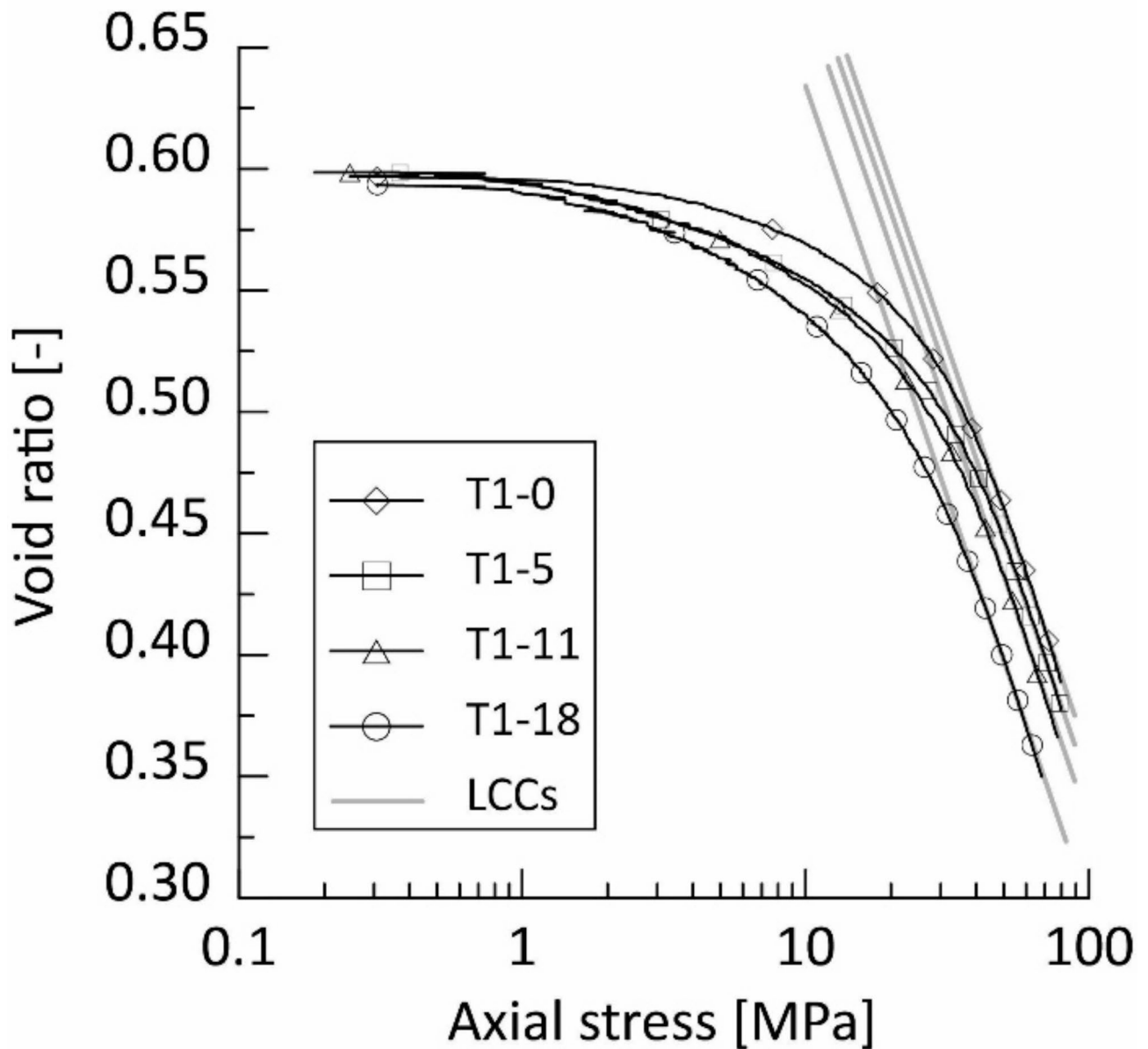
Fig. 7. Oedometric curves for samples prepared with different salt contents (series T1).

The movement of URL with dissolution can be attributed to increase in void ratio (decrease in density which was earlier shown in Fig. 1 (c)). On the other hand, translation of LCC is the result of material change, which was already identified that the LCC of salt-sand mixture was systematically dependent on the salt content (this can be linked to the response of change in material, Fig. 1 (a)). Since the material used in this study was not cemented, the effect of bonding was absent. Therefore, the mechanical behaviour reported here is the consequence of material change and density change. One more thing to address is that the LCC translated to the right-hand side on the void ratio – axial stress space with the same slope. This may, however, not be the case for other scenarios and would depend on the type of material. The upward translation of URL is, on the other hand, would most likely be the case as dissolution leaves behind higher void ratio than the original pristine state.

Constraints of the study

This study has shed light on the deformation characteristics of granular soil experiencing mineral dissolution. The research adopted an oedometer test, which is laterally confined and mainly examines the vertical stress and deformation. However, it is a well-known fact that the soil behaviour is dependent on lateral stress conditions. Furthermore, during mineral dissolution, lateral stresses may fluctuate due to changes in force network caused by particle disappearance[15,37]. Thus, to enhance our understanding of the effect of mineral dissolution on soil mechanics and to construct a complete constitutive framework, three dimensional experiments should be performed.
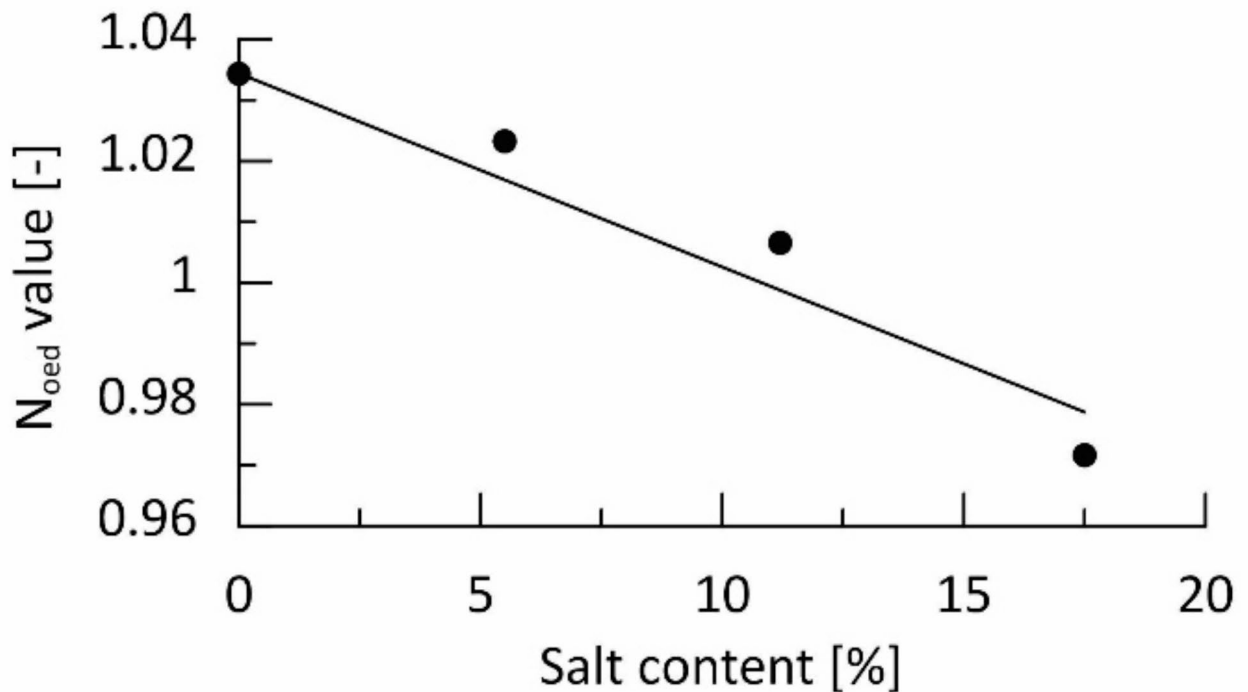
Fig. 8. N_{oed} values as a function of the salt content.

In practical scenarios, the complexity of the soil behaviour due to mineral dissolution would be significantly greater. In this study the focus was on granular materials, such as quartz sand and salt crystals. Quartz sands were selected since the mechanical behaviour is minimally affected by mild salinity under saturated conditions. This allowed for this study to focus as much on the densification effect and minimising other complex chemo-mechanical impacts. For the case for clay minerals, the mechanical behaviour would have been different as clay minerals are prone to change is mechanical behaviour when pore chemistry changes[38]. This means that for soils containing diverse minerals, the chemo-mechanical effects coming from pore water chemistry should be considered in addition to the changes in density.

To summarise, while this research provides valuable insights into the mechanical behaviour of granular soils undergoing mineral dissolution, it also shows the need for further research. Future studies should aim to explore the varying mineralogy and using more advanced experimental setups.

Conclusions

This paper first theorized the mechanical response due to mineral dissolution into three categories (material change, interparticle bond destruction and density decrease) that each impacts the material behaviour in different ways (Fig. 1). After the presenting the general phenomena, the paper narrowed its focus to the effect of density change on the mechanical behaviour. The process of dissolution was modelled in the laboratory through dissolution of salt grains, and the mechanical response was measured using an oedometer. The effects of two variables on soil behaviour was the focus of this study, i.e., the effects of the amount of grain dissolution (salt content) and stress state at which dissolution occurred. The following conclusions could be drawn from this study.

- The increased void ratio after dissolution was a good indicator for predicting the yield stress of dissolved material which is the point where LCC and URL intersects. This shows that the earlier hypothesis of shifting URL with the void ratio increase conforms to real soil behaviour.
- Grain dissolution induces an increase in the void ratio and spontaneous volumetric compaction. This response is opposite to the conventional soil mechanics theory, where a void ratio increase necessarily means volumetric expansion.
- Volumetric compaction depended on the salt content (amount of dissolution) and the current stress state. The dissolution-induced volumetric compaction was proportional to the salt content and the stress state. Increasing void ratio had an inverse relationship with salt content. More importantly, the increase in void ratio was dependent on the relative position of the void ratio at pre-dissolution to the LCC (part of the yield surface), which made it dependent on the current stress state of the soil.
- The physical threshold for dissolution-induced large volumetric compaction was the yield surface of the soil. The yield surface, which included the LCC, was a boundary at which the soil lost its physical integrity. Grain dissolution could produce significant shrinkage of yield surfaces in the stress space, and when finally reaching the current stress point, plastic deformation started to accumulate, leading to large bulk deformations.
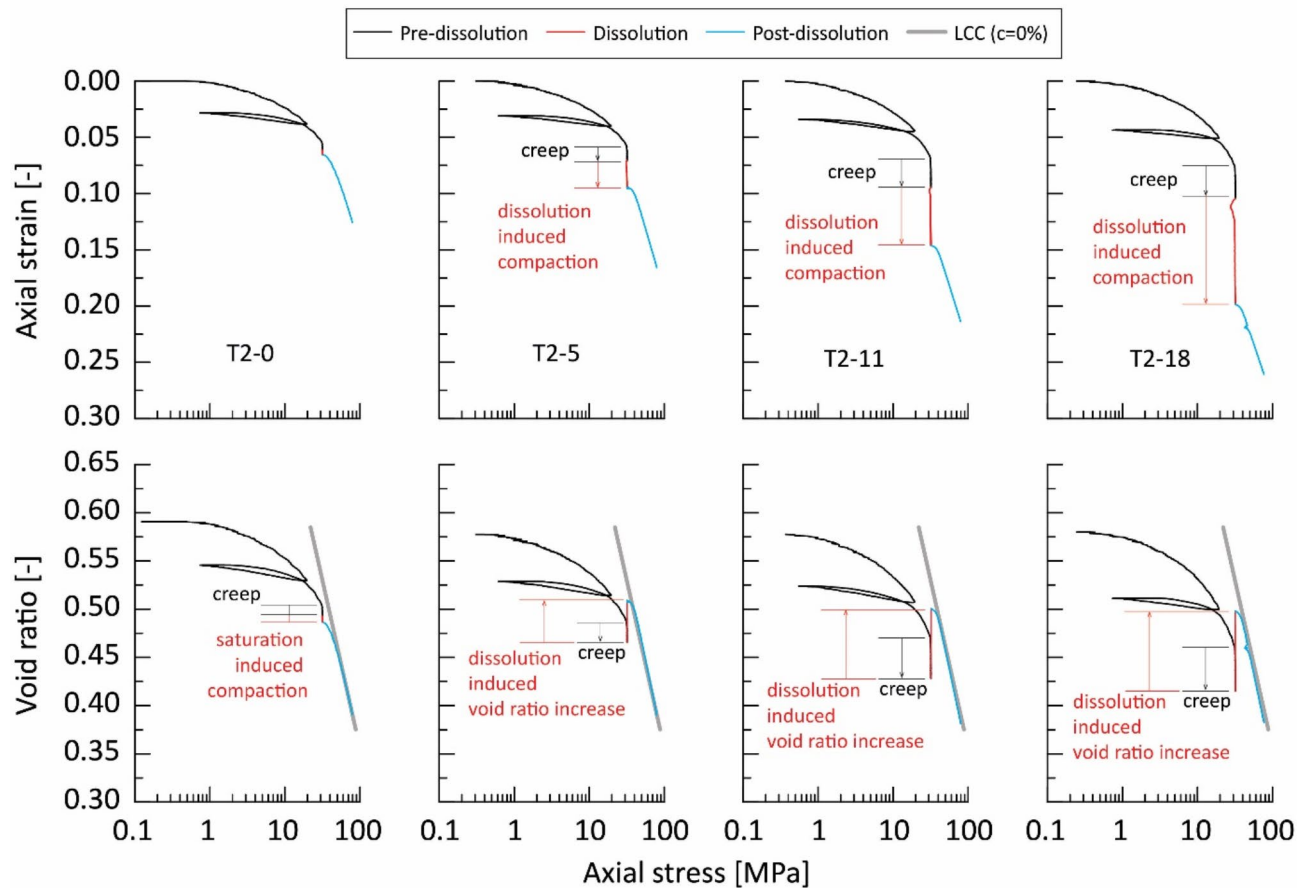
Fig. 9. Results of test T2: oedometric curves including dissolution at a vertical stress of 32 MPa for various salt contents (0, 5, 11 and 18%).

Finally, this study proved that the soil state and applied stress are of critical importance in properly analysing the effect of grain removal on the mechanical behaviour of granular soils. Thus, when dealing with geotechnical problems involving mineral dissolution, it is crucial to consider the stress state of the soil.

Engineering implications

Climate change induced severe and frequent extreme events can significantly impact the short- and long-term behaviour of earth structures and the response of earth slopes. For instance, increased precipitation can lead to higher rates of mineral dissolution, thereby accelerating the processes of soil degradation and structural instability.

This study underscores the importance of understanding the effects of mineral dissolution on the mechanical behaviour of granular soils. This understanding is crucial for predicting and mitigating the risks associated with geotechnical structures, particularly in the face of climate change[8,9]. In addition, the study emphasizes the importance of considering the current stress state of the soil when dealing with geotechnical problems involving mineral dissolution. This insight could guide future research and engineering practices, ultimately contributing to more resilient and sustainable infrastructure in the face of climate change[10].

Finally, the findings of this study have important implications for geotechnical engineering, particularly in the context of our rapidly changing environment. As our climate continues to evolve, the risk of mineral dissolution and subsequent grain loss in geomaterials may escalate. This could lead to a greater incidence in our infrastructures resting on the surface the soil. Therefore, it is crucial for engineers to consider these risks in their designs and mitigation strategies.
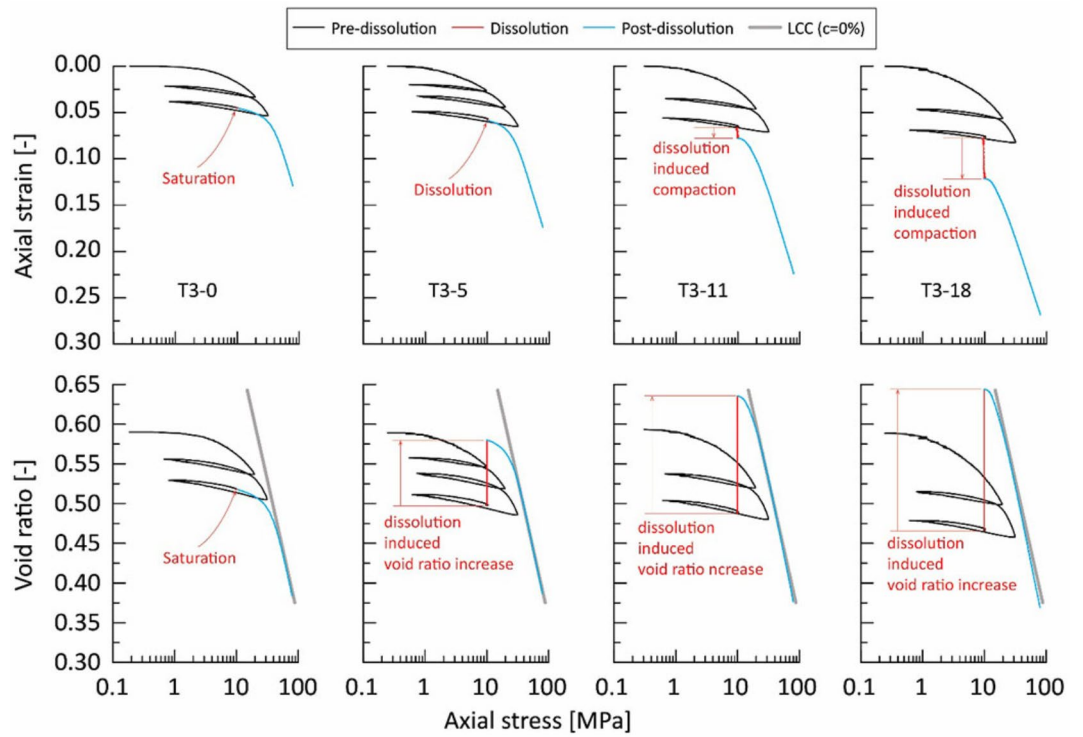
Fig. 10. Results of test T3: oedometric curves including a dissolution stage at a vertical stress of 32 MPa for various salt contents (0, 5, 11 and 18%).
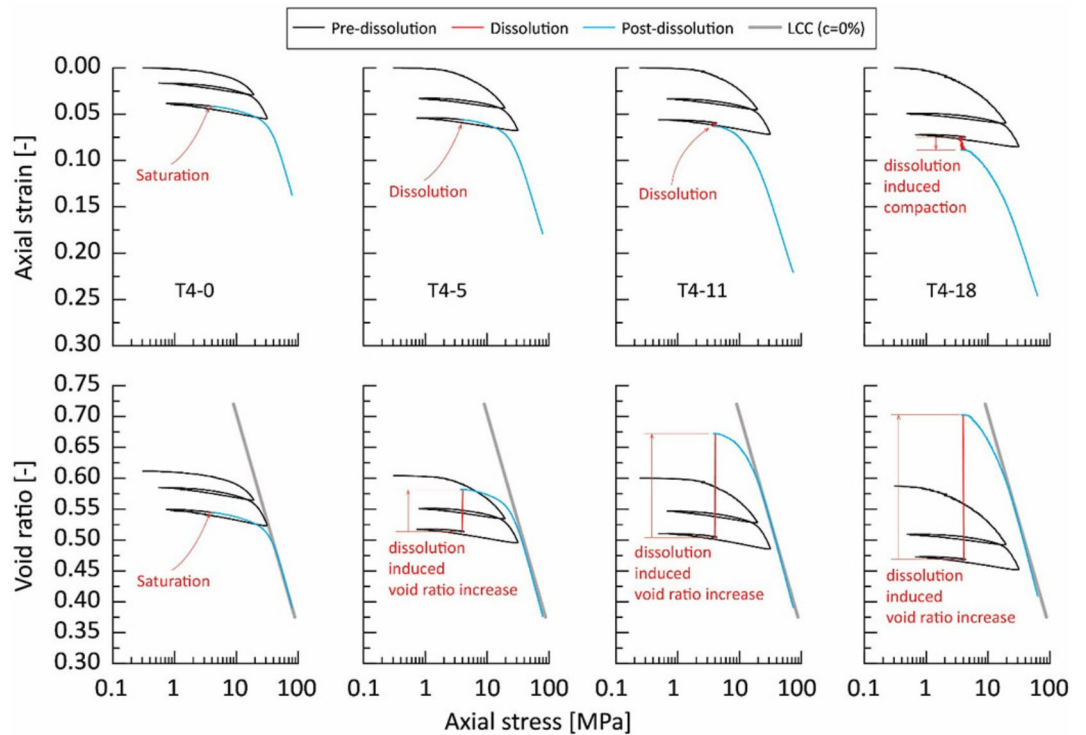

Fig. 11. Results of test T4: oedometric curves including a dissolution stage at a vertical stress of 32 MPa for various salt contents (0, 5, 11 and 18%) (Please note the scale differs from that in previous figures.)
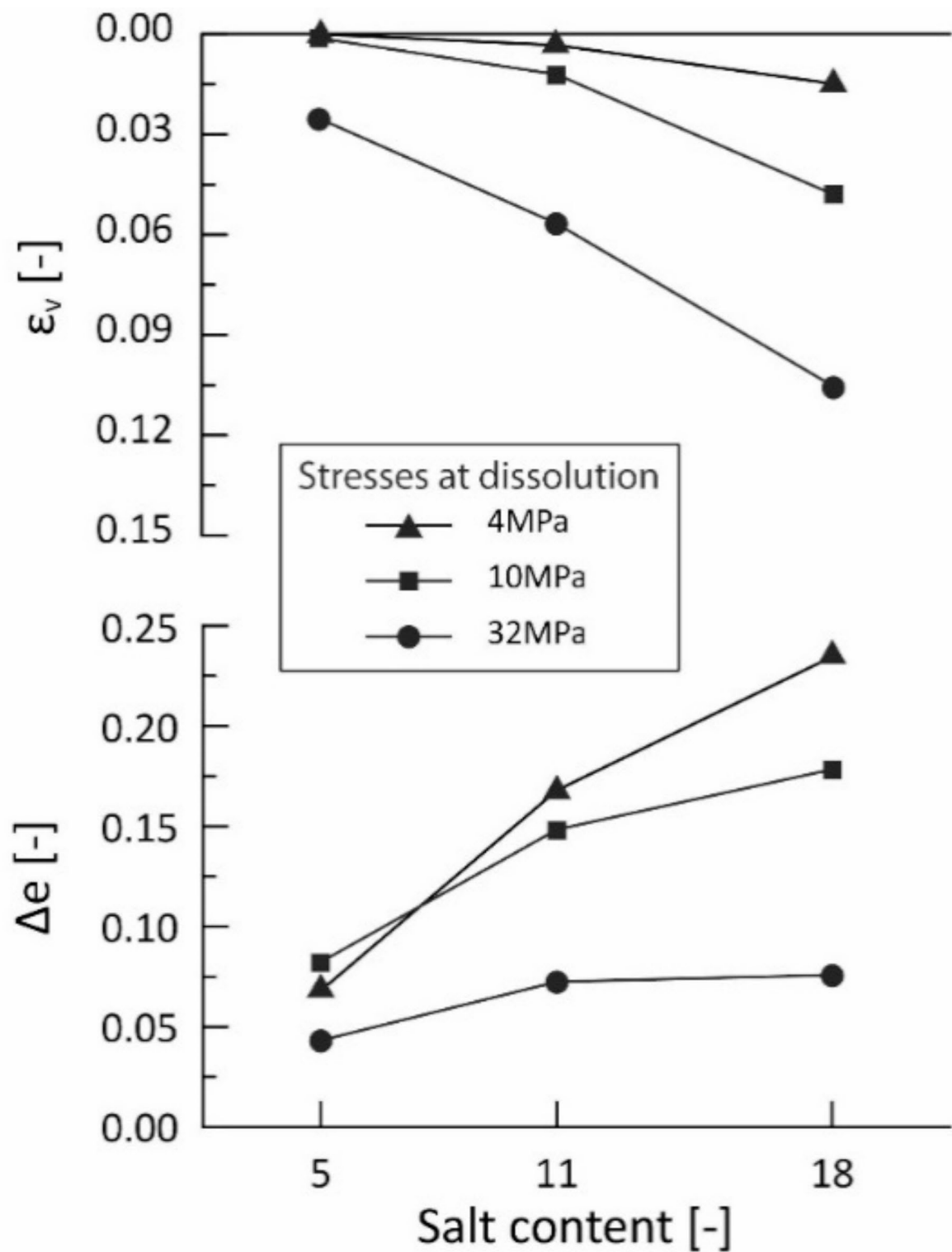
Fig. 12. Summary of the experimentally observed vertical deformations and void ratio variations as functions of the vertical stress and salt concentration.
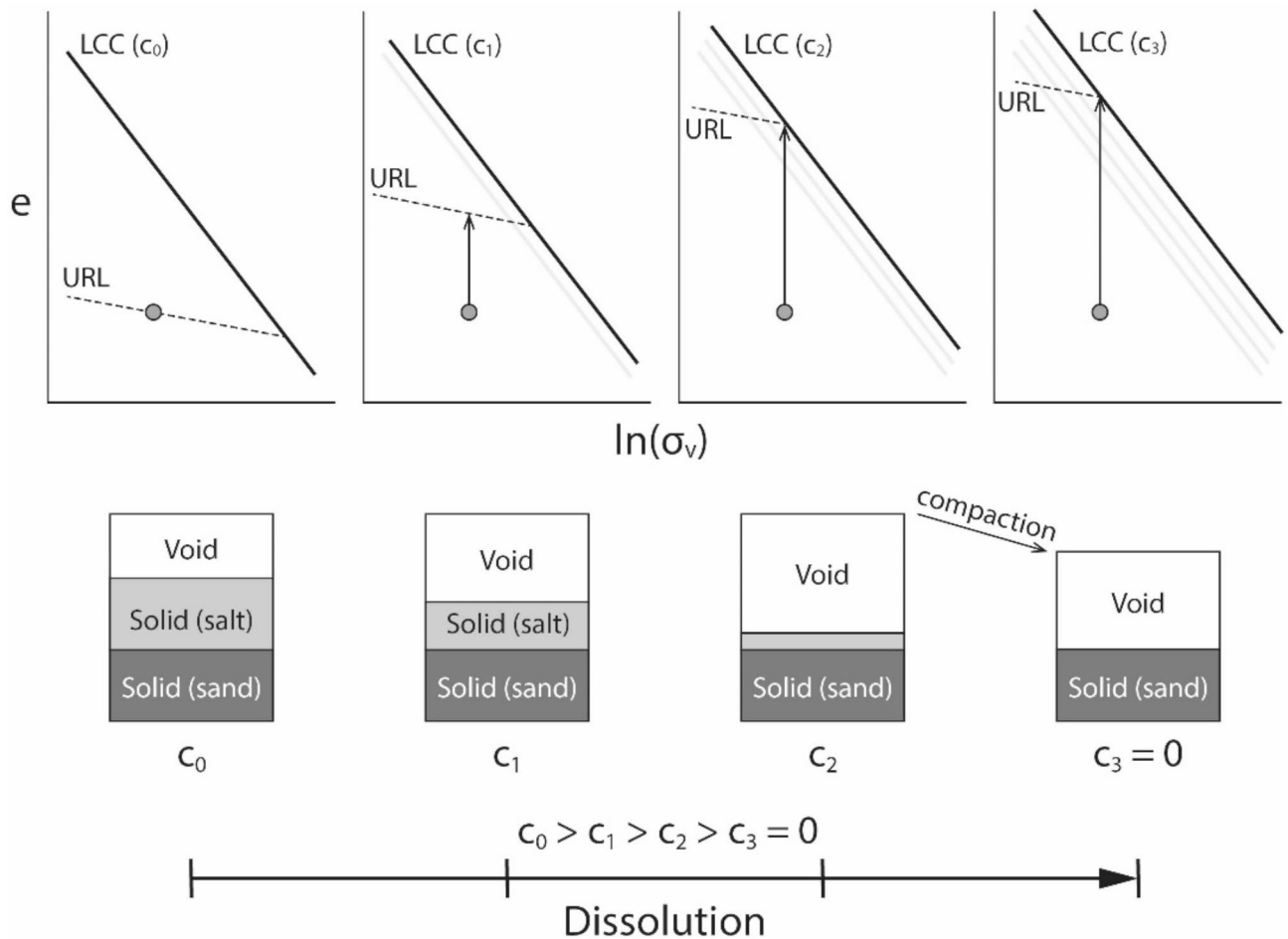
Fig. 13. schematic illustration of dissolution induced mechanical behaviour.

Data availability

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Author contributions

Taeheon Kim: Designed, performed experiment, analysed the results and drafted the manuscript; Alessio Ferrari: Analysed the results, Drafted and revised the manuscript; Lyesse Laloui: Designed the research, and drafted and revised the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to T.K.

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