AGING OF OIL/GAS-BEARING SEDIMENTS, THEIR COMPRESSIBILITY, AND SUBSIDENCE

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ABSTRACT: The in situ stiffness and apparent maximum preconsolidation stress of many soils and sediments appear to be higher than in the laboratory tests. We seek to verify experimentally whether this also holds for deep marine sediments. We also discuss an alternative explanation for this effect to the classical one, implying the sample damage during coring. We test numerically the explanation, suggesting possible unaccounted changes in stiffness, occurring in sediments in situ when subjected to aging, or secondary compression for geological scale time periods. Results of ''aging tests'' on sandy and clayey sediments are presented, involving secondary compression at the constant in situ stress level, during which strain develops together with other changes in properties. Only two weeks of aging produced a notable increase in the apparent maximum preconsolidation stress and in the stiffness below it, and above the in situ stress. A framework for a mathematical model is proposed, based on the supposition that during aging the sediment develops a secondary microstructure through reactions of local dissolution/precipitation of less stable minerals.

INTRODUCTION

Predictions of the land subsidence caused by soil fluid withdrawal are a key factor in decision making in the resource exploitation industry dealing with petroleum, natural gas, or water supply (Scott 1979). Especially in densely populated areas, subsidence may become an important social issue requiring careful consideration, and good understanding and reliable prediction. Unfortunately, 1D linear model predictions based directly on laboratory soil data tend to grossly overestimate the subsidence. Nonlinear models with back-calibrated empirical relationships for variable porosity, variable permeability, and specific storage (Kosloff et al. 1980; Teatini et al. 1995) lead to results much closer to those measured. However, by the very nature of the back-calibration and forward projection in a nonlinear domain such an empirical approach becomes less reliable when applied to conditions different from those used in the calibration (Rivera et al. 1991). On the other hand, a technique in which radioactive marker projectiles are shot into borehole walls allows one to monitor their subsequent displacements in conjunction with pore pressure changes. The predictions based on the assessment of compressibility measured with this technique yield subsidence values that are over an order of magnitude lower than those based on the classical lab data (Cassiani et al. 2000).

Clearly, there is a need to clarify the origin of the discrepancies between lab based and field based predictions, to reexamine the models used and a possible bias in experimental techniques and interpretation. In this paper we examine one possible source of the discrepancy between the predictions based on laboratory and field measurements, resulting from the inadequate representation of sediment history in the laboratory experimental procedures. We suggest that the current procedures in oedometric tests that are entirely based on primarily consolidation overestimate compressibility moduli. We contend that in determining sediment compressibility one cannot ignore a substantial increase in stiffness and in the apparent preconsolidation stress, developing during an extended secondary compression period, or aging.

We present experimental results from two deep cores, with a sandy clay, and a clayey sand. The objective of the tests was to identify and quantify principal changes in soil mechanical properties resulting from aging. We identify four principal characteristics of aging effects on soil stress-strain behavior and discuss them in terms of a two-component model. Such a model is based on the idea of the development during aging of a secondary structure as a result of a chemical reaction.

PHENOMENOLOGICAL BACKGROUND

Aging in soils has been recognized for a long time. It has been defined in the classical sources (Lambe and Whitman 1969; Mitchell 1993; Terzaghi et al. 1996) as a change in various mechanical properties resulting from secondary compression under a constant external load. Alternative terms such as age hardening, thixotropic hardening, delayed compression, and structuration are used to describe the evolution in mechanical and physical properties during secondary compression (Leonards and Altschaeffl 1964; Schmertmann 1964, 1991; Bjerrum 1972, 1973; Mitchell 1975, 1993; Zeevaert 1983; Lessard and Mitchell 1985; Ellstein 1991; Perret et al. 1995; Leroueil et al. 1996). While traditionally linked to clays, aging is also known to occur in sands, sandstones, and clayey sands (De Waal 1986; Mesri et al. 1990; Schmertmann 1991).

In what follows, we will limit ourselves to laboratory aging of soils that simulates a variety of physical and chemical phenomena occurring spontaneously at a constant in situ stress. This may be different from the natural phenomenon of aging of engineering materials such as concrete, steel, or rubber, or induced aging or age hardening of materials such as aluminum, or nickel-based alloys, or steels.

The essence of laboratory aging may be described as follows. A natural sediment sample is loaded in the laboratory under 1D strain conditions (in an oedometer), in 24 h stress steps up to its in situ stress (AB, Fig. 1). At each step, the end of primary consolidation is reached. It is therefore understood that the soil in this process is continuously in the state of normal consolidation. At the level of in situ stress, after completion of primary consolidation the sediment is left at a constant (in situ) load to develop secondary compression, BC. This process is meant to last for a sufficiently long time to represent the geological process of compaction. The lab representation of this practically never ending process will obviously be finite, and is referred to as an aging episode. During the secondary compression soil develops a certain strain, BC.

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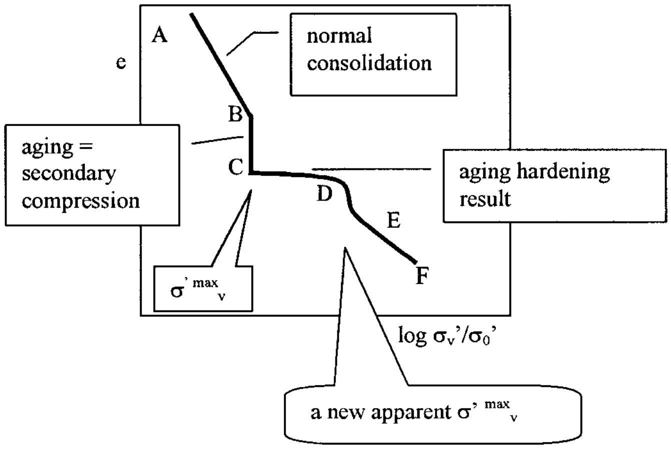

FIG. 1. Schematic of the Effects of an Aging Episode in a 1D Compression Test Represented in a Void Ratio (e)—Vertical Stress (σ'_v) Diagram; σ'_0 is a unit stress

When loaded subsequently over an effective stress increment, CD, the material exhibits an "*apparent* precompression stress." Below that threshold stress, soil is much less compressible, compared to that during the initial loading, AB. Upon further loading, DEF, beyond the threshold the compressibility tends to return, more or less smoothly, to the values typical of normally consolidated clay.

The aging phenomenon seems to be so universal for soils that it prompted Schmertmann (1991) to wonder in his Terzaghi lecture on that subject ". . . whether a natural clay, aging at a constant vertical effective stress . . . , ever exists in a truly normally consolidated state." The actual physicochemical processes leading to the overall process of aging are not exactly known. In earlier experiments [Denisov and Reltov 1961; Miura and Yamanouchi 1978; Mitchell and Solymar 1984; Lessard and Mitchell 1985 (at zero stress); Perret et al. 1995] changes in mechanical and physical properties have been correlated with specific changes in the ionic concentration of pore water, or its pH. Dissolution of some minerals (silica in the case of sand, and montmorillonite in the case of clays) facilitated by the intergranular stress concentration, followed by a change in electrolytic properties of the pore liquid (gel formation) may in turn contribute to building a secondary structure in the soil. This was suggested to occur via bonding of particles by silica acid gel film through the precipitation of silica from the solution or suspension; silica is acting as a cementing agent between the particles (Mitchell and Solymar 1984; Perret et al. 1995). More recently, water film diffusion was proposed to explain the deformation by the pressure solution, implying that matter is dissolved at the contact between two grains and transported through diffusion in an adsorbed water film (Renard and Ortoleva 1997). Interestingly, the thermal cycle on clay (up to 120°C) produces virtually the same type of response, i.e., growth in the apparent preconsolidation, and stiffness (Plum and Esrig 1969; Hueckel and Baldi 1990).

Most of the evidence concerning the effect of aging comes from laboratory experiments. However, Bjerrum (1972) discusses a number of field studies (Holtz and Broms 1972) indicating that almost all clays in situ show an aging effect depending on their plasticity index and geological history. Perret et al. (1995) reported on the offshore sediments, building strength by a series of chemical and biological processes.

Clearly, an important part of the aging process is secondary compression at a constant specific (in situ) stress. From the purely mechanical point of view, this could be perceived as creep. However, age hardening is also observed at zero stress (Lessard and Mitchell 1985), and thus has to be attributed to nonmechanical (most probably chemical) changes. Also, other elements of the process, such as the generation of overconsolidation, which implies that the stress state becomes elastic, point against the understanding of this process as creep.

LABORATORY AGING TESTS ON NORTH ADRIATIC SEDIMENTS AND EFFECT ON COMPRESSIBILITY

The objective of the experiments is to verify if and, in the positive case, to what extent the above described effects develop also in deep marine sediments at depths of thousands of meters. In particular, we would like to characterize the effects of aging in terms of basic soil mechanics variables. Two distinctly different materials are used—a clayey sand, DALIA 1, from the depth of 1,210 m, and a predominantly clay material, TEA 1, from the depth of 3,270 m. The initial void ratio of undisturbed specimens was of the order of 0.6 for DALIA 1 sand and 0.3 for TEA 1 clay. The main set of tests was performed on undisturbed samples in oedometers. Only samples "of good quality" (Holtz et al. 1986)—namely, those with a "recovery index" greater than 95% (defined by the "Quantification of Core Quality" guidelines adopted jointly by Agip, Elf, Shell, and IKU)—were used in the experiments. Additional tests were performed on remolded material, because of the limited number of undisturbed samples available and because of the general interest in fresh soils.

Undisturbed Specimens

A typical set of tests included one monotonic, incremental loading test, and one aging test with monotonic loading to the stress equal to that in situ, followed by constant loading of a duration of 14 days, followed then by the resumption of monotonic loading. It is obviously realized that such tests do not reproduce the loading history of the actual sediments exactly. The actual process is presumably composed of a series of loading episodes due to the deposition of new alluvia and of secondary compression between them. An average in situ effective stress was determined from stratigraphic data as 12.6 MPa for DALIA 1 and 35.04 MPa for TEA 1. Oedometers used for testing were appropriately adapted to withstand such high stresses without developing lateral strain. For the remolded materials, a value for the fictitious in situ stress has been chosen (0.808 MPa) based on the capacity of the apparatus employed. Some of the tests on the remolded materials were

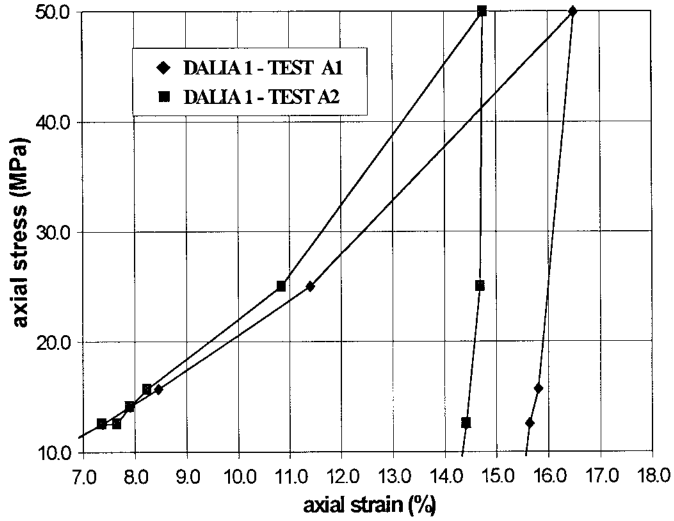

FIG. 2. Axial Stress-Strain Response (Detail) for Oedometer Tests on Undisturbed Specimens of DALIA 1 Sediment; Test A1 ◆ Monotonic Loading and Unloading; Test A2 ■ Involves Monotonic Loading, Aging at 12.6 MPa, Continued Loading and Unloading

conducted in a triaxial apparatus furnished with axial and lateral strain noncontact transducers and a computer controlled cell pressure to ensure one-dimensional strain states. To avoid osmotic swelling, a 30 g/L solution of NaCl was used to simulate the natural aquatic environment in the sediment.

Typical results for the undisturbed sediments in the oedometric stress-incremental tests are shown in Figs. 2 and 3. The response to monotonically loaded samples is compared to that subjected to a 14-day in situ stress aging. Only portions above the aging stress are shown. In these tests, it is possible to observe that (1) the aging of 14 days resulted in a relatively small secondary compression strain, when compared to the total strain amount reached in the test; (2) while the stress-strain curves below the in situ stress are nearly identical, they diverge significantly after the aging, showing a visible decrease in compressibility; (3) this decrease is of a comparable order in sand and clay, despite the difference in terms of depth, amount of the in situ stress, void ratio, and the total amount of strain reached; and (4) the decreased compressibility occurs over a limited stress range above the in situ stress.

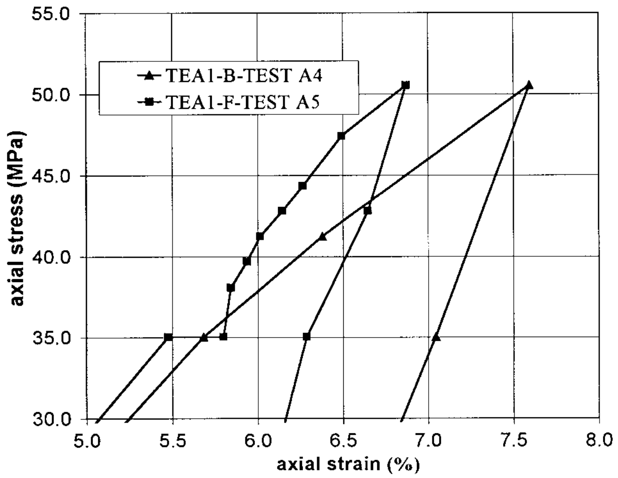

FIG. 3. Axial Stress-Strain Response (Detail) for Oedometer Tests on Undisturbed Specimens of TEA 1 Sediment; Test A4 ▲ Monotonic Loading and Unloading; Test A5 ■: Monotonic Loading, Aging at 35.04 MPa, Continued Loading and Unloading

Clearly, it is the range of stress above the in situ stress that is of direct interest in the present context. Indeed, in the case of oil/gas extraction, the decrease in pore pressure of the extracted fluid will induce a corresponding effective stress increase above the in situ stress level. The stress-strain behavior in this range is visibly nonlinear. The change in the soil behavior due to aging is characterized by four principal characteristics (circled call outs in Fig. 4). These are (1) the decrease in incremental moduli of compressibility in the postaging loading range; (2) the decrease in secant moduli of compressibility, also resulting in a strain reduction in the postaging stress range; (3) a stress range affected by characteristic 1; and (4) the strain developed during the aging period. The first three characteristics affect directly the numerical prediction of subsidence; the fourth one may be a factor in the experimental determination of the three former ones. There is another important characteristic of the postaging behavior, which is (characteristic 5) the total postaging stress range characterized by characteristic 2 or total strain reduction, defined as the total range in which stress is above, and strain is below, the corresponding values in reference monotonic tests. However, the values were not measured in the performed tests, because they were much higher than expected, and turned out to be outside the test range.

Note that the stress range (characteristic 3) affected by the incremental moduli decrease corresponds to the increase in the apparent preconsolidation. The stress ratio between the value at point C and the value at the in situ level, A, is what may be understood as an apparent overconsolidation ratio (*OCR*).

To convey the sense of the effects of aging numerically, relative (normalized) values calculated for the four character-

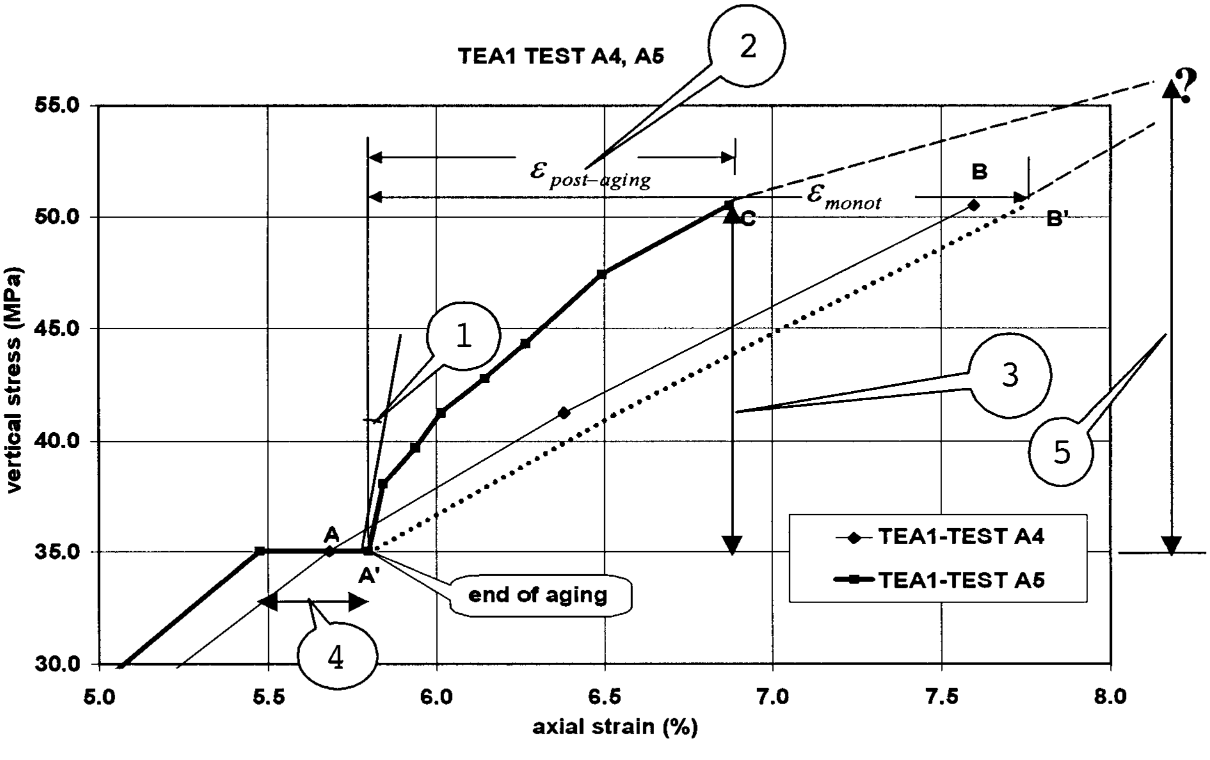

FIG. 4. Characteristic Elements of the Effect of Aging on the Stress-Strain Behavior above the In Situ Stress Level (See Text); Comparison between the Response, ■ A′C, to Loading above the In Situ Stress of a 14 Day Aged Material, A5, and That of a Nonaged Material, A′B′, Obtained by a Parallel Shifting of the Curve, ◆ AB, from a Monotonic Loading Test

istics discussed above are summarized in Table 1, in terms of the average values. Compressibility is quantified in terms of the following two incremental moduli: (1) the compression index, $C_c = de/d(\log \sigma/\sigma_0)$, for a law expressing the void ratio, e, as a function of a logarithmic measure of the axial stress component, σ, where σ_0 is a reference state on the considered stress-strain branch; and (2) the coefficient of volume change, $m_v = d\varepsilon/d\sigma$, known also as the uniaxial compressibility coefficient, c_M, in petroleum engineering literature. Here ε is the uniaxial strain.

The clayey sediment TEA 1 shows a more pronounced effect of aging on the moduli than does the sandy sediment DALIA 1. However, characteristically, sandy and clayey sediments show a very similar range of relative strain reduction, even if other characteristics differ between the two types of sediments.

TABLE 1. Aging Test Highlights (Undisturbed Material)

Material and sample type (all undisturbed)	Relative reduction in incremental compression index, C_c^a (1)	Relative reduction in incremental coefficient of volume change, m_v^a (1)	Relative strain reduction due to aging^b (2)	Stress range affected by aging^c (3)	Ratio of strain gain during aging to total strain at aging onset (4)
Average of DALIA	47.33%^{d}	49.4%^{d}	38.0%	12.0%^{f}	2.1%
Average of TEA	64.8%^{e}	69.9%^{e}	44.0%	45.0%	5.5%
Average of all undisturbed	56%	59.6%	41.0%	28.5%	3.8%

[a] (Monotonic test compressibility at the in situ stress − postaging compressibility)/monotonic test compressibility at the in situ stress.

[b] $(\varepsilon_{\text{monot}} - \varepsilon_{\text{postaging}})/\varepsilon_{\text{monot}}$.

[c] (Axial stress value at which coefficient of volume change is the same as that in the monotonic test − aging stress)/aging stress.

[d] At 112% of aging stress.

[e] At 116.6% of aging stress.

[f] This result is believed to underestimate the actual value, which appears to have exceeded the maximum stress value (expected and applied) in the tests.

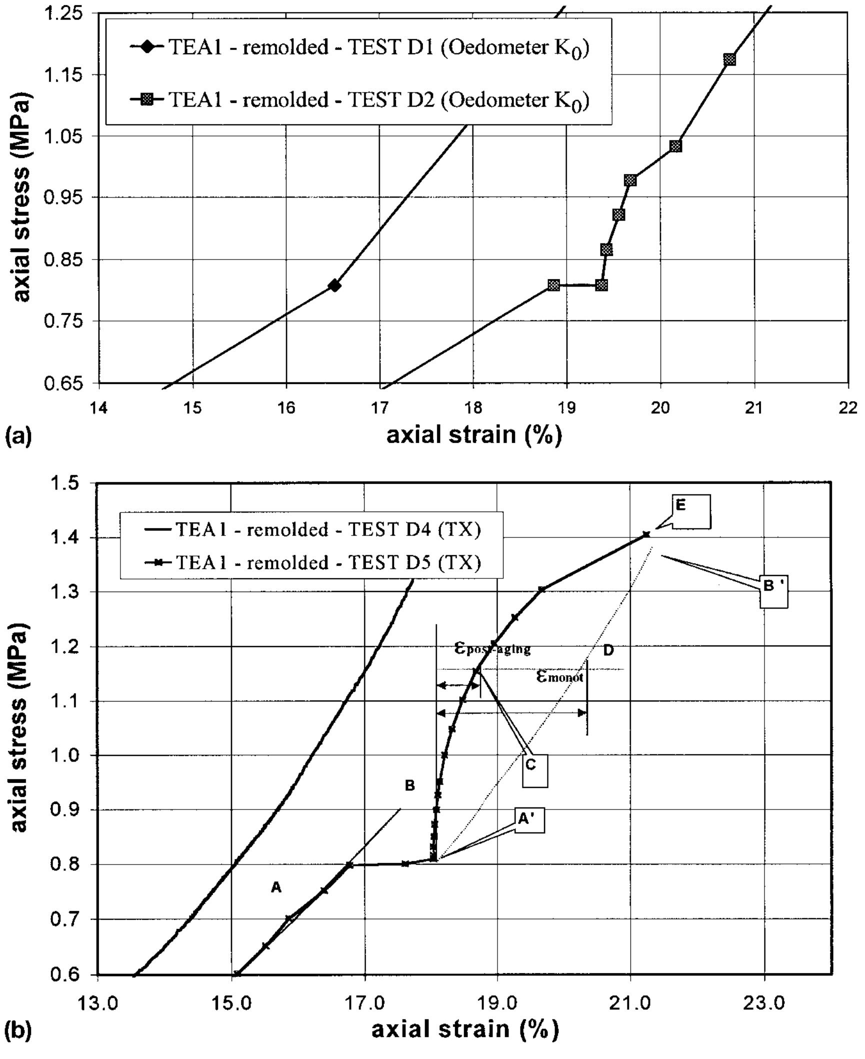

FIG. 5. Plot of: (a) Stress-Strain Curves above the Stress Level of Aging Episode for Remolded Clay (TEA 1) from Oedometric Test TEA 1-D2, ■ Shown against Results of a Monotonic Test D1 ◆; (b) Monotonic Test D4 and Aging Test D5, in K_0-Zero Lateral Strain Triaxial Conditions Simulating Oedometric Stress Path, on Remolded Clayey Samples TEA 1; A′B′ Is a Projection of the Monotonic Curve AB

A single most important value in the summary of Table 1 is the average 41% reduction in sediment deformation at a stress value of 13.3% above the in situ stress if 14-day aging is allowed. In other words, the deformation of the aged sediments beyond the in situ strain is only 60% of that of the nonaged sediments in laboratory testing. Locally, at one specific stress value a nearly 50% reduction incremental coefficient of volume change for sand, and nearly 70% for clay, is seen. While these values are clearly dependent on the stress increment over the in situ values, they certainly may have a paramount effect on subsidence prediction over the low to medium liquid/gas pressure reductions.

Remolded Specimens

Remolded materials were studied in the context of subsidence, because of an unlimited possibility for reuse of the remolded material, but also because of a general interest in the aging of embankment fill materials. The remolded material has a much higher void ratio than that of the undisturbed material. For sands (DALIA 1), it is, on average, 1.03 and 0.866 for oedometric and triaxial specimens, respectively, versus 0.588 for the undisturbed specimens. For remolded clays (TEA 1, series D) the void ratio was, on average, 0.785 and 0.602 for oedometric and triaxial specimens, respectively, versus 0.315 for the undisturbed specimens. Such high void ratios are concomitant with much larger strains than in the undisturbed material. The differences between the void ratios in the triaxial and oedometric tests are attributed to different protocols of compaction for the remolded material in these apparatuses.

The stress-strain curve above the stress level of aging of the remolded clay (TEA 1) from oedometric test D2 is shown against that from a monotonic test D1 in Fig. 5(a). An analogous comparison has been obtained from a zero-lateral-strain triaxial test D5 simulating the oedometric stress paths test shown against a monotonic test D4 in Fig. 5(b). For remolded sand (DALIA 1), details of the stress-strain curves from oedometric aging and monotonic tests (B2 and B1) are shown in Fig. 6. The order of the observed aging effects for remolded materials in terms of normalized values is very close to that for the undisturbed specimens. The most outstanding difference is observed in the incremental deformability immediately after the onset of postaging loading. It becomes extremely low, with a 10–20 times lower modulus than in the monotonic tests for DALIA 1, and about a 10 times lower modulus for TEA 1. The numerical values depicting the evolution of the postaging moduli for a remolded clay specimen in a triaxial test (D5) are presented in Table 2. The results for the remolded material display also another feature that has not been seen in the aging tests on the undisturbed material. Noticeably in clay [especially in test D5, Fig. 5(b)], the local compressibility has a tendency to return to the ‘‘normal’’ values unaffected by the aging episode, or even to slightly lower values. Such a tendency has been seen in many remolded materials studied by Leonards and Altschaeffl (1964), Bjerrum (1972), Perret et al. (1995), and others. These characteristics (marked as characteristics (3) and (5) in Fig. 4) may either be absent in undisturbed material, or may occur at higher stress levels than those attained in our test. From the industrial point of view, the presence of these features is very important. They determine to what degree the aging effect, as described above, will affect the prediction of subsidence for a given pore pressure drop.

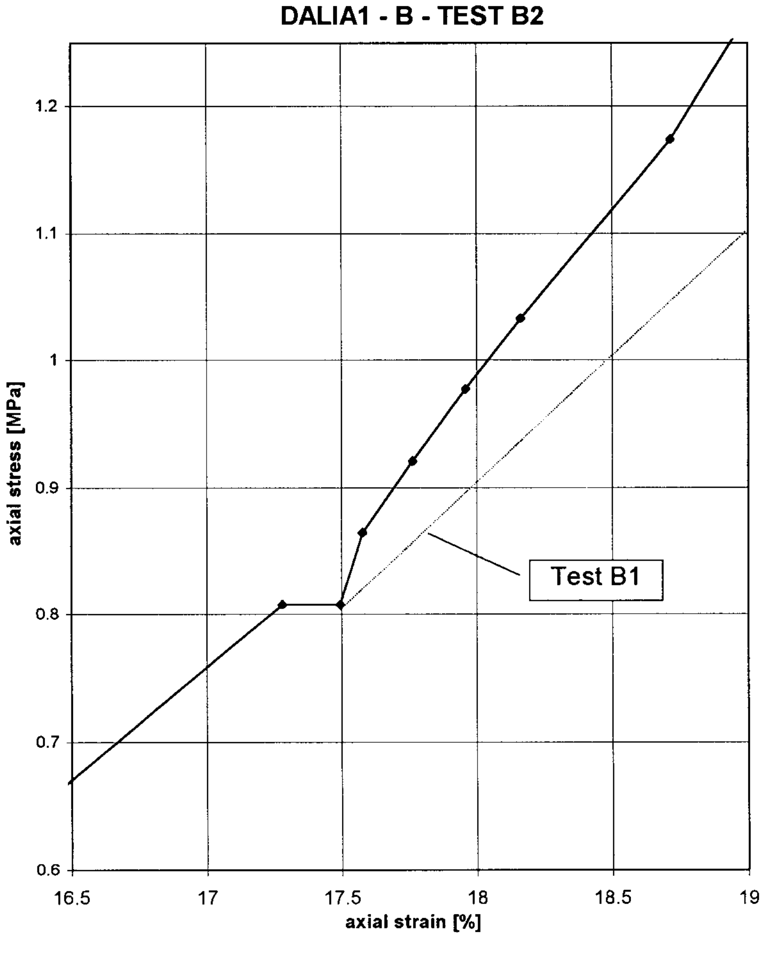

FIG. 6. Stress-Strain Curve, ■ above the Stress Level of Aging Episode for Remolded Sand DALIA 1 from Oedometric Test DALIA 1-B2, Shown against a Monotonic Test B1

TABLE 2. TEA 1—Remolded Clay—Test D5 (Triaxial K_0)

σ'_v (MPa)	Compression index C_c (-)	Decrease in C_c, relative to C_c^b	Coefficient of volume change m_v (MPa^{-1})	Decrease in m_v, relative to m_v^b
0.7980[a]	$C_c = 0.2816^b$	—	$m_v =$ 94.605[b]	—
0.9002	0.0302	89.2%	4.998	94.7%
1.0003	0.0742	73.7%	12.985	86.3%
1.4044	0.9760	−246.6%	155.662	−64.5%

[a] Aging stress level σ'_v = 0.809 MPa.
[b] At 116.6% of aging stress.

OTHER EFFECTS OF AGING

The following additional concerns related to aging were addressed in the context of subsidence prediction: (1) the accumulative effect of aging in a freshly consolidated material; (2) the influence of aging duration on the postaging characteristics; (3) the effect of a more complex aging history on postaging characteristics; (4) the influence of aging in the overconsolidation range; (5) a possible correlation between the postaging moduli and those in unloading and reloading; and (6) the evaluation of the lateral stress during aging in K_0 conditions imposed in the triaxial apparatus.

Accumulative Effect of Aging

Since the phenomenon of aging and the associated secondary compression might be expected to continue after the end of the extraction of gas or oil, a concern might arise that such further secondary compression deformation would annihilate the "benefit" of the decrease of deformability due to "first aging." However, it appears that this is not the case, and that sediments do have the memory of their previous aging episodes. Tests performed on remolded DALIA 1 B8 and B10 samples, Fig. 7, show that when aging is repeated at the same stress level after a cycle of partial unloading, the amount of strain per unit of time during the "second aging" is about one order of magnitude lower than during the first aging. The rates of straining for test B8 at an aging stress of 0.8 MPa, over the first two hours in both cases, were, respectively, 1.073×10^{-5} (1/min) during first aging and 2.11×10^{-6} (1/min) during second aging. For test B10 at a lower stress (0.5 MPa), for the first 16 min of aging the rates were 4.91×10^{-5} (1/min) and 1.125×10^{-5} (1/min), respectively. Thus, it appears clear that aging has an irreversible and accumulative effect.

Effect of Duration of Aging Episode

Fig. 8 shows strain during aging as a function of time in a test on remolded specimen DALIA 1 B5. It is clear that the rate of straining changes significantly after 24 h (understood

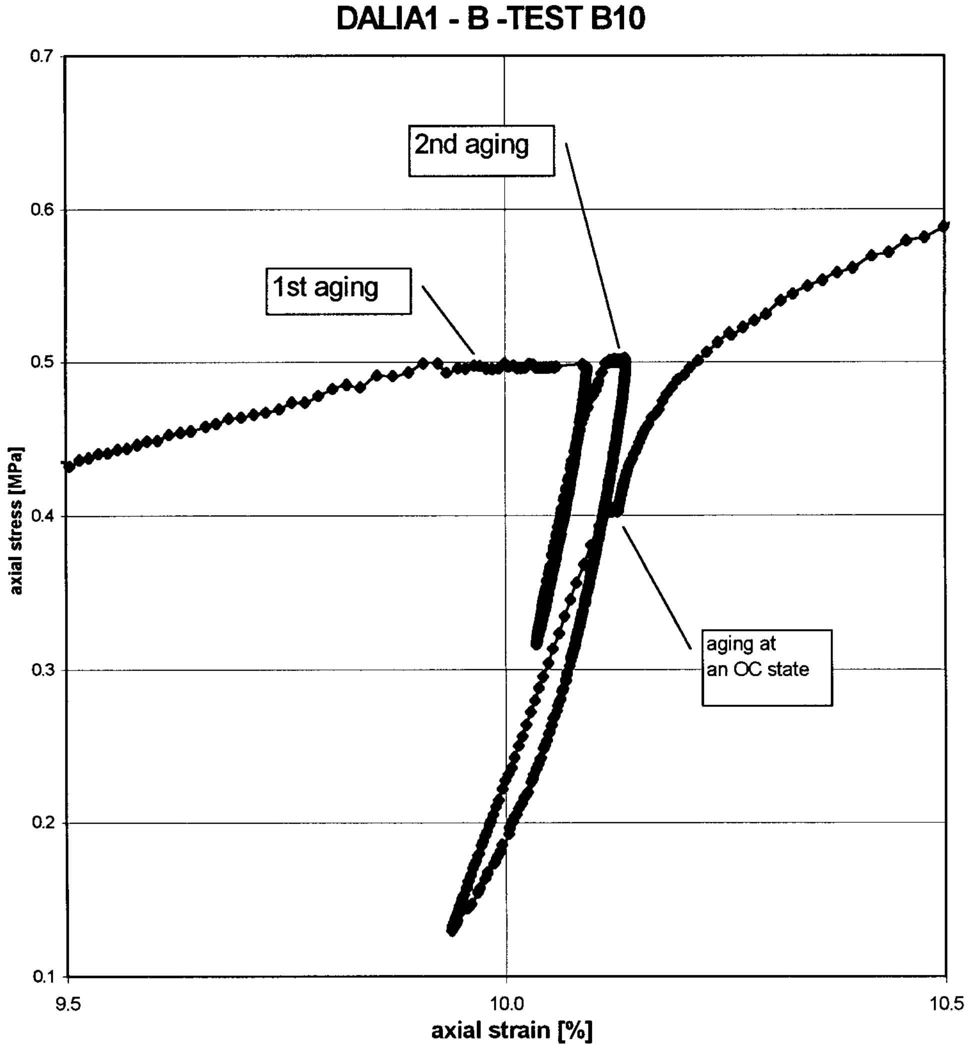

FIG. 7. Two Consecutive Episodes of Aging at 0.5 MPa in Remolded DALIA 1 Material in Test B10; First Aging Episode Follows Directly a Monotonic Loading; Second Aging Episode Follows a Partial Unloading-Reloading Loop; Also Shown Is a Short Term Aging Episode at an Overconsolidated Stress State

usually as a "switch" from the pore-pressure driven consolidation to secondary compression), but it is also clear that the rate of secondary compression does not decrease much further even after 14 days.

However, the material stiffening seems to occur much faster. Two accidental, short duration aging episodes were investigated. An aging episode of 2.5 h duration in test B4 on DALIA 1 sand shown in Fig. 9 was characterized by a significant decrease in deformability (75% local reduction of the coefficient of volume change). However, the stress range affected by the short-term aging is relatively small, 6% of the aging stress level against 28% for longer-term aging episodes on this material.

To further explore the effect of aging duration, effects of three-month and seven-month aging episodes on compressibility were investigated on DALIA 1 specimens. The most prominent observation is that there is relatively little difference between the effects of the three- or seven-month tests and the two-week tests. The largest difference [Fig. 10(a)] is in the strain developed during aging, with 0.759%, during seven months, against 0.165% in test A2 and 0.210% in test C1 (both with 14-day aging), with all tests on undisturbed specimens. As for compressibility, the decrease in the coefficient of volume change over seven months is from 4.70 × 10^{-3} MPa^{-1} to 1.97 × 10^{-3} MPa^{-1}—57.9%—against an analogous decrease for the 14-day tests, A2 and C1, of 49.4% and 54%, respectively. Thus, it appears that some effects of aging, such as strain amount or stress range, are more dependent on the duration of the aging episode than are others.

Strain Rate Dependence

It is worthwhile to report the results of a constant strain rate oedometric test W1, with an aging episode of 14 days, performed on DALIA 1 undisturbed material at 15.78 MPa. The imposed rate of straining was 2.5 × 10^{-6} [1/s], which is a low value for sands. Interestingly, the spontaneous rate of strain during the aging phase was only slightly lower, 1.9 × 10^{-6} [1/s]. While the aging stress was higher than in test A2, making a direct comparison impossible, the four characteristics of aging [Fig. 10(b)] were very close to those in the incremental

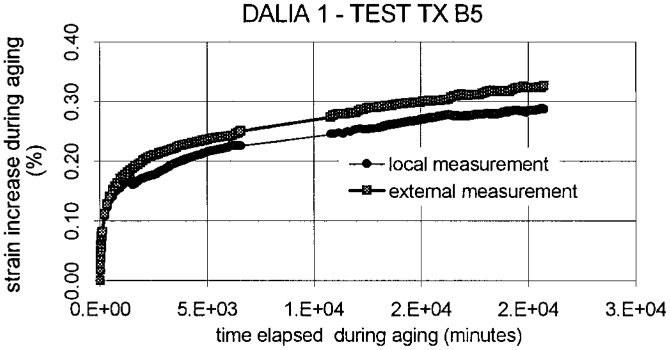

FIG. 8. Strain Development during Aging against Time in Remolded Material at Stress of 0.82 MPa; Test B5 on Remolded DALIA 1 Sand

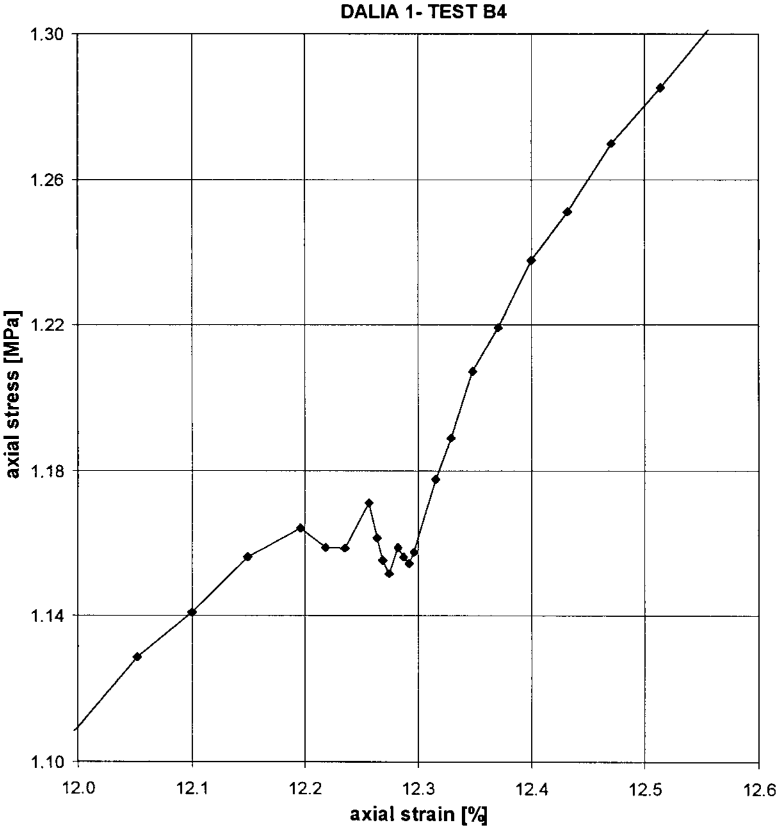

FIG. 9. Short Term Aging Episode (2.5 h) in Test on Remolded DALIA 1 Sand Material in Normally Consolidated State in Test B4

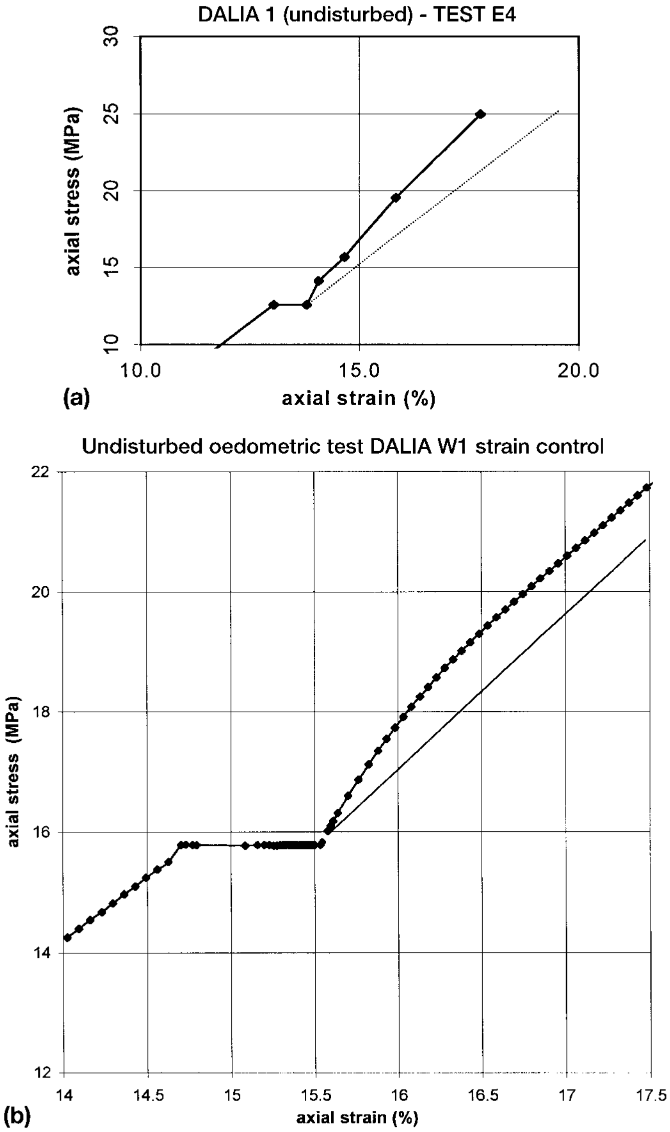

FIG. 10. Time Effects in Aging Tests: (a) Seven Month Aging Effect in Test E4 (Detail) on Undisturbed DALIA 1 Sand; (b) Aging Effect in Strain-Rate Controlled Oedometric Test W1 (Detail) on Undisturbed DALIA 1 Sand; Aging Occurred at 15.78 MPa

loading test A2 (Fig. 3). The reduction of the coefficient of volume change was about 53%, against 49.4% in A2, at 112% of the aging stress, while the relative strain reduction was 36% against 38%. It is thus concluded that whether the test was conducted with a relatively low rate or through instant stress increases left for 24 h, the differences in the effect of aging are negligible.

The rate dependence issue deserves an additional comment. Lessard and Mitchell (1985) observed an increase in the remolded strength and a decrease in the liquidity index [related to the undrained strength (Wood 1994)] during aging at zero stress. They have correlated these changes with specific chemical reactions. It is clear that since such changes occurred at zero stress they cannot be considered as a result of the creep phenomenon, as usually understood.

Aging Effects at Overconsolidation States

This issue could be examined by analyzing an accidentally induced aging episode during a technical arrest of loading in test B10 at 0.4 MPa, equivalent to OCR = 1.25 (Fig. 7). The duration of the arrest was 7.5 h. The relative strain gain during this period was clearly less than in normally consolidated (NC) states, 0.10% of the total strain, against a 2.5% average of all remolded specimens tested at NC states, and against 1% of the total strain (the short, 2.5 h stop in an NC state shown in Fig. 9). However, the effect on the moduli was of the order of those in the NC states, with a 46% decrease of the coefficient of volume change. In turn, the stress range affected by aging was relatively small—namely, 6% of the total stress—but consistent with the other short-term stop in the NC state (Fig. 9). Thus, it is concluded that aging is not to be excluded in overconsolidated states of soils, but the characteristics of its effects seem to be quantitatively different from those for normally consolidated states.

K_0 Effect

It seems appropriate to report that the lateral stress measured during the aging episode (Schmertmann 1983) has shown only a very slight increase, practically within the error margin.

Correlation with Various Elasticity Moduli

The form of the immediate postaging portion of the stress-strain curve suggests an increase in the overconsolidation domain and nearly elastic behavior. Thus, we will compare the postaging moduli with elasticity moduli, or, better, a series of unloading and reloading moduli. In Fig. 11 the results of aging test B5 on sandy DALIA 1 remolded material are compared with those from cyclic tests B6 and B8. The incremental compression index at 0.808 MPa during postaging loading in test B5 is C_C = 0.0056 against an average of 0.0087 during unloading, of 0.043 during reloading in large loops in B6 and B8, and of 0.0132 during reloading in the small loop in B8. As seen, the postaging loading modulus at the aging stress of 0.808 MPa in B5 is closest to the reloading modulus of a ‘‘smaller’’ unloading-reloading loop in test B8. As is clear from Fig. 11, the local incremental modulus is not much a function of the stress level, but much more of the unloading-reloading history (Hueckel and Nova 1979). Thus, one can speculate that aging at constant stress results in the generation of a slight overconsolidation through an expansion of the yield limit. Thus, in terms of standard terminology, the postaging loading would qualify as a ‘‘reloading’’ from the state of the in situ stress, with an incremental ‘‘initial’’ reloading modulus. It is worthwhile to notice also that the moduli of reloading taken for the ‘‘large’’ loops at the in situ stress level are by far most different from the postaging moduli.

MODELING OF AGING SEDIMENT WITH EVOLVING SECONDARY STRUCTURE

To render better the significance of the obtained results, an assessment of the aging effect on sediment subsidence prediction is made using the data on deformability reduction due to aging over 14 days for undisturbed materials. A 20 m thick layer bound from below and from above by a nondeformable sediment mass was considered. Its 1D, uniform deformation is predicted following the classical piecewise linear compression theory. Depletion pressures (equivalent to the effective stress loading) chosen are (1) 2 MPa, for the simulated 14 day aged DALIA 1 sand at a depth of 1,210 m, with the in situ stress of 12.6 MPa; and (2) 20 MPa, for the simulated 17 day aged TEA clay, at a depth of 3,270 m, with the in situ stress of 35 MPa. The simulated in situ stresses were taken as constant throughout the whole height of the layer. The results given below (Table 3) are for the piecewise linear law, characterized by m_v. It must be stressed that the applied relative stress increment was more modest for DALIA 1 than for TEA 1, and as mentioned above, the aging effect depends on the stress applied. The above result, based on very simple cal-

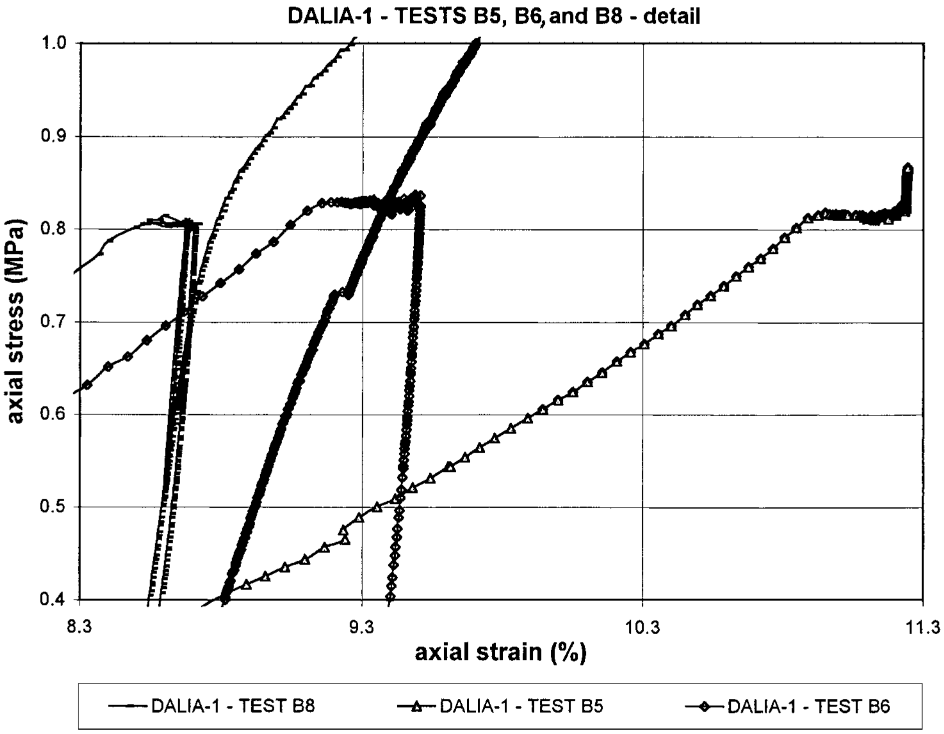

FIG. 11. Cycles of Loading, Unloading, and Reloading in Tests B6 and B8 on Remolded Sandy DALIA 1 Material to Compare the Unloading and Reloading Moduli to the Postaging Modulus in Test B5

TABLE 3. 1D Subsidence Simulation Highlights

Test condition	Sediment material	Source of data: Test number	Depletion stress (MPa)	Subsidence	
				Absolute value	Reduction of prediction
Monotonic	Sandy DALIA 1	A1	12.59-14.59 = 2 MPa	13.7 cm	—
With aging	Sandy DALIA 1	A2	12.59-14.59 = 2 MPa	7.00 cm	48.9%
Monotonic	Clayey TEA 1	A4	35.04-55.04 = 20 MPa	51.0 cm	—
With aging	Clayey TEA 1	A5	35.04-55.04 = 20 MPa	33.6 cm	34.1%

culations, and on the data from a test with a duration of aging of only 14 days, is very encouraging. Therefore, it may be argued that since subsidence is preceded in situ by an extensive aging process, the response of the sediment during oil/gas exploitation should be characterized by the postaging moduli.

To better understand the possible interplay between contributions toward stiffening of the material due to aging, we shall examine a model of the aging sediment with an evolving secondary structure, following the original hypothesis by Mitchell and Solymar (1984) and experiments by Denisov and Reltov (1961) of the local dissolution/precipitation of some geochemically less stable minerals in and from pore water. Several more recent scenarios regarding aging, linked in part to structuration, have been suggested (Lessard and Mitchell 1985), or may be suggested, including a mechanism of the formation of an array of structural ‘‘better interlocked’’ or ‘‘cold-welded’’ contacts leading to practically the same concept of a secondary, parallel structure.

In this model, the initial (primary) structure consists exclusively of a system of grains (Fig. 12). At the constant in situ stress, compressive strain may be increased over an irreversible strain of the primary structure during dissolution of the stressed mineral at the contact [Fig. 12(a)], linked to its ‘‘chemical softening’’ (Hueckel et al. 1999). Further, during the process the dissolved silica (or other mineral dissolved) precipitates onto the primary structure, forming a secondary structure [Fig. 12(b)]. This precipitation may or may not be localized near the contact points. The secondary material structure remains unstressed and unstrained if dissolution and precipitation are sequential, until the loading is increased. In the case of sample retrieval from the sediment mass, the loading process actually consists in a decompression of the system [Fig. 12(d), the last case]. This results in tensile stress in the material of the secondary structure and an unloading of the compressed primary structure. It is expected that the secondary structure material has a very low tensile strength, and behaves as a brittle material beyond the fracture point. Thus, it may contribute practically not at all to carrying the global stress in unloading. For further elaboration on the role of the reactions in the generation of chemical softening in material 1 and chemical hardening of material 2, see Hueckel et al. (1999).

Any further compressive stress in the fully developed structure is distributed between the two components, because the two materials now deform jointly. Thus, an increment in stress is a sum of the increment of the partial stresses, or a weighted sum of the specific partial stresses in the constituents

$$\dot{\sigma}_{ij} = \dot{\sigma}_{ij}^{(\mathrm{I})} + \dot{\sigma}_{ij}^{(\mathrm{II})} = \dot{\sigma}_{ij}^{(1)}\alpha + (1 - \alpha)\dot{\sigma}_{ij}^{(2)} \qquad (1)$$

The partial stress components $\sigma^{(\mathrm{I})}$ and $\sigma^{(\mathrm{II})}$ are stresses carried by the individual fractions, calculated per total area of the considered representative elementary volume, whereas $\sigma^{(1)}$ and $\sigma^{(2)}$ are specific partial stresses occurring in the material of each fraction, calculated per area of that fraction. In a simplest option coefficient α, $0 < \alpha < 1$ is related to the volume fractions of the two materials in the total volume of solids, con-

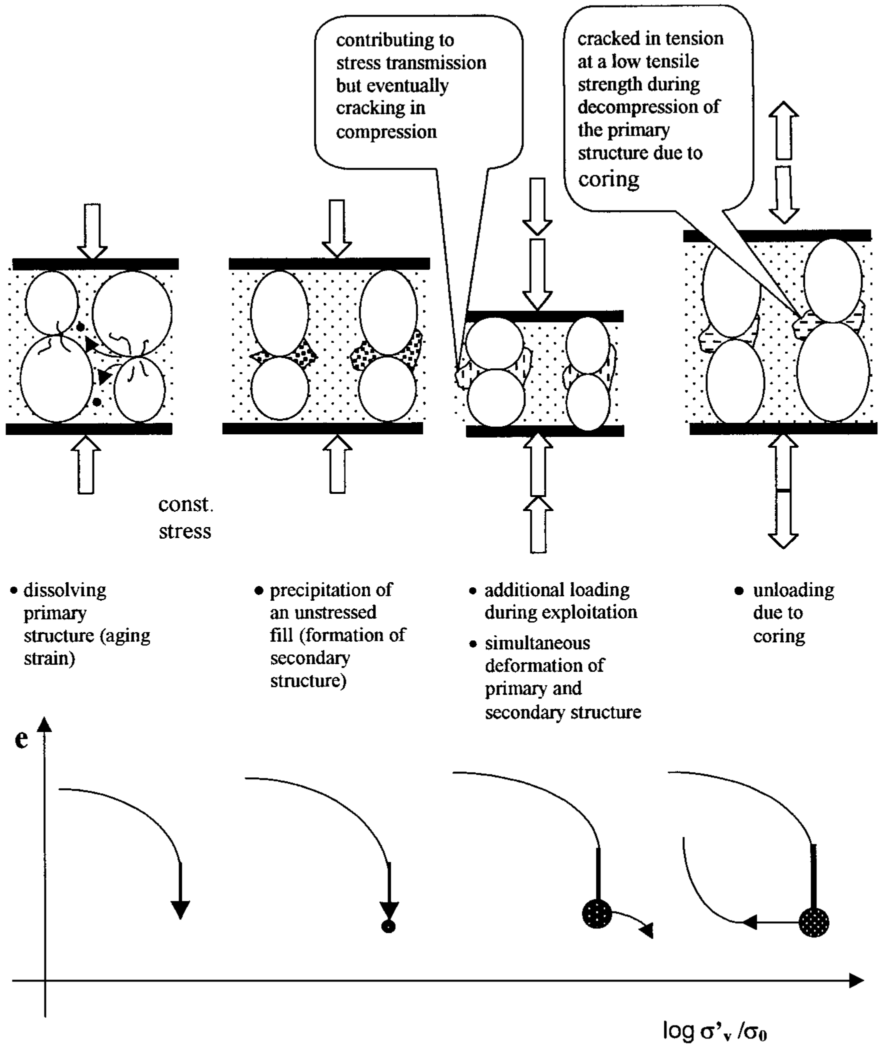

FIG. 12. Four Phases of the Evolution of the Microstructure of Aging Soil: (a) Loading to the In Situ Stress Level and Dissolution of the Mineral at Intergrain Contacts Leading to Irreversible "Aging Strain;" (b) Precipitation of the Solute on the Grain Structure and Formation of Jointly Deforming Parallel System; (c) Postaging Loading, Possibly Leading to Failure of the Secondary Structure of the Precipitate, in Compression; (d) Postaging Unloading during Sample Retrieval Leading to Failure of the Precipitate in Tension

sidered as constant. The two materials deform jointly, but with different deformability moduli. Also, the two materials have different yield limits.

The presented tests were all performed in one-dimensional strain conditions, and for undisturbed specimens the lateral stress was not measured, making the available database insufficient to develop a full, 3D material model. Still, a 1D simulation is possible, yielding an interesting insight. Thus, the axial total stress may be represented as

$$\sigma = \sigma_{ag} + \alpha\sigma_{ag} \exp\left[\frac{e_a - e}{K_3^{(1)}}\right] + (1-\alpha)\sigma_j^{(2)}\left\{1 + \exp\left[\frac{e_j^{(2)} - e}{K_{j+1}^{(2)}}\right]\right\}$$

$$\text{for} \quad e_j^{(2)} > e > e_{j+1}^{(2)} \qquad (2)$$

where $j = 0, 1, 2 \cdots$ = numbers of nodal points of the beginning of each segment of the piecewise stress–void ratio curve. The superscripts (1) and (2) refer to primary and secondary material, respectively. $K_i^{(1)}$ denotes the piecewise modulus for the segment $i - i + 1$, whereas $\sigma_i^{(1)}$ denotes stress values at the initial node of the segment.

It should be remembered that the primary material from the starting point of the joint deformation above the in situ stress is already in the plastic domain, and deforms substantially. At the same time, the secondary material is still in the elastic range, and its relatively small deformation implies a much larger stress in it. The yielding of the secondary material structure corresponds to what is seen in the experiment in terms of total stress at the end of the enhanced rigidity phase.

TABLE 4. Model Parameters to Simulate Postaging Behavior of DALIA A2

Material	σ_0[a]	σ_1	σ_2	σ_3	K_1	K_2	K_3	K_4
1	0.1	4.0	12.59	—	0.014	0.06	0.178	—
2	0.1	3.9	7.2	27.0	0.0009	0.0101	0.0305	0.055

[a] Stress unit (MPa); $e_0 = 0.59$; $\alpha = 0.629$.

Note that the objective of this exercise is to evaluate the roles of the primary and secondary structure in the postaging phase. The amount of the aging strain and the corresponding decrease in void ratio of Δe_a are taken directly from the experiments. The material parameters for the primary material were identified on the basis of the preaging phase behavior. The constants for the secondary material are back-calibrated to obtain a reasonable total stress simulation of the experimental curve. The numerical parameters used for the simulation are listed in Table 4, and the results of the simulations are presented in Fig. 13.

The most interesting result concerns the stress partition. Fig. 13(b) presents the recalculated specific partial stress difference–strain difference relationship above the aging stress in the linear stress scale; Fig. 13(c) shows the same, but in terms of partial stresses. It may be seen that the partial stress in the

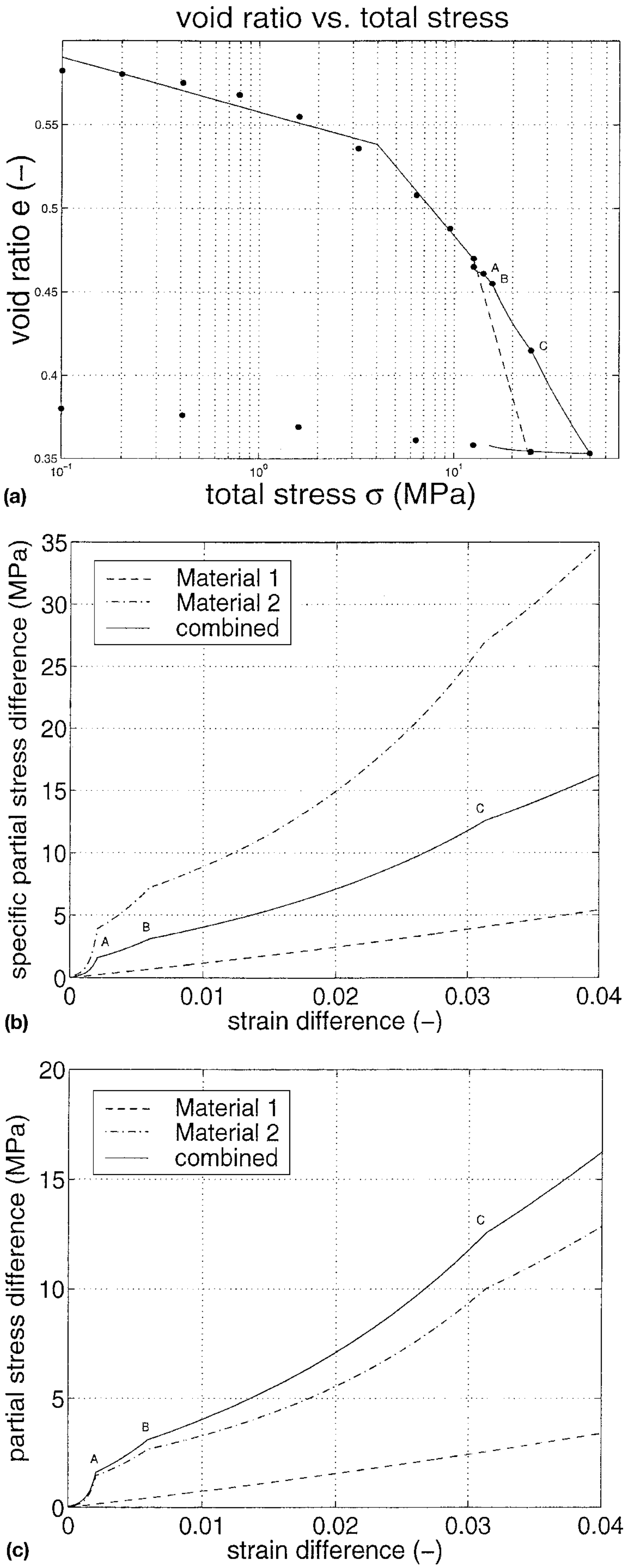

FIG. 13. Simulation of the Two-Component Structure of the Aging Material DALIA 1: (a) Total Stress versus Void Ratio Change; (b) Specific Partial Stress Components versus Strain; (c) Partial Stress Components versus Strain

secondary material is clearly higher than the corresponding partial stress difference above the aging stress in the primary material, with a ratio between 3 and 4. As for the specific partial stresses, this ratio climbs up to nearly 7. Three factors need to be realized while evaluating this result. First, the results show only the portion of the process related to the joint deformation process, above the aging stress. That implies that the total partial stress in material 1 is the stress difference seen in Fig. 13 plus its initial aging stress, that is, 12.59 MPa, whereas in material 2 the initial stress is zero. Thus, the absolute partial stress in material 2 is lower than that in material 1 until the strain difference of 0.05 above the end of the aging state is reached [Fig. 13(c)]. Second, the specific partial stress in the primary material at the in situ total stress of 12.59 MPa is 19.07 MPa. Therefore, the specific partial stress in the primary material is larger than that in the secondary material up to the strain of about 0.03. It should be noted that stress partitioning into specific partial stresses is controlled by the coefficient of partition, α, assumed here as equal to the solid volume fraction. Third, even though it is not explicitly stated in the constitutive law, (2), the primary material, by the very definition of normal consolidation, is in the plastic range above the stress of 12.59 MPa, and thus in the whole range above the aging stress (before unloading). The secondary material reaches yielding at the value of 4.2 MPa of the specific partial stress, corresponding to the partial stress of 2.18 MPa and to the total stress of 14.77 MPa. Thus, even if in terms of stress differences material 2 carries more load than material 1, in terms of the absolute stress values this is not the case. Actually, in terms of the preconsolidation stress, material 2, at the moment of its yielding, carries less than 1/4 of the specific partial stress that is carried by the primary material.

From the engineering point of view, it is the load above the in situ stress that is important. In carrying this load, the role of the secondary material is numerically more important than that of the primary material. Consequently, its yielding point is extremely important, because it defines the postaging range. Thus, the prediction of its strength is crucial for the prediction of the stress range in which the decreased compressibility occurs.

CONCLUSIONS

Experiments on undisturbed clayey and sandy sediments subject to a moderate duration aging (14 days) at the in situ stress level indicate that the sediments respond to a further loading with a deformability reduced nearly 40%, when compared to those tested in a traditional way with monotonic loading. That leads to a proportional (~40%) reduction of subsidence prediction according to 1D, linear compression theory. This effect occurs in a stress range in excess of the in situ stress of 12%–45% of the in situ stress value. It is argued that subsidence of sediments is preceded in situ by an extensive aging process, and thus its response should be characterized by the postaging moduli. Rate-dependence effects seem to play a minor role in sediment stiffening. Earlier hypotheses that during aging a secondary structure develops in the soil are preliminarily calibrated in a 1D model. It appears that such a secondary structure would carry a major part of the load above the in situ stress level, until its failure would return the material to a one-component mode, with compressibility near the preaging values. However, the contribution of the secondary structure before its failure may play a fundamental role not only in petroleum or gas exploitation applications, but also in engineering applications. It is obvious that the model presented is only partially representing the processes hypothesized to occur. Further experimental and modeling studies are needed to describe the effect of aging at triaxial stress paths to failure, possibly linking explicitly the aging effect to that of structuration (and destructuration) as described by Schmertmann (1991).

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