Deformability of clays under non isothermal conditions

A. BURGHIGNOLI*, A. DESIDERI** S. MILIZIANO*

SUMMARY. This paper presents the findings of an experimental study aimed at investigating some aspects of the thermo-mechanical behaviour of clays. In particular, attention is focused on the influence of the stress history on the behaviour of soil when subjected to temperature variations and, conversely, on the influence of the thermal history on mechanical behaviour. Natural and remoulded clayey soils were subjected to temperature cycles in drained conditions. The results show that the variations of temperature produce irreversible volume change that is strictly dependent on the rate of viscous deformations exhibited by the solid skeleton when the thermal load is applied. It is shown that a temperature cycle on a normally consolidated clay produces an effect 'quasi-preconsolidation' with a stiffness increment that depends on the subsequent stress path. The memory of the thermal cycle fades progressively moving away from the strain and stress state connected with the cycle. Finally, the analysis of the interaction between thermal and mechanical behaviours suggests some hypotheses on the nature of the irreversible deformations produced by temperature variations and about the similarities with viscous deformations of the solid skeleton.

1. Introduction

Over the last few years the Department of Structural and Geotechnical Engineering at the University of Rome «La Sapienza» has been focusing its attention on the thermo-mechanical behaviour of clays. Apart from the large temperature variations (hundred of °C) relevant to particular applications, such as the exploitation of geothermal sources, the extraction of hydrocarbons from oil bearing sands and the burying of radio active waste, temperature variations of the order of tens of °C occur in soils in normal conditions. At this regard it is sufficient to mention the temperature fluctuations in the topsoil of natural deposits, the temperature variations induced by sampling and transportation, and those occurring during the course of long-term laboratory tests.

The importance that even slight temperature variations may have on the mechanical behaviour of soils is easily shown by the significant dependence upon temperature of the interaction forces between clayey grains and water and hence of the Atterberg limits [YOUSSEF *et al.*, 1961]. Of some importance is also the increase in the rate of consolidation phenomena caused by temperature [FINN, 1951; HABIBAGAHI, 1973; BURGHIGNOLI and DESIDERI, 1988]. Significant volume changes are produced by heating a clayey soil in drained conditions [CAMPANELLA and MITCHELL, 1968; DESIDERI, 1988] and vice-versa significant pore pressures are generated during a heating process in undrained conditions (constant mass) due to the interaction between solid skeleton and pore water.

In this paper attention is paid to the study of volume changes produced in drained conditions by cyclic thermal loads and of the mechanical behaviour subsequent to the temperature cycle. The typical range of temperatures was between 15 and 60°C. The main findings reported in the literature on this topic show that cyclic changes of temperature generally produce irreversible volume changes [PAASSWELL, 1967; CAMPANELLA and MITCHELL, 1968; PLUM and ESRIG, 1969; DEMARS and CHARLES, 1982; BURGHIGNOLI and DESIDERI, 1988]. While most Authors agree on a decrease in volume with temperature for normally consolidated clays, the results corresponding to overconsolidated clays are widespread, since both swelling and compression can be observed. With respect to an initial state of normally consolidation, it has been pointed out that a thermal cycle produces quasi-preconsolidation effects similar to those caused by aging [PLUM and ESRIG, 1969; BURGHIGNOLI and DESIDERI, 1988].

The present investigation was aimed at studying the volume changes of normally consolidated and overconsolidated clays, produced by cyclic thermal loads, and in particular at clarifying the above-mentioned controversial aspects. The study was furthermore extended to the 'quasi-preconsolidation' effects caused by a temperature cycle, by examining the mechanical response to different stress paths. The study provides some insight into the dependence of the thermal stress effects upon the stress history and, vice-versa, of the influence of the history of thermal stresses on mechanical behaviour. This provides a better understanding of the nature of the irreversible deformations produced by thermal stresses.

In the following, the results of the investigations are discussed and some of the literature findings are

---

* Università di Roma «La Sapienza».
** Università di Napoli Federico II.

re-examined in order to provide a comprehensive framework for the observed behaviours.

2. Clays used for testing

Most of the tests were carried out on remoulded Todi clay. A smaller number of tests were carried out on undisturbed samples of Fiumicino clay and Bologna clay. Table I summarises the index properties of the three clays. They are all high plasticity clays consisting of clay and silt grains in approximately equal proportion, and a very low sandy fraction.

Table I - *Index Properties of the Tested Soils*

Soil	WL (%)	IP (%)	USC	Grain-size Clay-Silt-Sand
Todi clay	52	30	CH	45-53-2
Fiumicino clay	55	32	CH	45-52-3
Bologna clay	63	38	CH	54-46-0

The Todi clay specimens were prepared from samples obtained by consolidating a slurry at an effective vertical stress of 50 kPa. The slurry was prepared by remoulding the material passing through an ASTM n. 60 sieve at a water content equal to 1.5 times the liquid limit.

In order to obtain homogeneous samples to the possible extent the slurry was poured into a consolidometer using a vacuum technique.

3. Test equipment and experimental procedures

The tests were carried out using triaxial cells of different sizes, properly modified to control and measure temperature. Fig. 1 shows an axial section of a typical cell. Temperature control was made possible by circulating water from a thermostatic bath into a hollow metal coil placed within the cell. A Fe-Co thermocouple and a needle micropiezometer [Burghignoli and Caruana, 1979] pushed inside the specimens, allowed the measurement of temperature and pore pressure (Fig. 1). Volume variations were obtained by measuring the volume of water expelled by the sample using a volume gauge connected to the drainage line. Since the volume variations have been measured after the thermal cycles, at a temperature which was the same as at the beginning of the cycle itself, it was not necessary to calibrate the measurement system. Samples of different size (38.1, 50.8 and 101.6 mm dia) were used in the experimental program. To obtain full saturation of the specimens, the tests were conducted under a backpressure of 200 kPa. Further information on the equipment can be found in Desideri [1988] and Miliziano [1992].

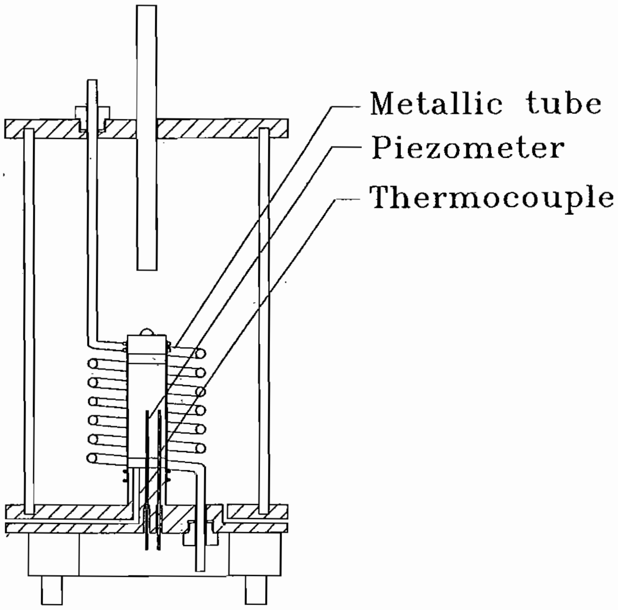


Fig. 1. Schematic section of the modified triaxial cell.

In order to isolate the effect due only to temperature variation, the effective state of stress was kept constant during the temperature cycles. This latter condition was secured by keeping total stresses constant and by varying the temperature very slowly. By means of the inner micropiezometers it was possible to verify that drained conditions persisted throughout the thermal cycle.

Table II summarises the characteristics of the main tests carried out (Todi, Bologna and Fiumicino clays are respectively denoted as TD, BL and FM). The amplitude of the temperature range ΔT, of the heating time, Δt_h, of the cooling time, Δt_c, and of the time, Δt_0, elapsed between the end of hydrodinamic consolidation following the last mechanical stress and the beginning of the cycle are given for each thermal cycle. The values of the mean effective stress p' and of the degree of overconsolidation R_p at which the cycle was performed are also indicated. The results are presented in the following to highlight the importance of the history of mechanical and thermal stresses and of time on the thermal compressibility of clays.

4. Volume changes produced by thermal cycles

Fig. 2 shows the values of the water volumes absorbed or expelled by the sample versus time, as recorder during the first temperature cycle of the TD9 test. During the heating stage (h, in figure) the sample expels water. As already pointed out by Campanella and Mitchell [1968], the amount of relea-

Table II - *Characteristics of the tests carried out*

Test	Specimen dimensions H (mm)	d (mm)	p′ (kPa)	R_p	ΔT (°C)	Temperature range (°C)	Δt_0 (hours)	Δt_h (hours)	Δt_c (hour)
TD1-C1	38.1	76.2	98	1.0	29	25-54-25	25	24	24
TD2-C1	38.1	76.2	392	1.0	29	25-54-25	24	24	24
TD3-C1	38.1	76.2	196	1.0	29	25-54-25	96	24	24
TD4-C1	38.1	76.2	20	6.0	19	22-42-22	16	24	24
TD4-C2	38.1	76.2	61	4.0	20	22-42-22	13	24	24
TD4-C3	38.1	76.2	245	2.0	20	22-42-22	9	24	24
TD4-C4	38.1	76.2	979	1.0	20	22-42-22	24	24	24
TD5-C1	38.1	76.2	69	5.7	21	19-40-19	23	12	12
TD5-C2	38.1	76.2	633	1.0	21	19-40-19	16	12	12
TD6-C1	101.6	127.0	25	4.0	30	18-48-18	1	24	24
TD6-C2	101.6	127.0	440	1.0	30	18-48-18	24	42	48
TD7-C1	50.0	100.0	128	1.0	40	18-58-18	15	22	24
TD8-C1	50.0	100.0	98	1.0	40	18-58-18	45	12	8
TD9-C1	50.0	100.0	196	2.0	40	18-58-18	24	12	8
TD10-C1	101.6	127.0	98	1.0	25	25-50-25	168	65	95
TD10-C2	101.6	127.0	98	1	25	25-50-25	—	70	70
TD10-C3	101.6	127.0	98	1	25	25-50-25	—	70	80
BL1-C1	38.1	76.2	392	1.0	20	24-44-24	—	24	24
BL1-C2	38.1	76.2	20	20.0	20	24-44-24	—	24	24
BL1-C3	38.1	76.2	98	4.0	20	24-44-24	—	24	24
BL1-C4	38.1	76.2	785	1.0	20	24-44-24	—	24	24
FM1-C1	38.1	76.2	59	1.3	28	18-46-18	144	48	24
FM1-C2	38.1	76.2	59	—	28	18-46-18	—	48	24
FM1-C3	38.1	76.2	235	1.0	28	18-46-18	120	48	24
FM1-C4	38.1	76.2	235	4.0	28	18-46-18	96	48	24
FM2-C1	50.0	100.0	59	1.3	28	18-46-18	144	48	24
FM2-C2	50.0	100.0	59	8.0	28	18-46-18	72	24	24
FM3-C1	97.0	107.0	147	1.0	28	20-48-20	288	—	—

sed water depends on a number of factors, such as the thermal dilation of pore water and of the solid grains, the volume changes of the solid skeleton and, finally, the volume change of the measuring system. In the subsequent cooling phase (c, in figure) the sample reabsorbs water. The volume difference between the water released during heating and the water absorbed during cooling, represents the volume change of the sample produced by the temperature cycle (ΔV_{TC}). This result, which is qualitatively similar for all tests, shows that a thermal cycle produces an irreversible volume change. In particular, the results of Fig. 2, relative to normally consolidated Todi clay, show that the temperature cycle produces a reduction of volume.

Similar conclusions have also been reached by the cited researchers. Fig. 3, for instance, shows the results of an isotropic compression test with two loading and unloading cycles carried out by Demars and Charles on a high plasticity clay.

The solid line refers to the isothermal isotropic compression with T = 25 °C, whereas the dashed line joins the values of the void ratio after drained thermal cycles between 25 and 50°C. The distance between the two lines represent the void ratio variations due to the thermal cycle, Δe_{TC}. It is noted that

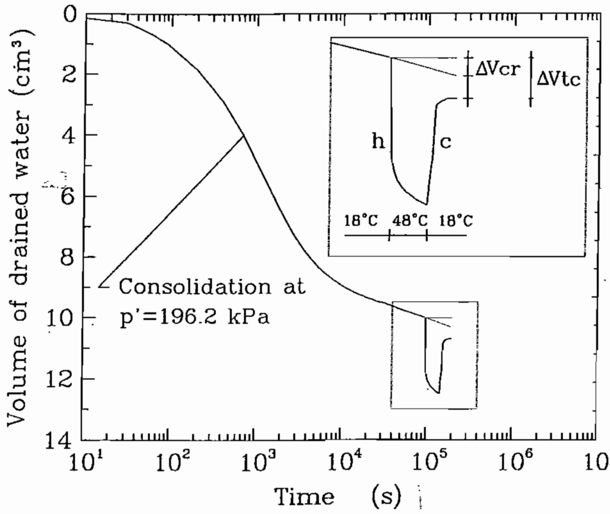


Fig. 2. Volumes of water drained during a thermal cycle (test TD9).

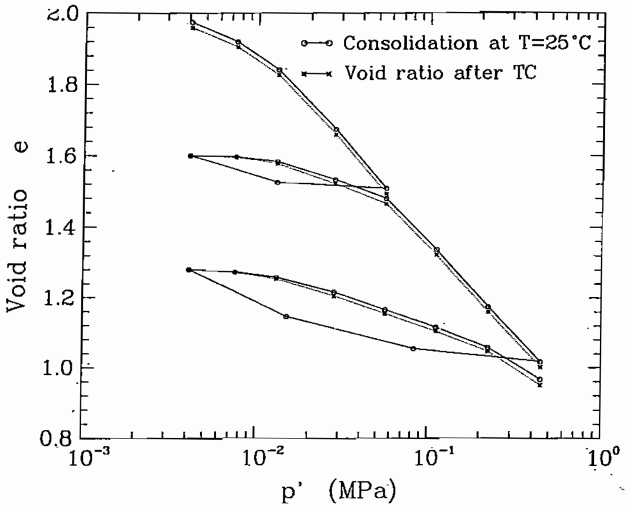


Fig. 3. Void ratio variations due to thermal cycle (after Demars and Charles, 1982)

the solid and dashed lines are parallel: hence, for normally consolidated clays in isotropic conditions, the value of Δe_{TC} does not depend on the level of the mean effective stress. Rather, it depends on the magnitude of the temperature cycle and on soil plasticity; a linear relationship with the plasticity index IP is reported in Fig. 4.

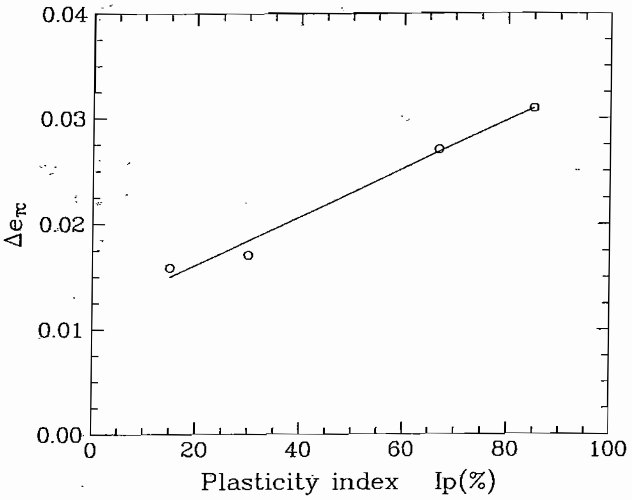


Fig. 4. Relationship between Δe_{TC} and plasticity index (after Demars and Charles, 1982)

Influence of the Stress History

Fig. 5 shows the results of an isotropic compression test (TD4) with intermediate 20°C temperature cycles. In conditions of normal consolidation, the temperature cycle produces a significant decrease of the void ratio whereas the cycles carried out after mechanical unloading result into an increase of the void ratio which is more and more pronounced as the degree of overconsolidation increases.

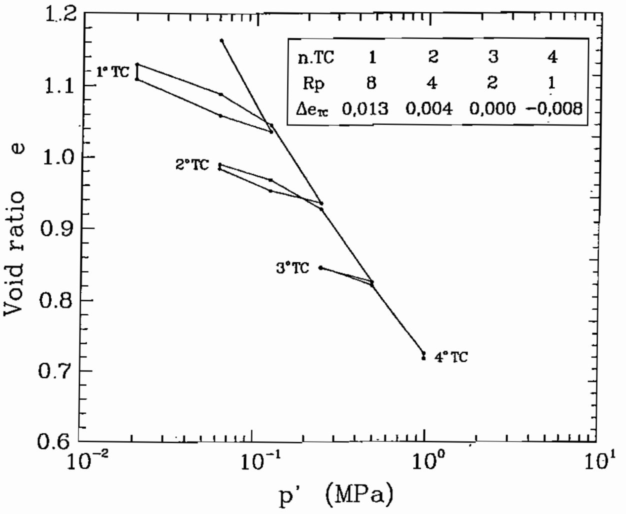


Fig. 5. Isotropic compression test with intermediate thermal cycles (test TD4).

This result suggests that both the magnitude and the sign of Δe_{TC} significantly depend upon the degree of overconsolidation of the clay; as already pointed out in a previous paper [Burghignoli and Desideri, 1988] passing from conditions of normal consolidation to conditions of overconsolidation, the tested clay shows progressive change from thermically contracting to thermically dilating behaviours.

Fig. 6 presents the results of an isotropic compression test with intermediate thermal cycles (BL1). In this case, while the values of Δe_{TC} for conditions of normal consolidation, confirm the above results (contracting behaviour), the values obtained for $R_p > 2$ have both contracting and dilating behaviours. In particular, the thermal cycle carried out for a value of $R_p = 20$, after mechanical unloading, produces an increase in the void ratio; whereas, in the thermal cycle carried out at $R_p = 4$, after a reloading phase, there is a volume reduction.

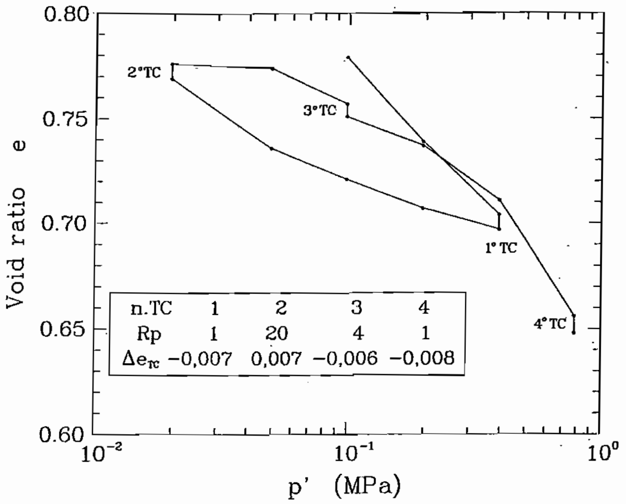


Fig. 6. Isotropic compression test with intermediate thermal cycles (test BL1).

The results discussed so far show that the variations of the void ratio produced by temperature cycles depend, in value and sign, not only on the degree of overconsolidation, but also on the recent stress history; indeed, the unloading phases are accompanied by a thermally dilating behaviour which increases as R_p increases, whereas the loading and reloading phases are accompanied by a thermally contracting behaviour.

The results obtained by DEMARS and CHARLES for virgin loading and reloading, previously shown in Fig. 3, appear to confirm such a result (the Authors did not perform any test during unloading). In addition, the thermal contraction increases as the magnitude of the reloading increases, and reaches a maximum for conditions of normal consolidation.

Fig. 7 shows the variation of Δe_{TC} with R_p during the two reloading paths of the isotropic compression test, whose results are reported in Fig. 3; the large difference between the two curves suffice to demonstrate that the dependence of Δe_{TC} on stress history is likely to be rather complex, and that predictions based upon the value of the degree of overconsolidation alone may be quite widespread.

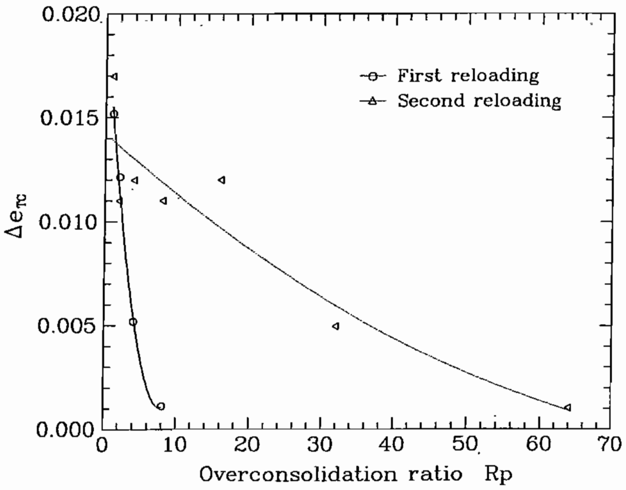


Fig. 7. Δe_{TC} versus R_p (after DEMARS and CHARLES, 1982).

Influence of the Thermal History

Table III presents the results obtained for the test TD10, in which the specimen, normally consolidated under a pressure $p' = 98$ kPa, is subjected to 3 consecutive temperature cycles. It is noted that contraction decreases progressively with increasing the number of temperature cycles; this is in agreement with the concept of thermal cyclic stabilization suggested by CAMPANELLA and MITCHELL [1968]. Hence, the effect produced by a cyclic thermal load depends also on the history of temperature stresses.

Table III - *Variations of the void ratio produced by successive cycles (test TD10)*

Cycle n°	Δe_{TC}
1	– 0.0121
2	– 0.0018
3	– 0.0002

Influence of Time

Table IV presents the results of two pairs of tests in which the same temperature variations were applied at different time, Δt_0, after the end of hydrodinamic consolidation. In both cases, as Δt_0 increases (i.e., with the progress of creep deformations) there is a significant reduction in Δe_{TC}. Hence, the soil response to thermal stress depends not only on the previous mechanical and temperature histories, but also upon time.

Table IV - *Dependence of the Δe_{TC} value on the time elapsed from the end of primary consolidation*

	ΔT (°C)	Δe_{TC}	Δt_0 (hours)	Δt_{TC} (hours)
TD6-C1	30	– 0.0363	1	48
TD7-C1	40	– 0.0202	15	46
TD9-C1	40	– 0.0115	24	20
TD8-C1	40	– 0.0064	45	20

5. Analysis of results

In the literature on this topic, the deformation processes generated by a thermal stress have often been interrelated, in terms of quality, with the viscous behaviour of the solid skeleton [CAMPANELLA and MITCHELL, 1968; DEMARS and CHARLES, 1982; BURGHIGNOLI and DESIDERI, 1988]; it is believed that positive temperature changes, by introducing energy into the system, accelerate the creep deformations which are in progress.

The factors identified in the previous paragraph, affecting the soil behaviour during a thermal cycle, tend to confirm the existence of a close correlation between the deformations induced by temperature and those induced by viscosity.

Indeed, also for the rate of viscous deformation it is possible to establish a relationship with the plasticity characteristics of the material and with the stress history, which is qualitatively similar to that evidentiated for irreversible thermal deformations.

Fig. 8 shows the variation of the secondary compression index $C_{\alpha e}$ with the mean effective stress p' during loading, unloading and final reloading in an

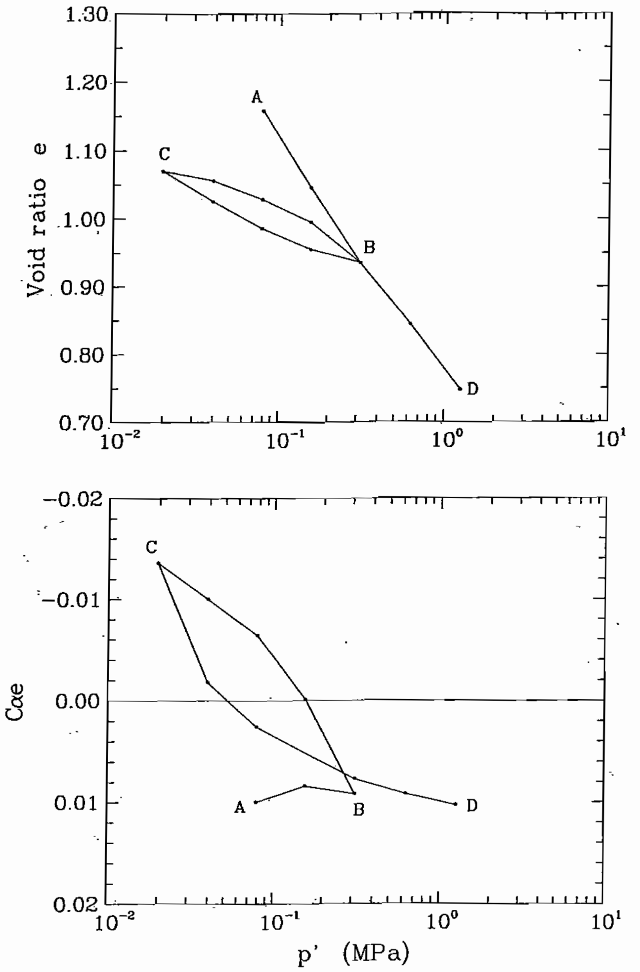


Fig. 8. Influence of stress history on secondary compression index Cαe.

isotropic compression test (IL, $\Delta p/p = 1$) carried out on remoulded Todi clay.

In conditions of normal consolidation $C_{\alpha e}$ is positive (volume reduction) and is substantially independent of the stress level. During unloading from B to C, Cαe decreases monotonically and changes sign (i.e., the soil expands) at values of the degree of overconsolidation $R_p > 2$. In the subsequent reloading phase from C to D, the tendency is inverted and the values of Cαe increase monotonically until reaching a constant maximum in n. c. conditions (points B, D).

To evidentiate the similarity between creep and thermal volumetric deformations, let us define with Δe_{cr} the void ratio variation due to creep in isothermal conditions:

$$\Delta e_{cr} = \frac{\Delta V_{cr}}{V_s}$$

where V_s is the volume of solid phase and ΔV_{cr}, as illustrated in Fig. 2, represents the creep volume change occurring during a time interval equals to that elapsing between the beginning and the end of a temperature cycle.

It is pointed out that Δe_{cr} depends not only on Cαe, but also on the time elapsed since the end of primary consolidation and on the duration of thermal cycle.

Fig. 9 reports the values of Δe_{TR} obtained in the test carried out on Todi clay as a function of Δe_{cr}.

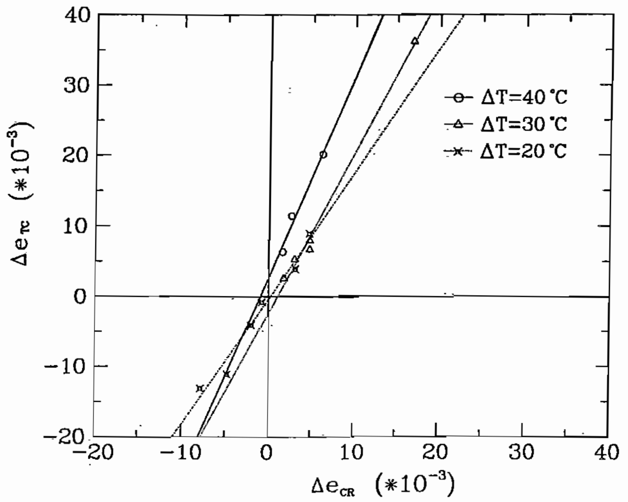


Fig. 9. Δe_{TC} versus Δe_{cr} for thermal cycles having different magnitudes (remoulded Todi clay).

The figure clearly shows that, for each amplitude of the temperature cycle, the experimental results are concentrated with little scatter along lines passing approximately through the origin of the axes, with slopes that increase with such amplitude. Therefore, a relationship of the following type is obtained:

$$\Delta e_{TC} = K \, \Delta e_{cr}$$

where K varies between 1.8 and 2.8, depending on thermal cycle amplitude

Since the lines pass through the origin of the axes, when the solid skeleton does not present appreciable creep deformation rates ($\Delta e_{cr} \cong 0$), also the volume deformations produced by a temperature cycle are barely appreciable ($\Delta e_{TC} \cong 0$). Hence, it might be suggested that the structural rearrangements occurring as a result of a temperature load are an amplification of those governing creep deformations of the solid skeleton. Knowing the rate of creep volumetric deformation, the range of the temperature cycle and its duration, by using the above relationship the volume variations produced by a cyclic temperature stress can be predicted.

6. Influence of a thermal cycle on soil stiffness

The dependence of mechanical behaviour on stress history has been investigated only for the remoulded Todi clay. Two triaxial cells were simultaneously employed to compare the mechanical behaviour of the clay subjected to a cyclic temperature stress and the one of a clay kept at constant temperature. In a first stage, each pair of specimens was consolidated isotropically, in isothermal conditions, until reaching conditions of normal consolidation. Then, one of the specimens was subjected to a drained temperature cycle, whereas the other was kept at constant effective stress and temperature. Finally, the two specimens were subjected to the same stress path; in particular, isotropic compression (at constant rate of loading), triaxial compression (CIU) and resonant column tests were carried out.

Fig. 10a shows the results of the isotropic compression test. The specimen subjected to a 30°C thermal cycle (18-48-19°C) presented a void ratio reduction $\Delta e_{TC} = -0.03$, whereas the other, as a result of creep deformation alone, reported a lower reduction, $\Delta e_{cr} = -0.015$. It must be pointed out that also in this case the previously found relationship, $\Delta e_{TC} = K\ \Delta e_{cr}$, still hold (with K corresponding, in Fig. 9, to $\Delta T = 30°$).

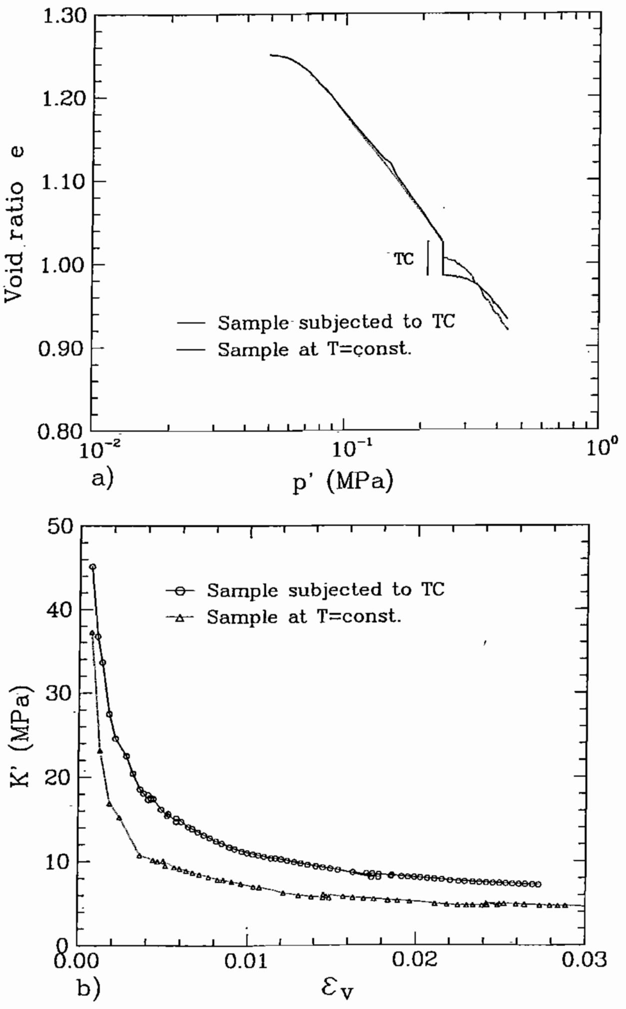


Fig. 10. a) Compressibility curve; b) Variation of the secant bulk modulus with volumetric deformation ε_v during the recompression phase.

In the subsequent recompression stage the specimens show similar qualitative behaviours; in both cases, the reloading shows initially a very stiff behaviour and then reaches the typical slope of normal consolidation conditions. The yield threshold, which can be clearly identified in the passage between the two behaviours, is higher for the temperature treated specimen.

Similar results have been obtained by PLUM and ESRIG [1969] and by BURGHIGNOLI and DESIDERI [1988]. The effect of the temperature cycle decreases gradually as the reloading increases and, when the sample reach a state of normal consolidation, the material has totally lost the memory of the temperature stress it had been subjected to.

Fig. 10b shows the variations of the secant bulk modulus K', as a function of volume deformation ε_v, during the recompression phase. The cyclic temperature stress produces an increase in K' of about 35%, for a reference value $\varepsilon_v = 0.01$.

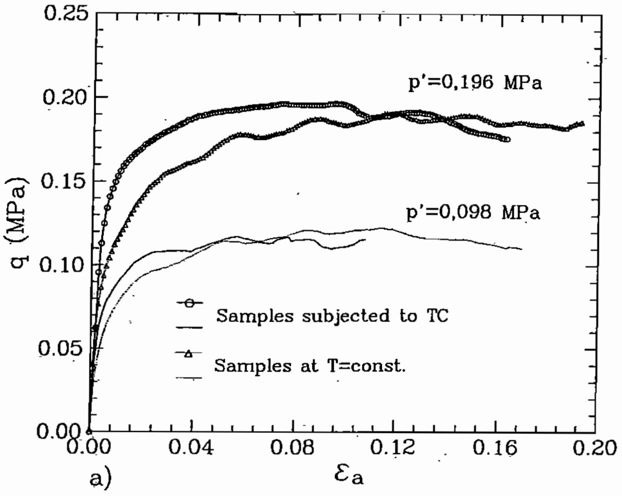
In conclusion, a thermal cycle induces a quasi-preconsolidation effects similar to those produced by the creep deformations [BJERRUM, 1967; LEONARDS and RAMIAH, 1960]. The larger volume deformations undergone by the temperature loaded specimen emphasise and enhance these behaviours.

Fig. 11a presents the results of the undrained compression tests for two pairs of specimens isotropically consolidated at p' = 98 kPa and p' = 196 kPa. It is noted that the initial portion of the q-ε_a curves for the specimens subjected to the temperature cycle lie above the ones corresponding to the specimens maintained at constant temperature. At larger strains, the q-ε_a curves tend to converge and finally merge when critical state condition is reached.

Fig. 11b shows the corresponding variations of the secant Young modulus, E_u, versus axial deformation ε_a; for $\varepsilon_a = 0.01$, the thermal cycle results into an average increase of E_u of the order of 15%, whereas for $\varepsilon_a = 0.04$ the values of E_u virtually coincide.

Fig. 12 shows the results obtained in a resonant column device. Also in this case, the temperature cycle results into a greater secant shear modulus G, with an increase of 18% of the initial modulus G_0. As the deformations increase, the stiffness of the two specimens tend to coincide.

The above results show that a thermal cyclic applied to a normally consolidated clay induces a state of 'quasi-preconsolidation', which can be found whenever the state of stress is changed. The effects produced depend on the stress path followed after the cycle, and are significant in a rather small range of stresses and deformations close to the initial state. As the stresses or deformation increase, the soil gradually loses memory of the previous temperature



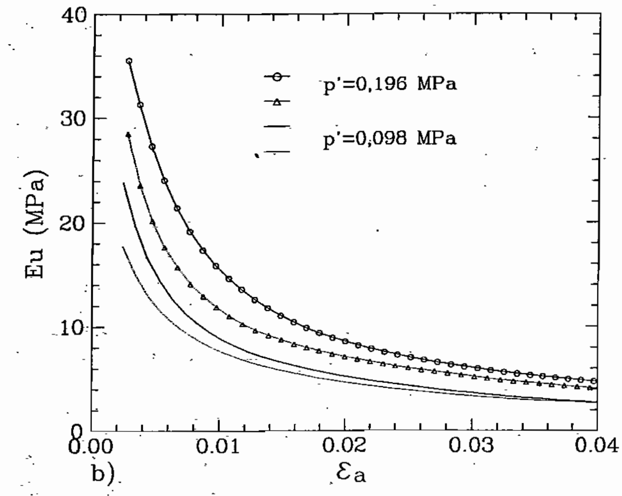


Fig. 11. a) Deviatoric stress q versus axial deformation ε_a; b) variation of the secant modulus E_u with ε_a.

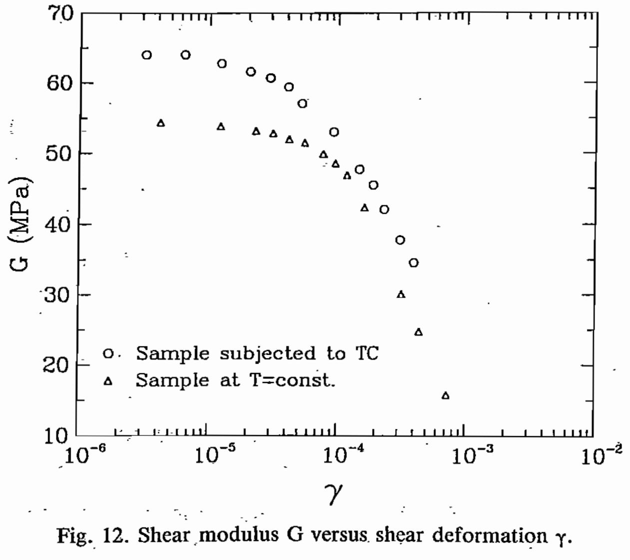


Fig. 12. Shear modulus G versus shear deformation γ.

treatment it was subjected to. In qualitative terms, this behaviour is similar to that found for accumulation of volumetric creep deformations in isothermal conditions, but in quantitative terms it is much larger. The larger volume reduction experienced by the specimens as a result of the temperature cycle, can quantitatively justify the enhancement of stiffness evidenced above. This agrees also with the assumption that the volume deformations in the two processes are of the same nature and that both arise from the same structural changes in the solid skeleton.

7. Conclusion

The experimental results obtained in this study have pointed out that cyclic temperature variations generally produce irreversible volume changes, whose magnitude increases with the amplitude of the thermal cycle. Such volume changes depend on:

- the stress history as a whole, that is, the degree of overconsolidation and the recent stress history of the soil;
- the history of thermal stresses (cyclic stabilization);
- the time (duration of the cycle and time elapsed from the previous mechanical consolidation).

In analysing the results, it was noticed that there is a linear relationship between the void ratio variation produced by the cycle itself (Δe_{TC}) and the void ratio variations due to volumetric creep in isothermal conditions. This observation, together with the simultaneous absence of both thermal and creep effects ($\Delta e_{TC} = 0$ when $\Delta e_{cr} = 0$) has suggested that thermal loads produce a mere acceleration of mechanical creep phenomena. This interpretation, which provides a global framework for a better understanding of the observed behaviours opens up new possibilities to future research. Indeed, it is obvious that, if on one hand the thermal behaviour may be fully understood only when the mechanism underlying creep deformation in the solid matrix is clear, on the other hand the temperature variations may conveniently be utilised to study creep deformations.

Finally, the experiments carried out to investigate the mechanical behaviour occurring after a temperature cycle showed in all the tests, the presence of 'quasi-preconsolidation' phenomena similar to those produced by volumetric creep deformations in isothermal conditions, but larger in quantitative terms. Such effects, made evident by the increase in stiffness, depend on the stress path followed, and gradually decrease moving away from the stress and deformation states at the end of the temperature cycle. It is likely that the more marked effects of quasi-preconsolidation exhibited by the specimens subjected to temperature loads can be wholly attributed to the larger reduction of void ratio induced by the temperature cycle.

REFERENCE

Bjerrum L. (1967) - *Engineering geology of norwegian normally consolidated marine clays as related to settlements of buildings.* 7th Rankine Lecture, Géotechnique, vol. XVII, n. 2, pp. 81-118.

Burghignoli A., Caruana R. (1979) - *Indagine sperimentale sugli effetti dell'infissione dei pali in terreni coesivi teneri.* RIG, vol. IX, n. 2, pp. 87-93.

Burghignoli A., Desideri A. (1988) - *Influenza della temperatura sulla compressibilità delle argille.* CNR - Gruppo Nazionale di Coordinamento per gli Studi di Ingegneria Geotecnica, Convegno di Monselice, pp. 19-34.

Campanella R.G., Mitchell J.K. (1968) - *Influence of temperature variations on soil behaviour.* Journal of Geotechnical Engineering, ASCE, vol. XCIV, n. 3, pp. 709-734.

Demars K.R., Charles R.D. (1982) - *Soil volume changes induced by temperature cycling.* Canadian Geotechnical Journal, vol. XIX, n. 2, pp. 188-194.

Desideri A. (1988a) - *Compressibilità delle argille in condizioni non isoterme.* Tesi di Dottorato in Meccanica Applicata, Università di Roma «La Sapienza».

Desideri A. (1988b) - *Determinazione sperimentale dei coefficienti di dilatazione termica delle argille.* CNR - Gruppo Nazionale di Coordinamento per gli Studi di Ingegneria Geotecnica, Convegno di Monselice, pp. 193-206.

Finn F.N. (1951) - *The effects of temperature on the consolidation characteristics of remoulded clay.* Special Technical Publication n. 126, ASTM, pp. 65-71.

Habibagahi K. (1973) - *Temperature effect on consolidation behaviour of overconsolidated soils.* Proceedings of the 8th International Conference on Soil Mechanics and Foundation Engineering, vol. X, pp. 12-24.

Leonard G.A., Ramiah B.K. (1959) - *Time effects in the consolidation of clays.* Symposium on time rate of loading in soils. Special Technical Publications of Clays n. 254, ASTM, pp. 116 - 130

Mesri G., Godlewski, P.M. (1977) - *Time and stress-compressibility interrelationship.* Journal of Geotechnical Engineering Division, ASCE, vol. CIII, n. 5, pp. 417-430.

Mesri G., Ullrich C.R., Choi Y.K. (1978) - *The rate of swelling of overconsolidated clays subjected to unloading.* Géotechnique, vol. XXVIII, n. 3, pp. 281-307.

Miliziano S. (1992) - *Effetti della temperatura sul comportamento meccanico delle terre coesive.* Tesi di Dottorato in Ingegneria Geotecnica, Università di Roma «La Sapienza».

Paaswell R.E. (1967) - *Temperature effects on clay soil consolidation.* Journal of Soil Mechanics and Foundations Division, ASCE, vol. XCIII, n. 3, pp. 9-22.

Plum R.L., Esrig M.I. (1969) - *Some temperature effects on soil compressibility and pore water pressure.* Special Report n. 103, HRB, pp. 231-242.

Youssef M.S., Sabry A., El Ramli A.H. (1961) - *Temperature changes and their effects on some physical properties of soil.* 5th ICSMFE, Paris, vol.I, pp.419-421.

SOMMARIO

Deformabilità delle argille in condizioni non isoterme

In questo articolo sono riportati i risultati di una indagine sperimentale di laboratorio volta a determinare alcuni aspetti del comportamento termo-meccanico delle argille. L'attenzione è stata posta allo studio delle deformazioni volumetriche prodotte in condizioni drenate da variazioni cicliche della temperatura di modesta ampiezza (15-60 °C), ed al successivo comportamento meccanico.

In particolare, è stata studiata l'influenza delle sollecitazioni meccaniche sulla compressibilità termica e viceversa l'influenza delle sollecitazioni termiche sulla deformabilità meccanica. Nella sperimentazione sono stati sottoposti a cicli termici drenati terreni argillosi di alta plasticità (CH) ricostituiti e naturali.

I principali risultati riportati in letteratura su questo argomento, mostrano che le sollecitazioni termiche cicliche generalmente producono variazioni di volume di natura irreversibile [Paaswell, 1967; Campanella e Mitchell, 1968; Plum and Esrig, 1969; Demars and Charles, 1982; Burghignoli and Desideri, 1988; Desideri, 1988b]. Mentre tutti gli Autori hanno trovato per le argille normalmente consolidate ($Rp = 1$) un comportamento termicamente contraente (diminuzione di volume), i risultati riguardanti stati iniziali di sovraconsolidazione ($Rp > 1$) non sono concordi; sono stati rilevati, infatti, sia comportamenti dilatanti sia comportamenti contraenti.

Con riferimento alle condizioni iniziali di consolidazione normale, è stato inoltre evidenziato che un ciclo termico produce effetti di 'quasi-preconsolidazione' analoghi a quelli che si producono per 'aging' a causa del comportamento viscoso dello scheletro solido [Plum and Esrig, 1969; Burghignoli and Desideri, 1988].

La ricerca sperimentale è stata finalizzata allo studio delle variazioni di volume di argille normalmente consolidate e sovraconsolidate, prodotte dalle sollecitazioni termiche cicliche ed in particolare a chiarire gli aspetti controversi prima evidenziati. Si è inoltre estesa l'indagine sugli effetti di quasi-preconsolidazione prodotti da un ciclo termico, studiando il comportamento meccanico a seguito di diversi percorsi di sollecitazione. La sperimentazione è stata eseguita impiegando celle triassiali opportunamente modificate allo scopo di consentire il controllo della temperatura e la misura di temperatura e pressione interstiziale all'interno del provino (Fig. 1).

I risultati ottenuti nei cicli termici eseguiti in condizioni di consolidazione normale, sono concordi con quelli riportati in letteratura (comportamento termicamente contraente). La sperimentazione eseguita su argille sovraconsolidate, ha consentito di mettere in evidenza che le deformazioni volumetriche prodotte dal ciclo termico (Δe_{TC}) dipendono, in valore e segno, non solo dal grado di sovraconsolidazione, ma dalla storia delle sollecitazioni nel suo complesso. Infatti, se il ciclo termico è eseguito dopo una fase di scarico, Δe_{TC} assume valori positivi via via crescenti al crescere dell'entità dello scarico (Fig. 5); viceversa, se il ciclo termico viene eseguito ancora per $Rp > 1$, ma dopo che il provino ha subito una fase di ricarico meccanico, Δe_{TC} risulta negativo ed in valore assoluto crescente al diminuire di Rp. Il limite superiore del valore assoluto di Δe_{TC} in ricarico è quello che compete alle condizioni di consolidazione normale, per le quali Δe_{TC} risulta indipendente dallo stato tensionale efficace (Figg. 6 e 7).

L'esecuzione di più cicli termici su una argilla in condizioni iniziali di normale consolidazione, evidenzia un comportamento sempre contraente con valori di Δe_{TC} via via più piccoli. In accordo con quanto già evidenziato da Campanella e Mitchell, [1968] si riscontra, pertanto, un fenomeno di stabilizzazione termica ciclica analogo a quello che si verifica per le sollecitazioni meccaniche cicliche (Tab. III).

Alcuni risultati evidenziano, inoltre, che anche la variabile fisica tempo influenza significativamente la risposta del terreno alle sollecitazioni termiche. In particolare, a parità di ampiezza e di durata del ciclo termico, le deformazioni volumetriche prodotte crescono al diminuire dell'intervallo di tempo che intercorre tra la fine della precedente consolidazione meccanica e l'inizio del ciclo (Tab. IV). In altre parole, l'effetto prodotto da una sollecitazione termica ciclica dipende, oltre che dalla storia delle sollecitazioni meccaniche, anche dalla storia delle sollecitazioni termiche e dalle modalità con cui il ciclo stesso viene eseguito.

L'identificazione delle grandezze che influenzano in maniera più significativa le deformazioni volumetriche irreversibili generate da un ciclo termico suggerisce una stretta correlazione tra deformazioni termiche e deformazioni viscose. Infatti, anche per l'indice di compressione secondaria $C_{\alpha e}$, a cui la velocità di deformazione viscosa è direttamente legata, è possibile stabilire una relazione con la storia delle sollecitazioni meccaniche del tutto analoga a quella evidenziata per le deformazioni termiche irreversibili. I risultati di una prova

di compressione isotropa IL ($\Delta p/p = 1$) condotta sull'argilla di Todi ricostituita (Fig. 8a, b), mostrano che in condizioni di consolidazione normale l'indice di compressione secondaria $C_{\alpha e}$ è positivo (riduzione di volume) e sostanzialmente indipendente dal livello tensionale, risultato già noto per le argille ricostituite [Mesri e Godlewski, 1977]. In scarico, $C_{\alpha e}$ assume un valore praticamente nullo in corrispondenza del primo scarico ($Rp = 2$), mentre negli scarichi successivi, cioè per valori di $Rp > 2$, assume valori negativi (aumento di volume), in valore assoluto crescenti al crescere dell'entità dello scarico. Anche questo risultato è stato ottenuto su altri tipi di argille da Mesri *et al.*, [1978]. In ricarico, $C_{\alpha e}$ assume un valore praticamente nullo in corrispondenza del primo ricarico, ed al crescere dell'entità del ricarico, assume valori positivi via via più grandi. Il limite superiore di $C_{\alpha e}$ in ricarico è rappresentato dal valore che compete allo stato di consolidazione normale.

È evidente la corrispondenza qualitativa tra l'andamento di $C_{\alpha e}$ e di Δe_{CT} con la storia delle sollecitazioni meccaniche.

Per chiarire il tipo di relazione esistente tra la tendenza dello scheletro solido a deformarsi per creep e gli effetti prodotti dal ciclo termico, si è definita una grandezza Δe_{CR} (idonea ad essere confrontata con Δe_{CT}) che rappresenta la variazione dell'indice dei vuoti che si sarebbe prodotta per sola deformazione viscosa nell'intervallo di tempo compreso tra l'inizio e la fine del ciclo termico (Fig. 2). Si noti che Δe_{CR}, oltre a dipendere da $C_{\alpha e}$, e quindi dalla storia delle sollecitazioni meccaniche, dipende anche dal tempo intercorso tra la fine della precedente consolidazione meccanica e dalla durata del ciclo termico. La rappresentazione di Δe_{CT}, per le prove eseguite sull'argilla di Todi ricostituita, in funzione di Δe_{CR}, mostra che nel campo di valori della temperatura in cui si è indagato, esiste una relazione lineare del tipo $\Delta e_{CT} = K \Delta e_{CR}$, con valori di K crescenti al crescere dell'ampiezza del ciclo termico. In altre parole, al crescere della velocità di deformazione viscosa dello scheletro solido, cresce proporzionalmente anche l'effetto prodotto dal ciclo termico (Δe_{CT}); inoltre, quando lo scheletro solido non manifesta apprezzabili velocità di deformazione viscosa ($\Delta e_{CR} = 0$), anche le deformazioni volumetriche prodotte da un ciclo termico sono inapprezzabili ($\Delta e_{CT} = 0$) (Fig. 9).

I precedenti risultati consentono di avanzare l'ipotesi che le deformazioni volumetriche, che si generano per effetto di una sollecitazione termica ciclica, siano dovute al comportamento viscoso dello scheletro solido e che le variazioni di temperatura producano una semplice accelerazione dei fenomeni deformativi in atto nel provino. Questa interpretazione fornisce, inoltre, una giustificazione dei fenomeni di stabilizzazione termica ciclica di cui si è detto in precedenza.

Note che siano la velocità di deformazione viscosa, l'ampiezza del ciclo termico e la sua durata, la relazione trovata permette, per l'argilla di Todi ricostituita, la previsione delle variazioni di volume prodotte da una sollecitazione termica ciclica.

Per indagare sul comportamento meccanico successivo al ciclo termico sono state eseguite alcune prove mirate al confronto tra provini di argilla sottoposti a sollecitazioni termiche cicliche e provini mantenuti a temperatura costante. Le prove sono state eseguite operando contemporaneamente su una coppia di provini, provenienti dallo stesso campione di argilla rimaneggiata. In una prima fase, ciascuna coppia di provini è stata consolidata isotropicamente fino a raggiungere le condizioni di normale consolidazione. Successivamente, uno dei provini è stato sottoposto ad un ciclo termico drenato (18-48-18°C), mentre l'altro è stato mantenuto a tensione efficace e temperatura costanti. Infine, i due provini sono stati sottoposti allo stesso percorso di sollecitazione; in particolare, sono state eseguite prove di compressione isotropa, di compressione triassiale (CIU) e prove di torsione ciclica in colonna risonante.

Nella fase di ricompressione della prova isotropa, i provini mostrano comportamenti qualitativamente analoghi. In entrambi i casi, infatti, la curva di ricarico presenta un tratto iniziale sub-orizzontale, per assumere successivamente la pendenza caratteristica delle condizioni di consolidazione normale. Il passaggio tra i due comportamenti, che avviene in modo graduale, permette di individuare una soglia di snervamento, il cui valore è significativamente maggiore per il provino sottoposto a ciclo termico (Fig. 10).

Analoghi risultati sono stati ottenuti in precedenza da Plum ed Esrig [1969] e da Burghignoli e Desideri [1988]. L'effetto del ciclo termico va progressivamente riducendosi al crescere dell'entità del ricarico e quando si ritorna sulla linea della consolidazione normale il materiale ha perso completamente 'la memoria' della sollecitazione termica subita. La sollecitazione termica ciclica ha prodotto un incremento del modulo di compressibilità secante K' che, in corrispondenza di $\varepsilon_v = 0.01$ è approssimativamente del 35%.

In definitiva, il ciclo termico produce effetti analoghi a quelli prodotti dalle deformazioni viscose, noti in letteratura come effetti di quasi-preconsolidazione [Bjerrum, 1967; Leonards e Ramiah, 1960]. Le maggiori deformazioni volumetriche subite dal provino sottoposto a ciclo termico, accentuano ed esaltano questi comportamenti.

I risultati relativi alle prove di compressione triassiale (Fig. 11), mostrano che le curve q-ε_a relative ai provini che hanno subito il ciclo termico, si dispongono al di sopra delle corrispondenti curve relative ad i provini mantenuti a temperatura costante. Al crescere del livello di carico le differenze tendono a ridursi fino ad annullarsi in corrispondenza delle condizioni ultime. Il ciclo termico produce un incremento del modulo secante E_u, che per $\varepsilon_a = 0.01$ è del 15% circa, e che tende ad annullarsi al crescere della deformazione assiale.

Infine, i risultati ottenuti in colonna risonante (Fig. 12), mostrano che il provino sottoposto al ciclo termico presenta una rigidezza maggiore di quella del provino tenuto a temperatura costante, con un incremento del modulo iniziale Go del 18% circa. Come in precedenza al crescere della deformazione le risposte dei due provini tendono a coincidere.

In conclusione, tutti i risultati illustrati mostrano che una sollecitazione termica ciclica applicata ad una argilla normalmente consolidata induce uno stato di quasi-preconsolidazione, l'entità di tale effetto dipende dal percorso di sollecitazione seguito e risulta significativa in un modesto campo di tensioni e di deformazioni attorno allo stato iniziale. Al crescere delle tensioni o delle deformazioni, infatti, il terreno perde gradualmente 'memoria' del ciclo termico subito in precedenza. Questo comportamento è qualitativamente analogo a quello che si riscontra per accumulo di deformazioni viscose in condizioni isoterme, ma quantitativamente più accentuato. Le maggiori deformazioni volumetriche sviluppate dai provini per effetto del ciclo termico, possono da sole giustificare anche quantitativamente l'amplificazione dei comportamenti già evidenziati. L'aver riconosciuto che le deformazioni volumetriche prodotte da variazioni di temperatura sono ben correlabili con quelle dovute alla viscosità strutturale, rende plausibile l'ipotesi che le prime abbiano la stessa natura delle seconde e che entrambe derivino dalle stesse modificazioni strutturali dello scheletro solido. Questa ipotesi richiede ulteriori conferme sperimentali; infatti, non si può escludere che le sollecitazioni termiche cicliche possano anche indurre effetti di 'quasi-preconsolidazione' a prescindere dalle deformazioni volumetriche accumulate.

L'avere individuato il ruolo svolto dal comportamento viscoso dello scheletro solido nei processi deformativi connessi all'applicazione delle sollecitazioni termiche, ha consentito di inquadrare in maniera organica i differenti comportamenti sperimentali osservati, aprendo la strada a futuri sviluppi della ricerca. Appare evidente, infatti, che se da un lato il comportamento termico potrà essere interamente compreso quando saranno chiari i meccanismi che governano i fenomeni di deformazione viscosa, dall'altro la variabile temperatura potrà utilmente essere impiegata per lo studio dei fenomeni viscosi.