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SHRINKING AND SWELLING BEHAVIOR OF PINDOS AND IONIOS FLYSCH SEDIMENTS ON TUNNELING

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ABSTRACT

The sedimentary layers of Pindos-Flysch (graded turbidites) showed no significant disintegration problems, deformations or swelling (floor heave) by excavations. "Slaking" of the Pindos pelites was visible in tunnel or open road cuts only after some months due to repeated wetting and drying. On the contrary, wall protection with torkretbeton was needed immediately after excavations of the Tailrace Tunnel to avoid the rapid breakdawn of Ionios sediments (mud turbdites). Observations over a longer period of time (months) revealed considerable deformation of tunnel profile as well as floor heave. The capillary suction pressures, occuring under moisture conditions of the "linear schrinkage," cause 80 % of the total swelling/shrinkage values related to 13-18 % decrease of initial water content and lead to rock breakdown. The "linear schrinkage" takes place under 92-100 % moisture conditions and is responsible for the development of a zone of loosening up to ca. 60 cm depth under the tunnel surface. Floor heave are connected with updoming processes due lateral layer expansion of the Ionios pelites under the floor of Metsovitikos valley.

ΠΕΡΙΛΗΨΗ

Τα ιζήματα του Πινδικού Φλύσχη (καλά διαβαθμισμένοι Τουρμπιδίτες) δεν παρουσίασαν ιδιαίτερα προβλήματα αποσαθρωσης ή ευστάθειας κατά τη διάρκεια και μετά το πέρας της διάνοιξης των σηράγγων. Φαινόμενα αποσάθρωσης στα παραπάνω στρώματα ήταν ορατά στις σήραγγες και στις ανοιχτές εκσκαφές μόνο μετά από διέλευση αρκετών μηνών εξ αιτίας επαναλαμβανόμενης ξήρανσης και ύγρανσης.

Αντιθέτως μέτρα προστασίας με εκτοξευόμενο σκυρόδεμα ήταν απαραίτητα, αμέσως μετά τις εργασίες εκσκαφής της Σήραγγας Φυγής, για να αποφευχθεί η ταχύτατη αποσάθρωση των ιζημάτων του Ιόνιου Φλύσχη (αδιαβάθμητοι Τουρμπιδίτες). Κατόπιν μετρήσεων πολλών μηνών διαπιστώθηκαν σοβαρές διογκώσεις του δαπέδου της σήραγγας καθώς επίσης και παραμορφώσεις της διατομής της, με επιπτώσεις στην ευστάθειά της. Με εργαστηριακές έρευνες προσδιορίστηκαν οι μηχανικές παράμετροι των πετρωμάτων αυτών καθώς και οι επιπτώσεις στη συνοχή τους που απορρέουν από τη δράση των δυνάμεων των τριχοειδών κάτω από συνθήκες μεταβαλλόμενης υγρασίας της ατμόσφαιρας. Οι δυνάμεις των τριχοειδών, που αναπτύσσονται στην περιοχή της "γραμμικής συρίκνωσης", μπορούν να προκαλέσουν το 80% της συνολικής συρίκνωσης ή διόγκωσης, με ταυτόγχρονη μεταβολή της υγρασίας του πετρώματος από 13-18 %, καθώς και παράλληλη μείωση της συνοχής του. Η "γραμμική συρίκνωση" λαμβάνει χώρα σε συνθήκες υγρασίας της ατμόσφαιρας από 92-100 % και είναι υπεύθυνη για τη δημιουργία μιας ζώνης χαλάρωσης μέχρι 60 cm κάτω από την επιφάνεια της σήραγγας. Οι διογκώσεις του δαπέδου και οι παραμορφώσεις της διατομής οφείλονται σε φαινόμενα πλευρικής διαστολής των Πηλιτικών στρωμάτων, τα οποία μπορούν να οδηγήσουν στην αναθόλωση των υποκείμενων στρωμάτων της κοιλάδας του Μετσοβίτικου.

INTRODUCTION

Swelling and shrinkage of pelitic rocks due to wetting and drying (hydration/dehydration) lead to their complete breakdown. The process is called "slaking" and its mechanism was studied by DUNN & HUDEC (1966) and HUDEC (1977). Field observations and laboratory investigations

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on slaking bahavior of pelites in SW-Germany are described by LEMPP (1979), MERKLEIN (1982), RUCH (1986), and WETZEL (1986). Sand/clay content, carbonate content, the pore system of the rock and its permeability are the most important factors influencing rock slaking, which is discussed in the publications of the authors mentioned above.

Capillary tension, which is directly proportional to surface tension of water and inversely to the capillary size, causes a suction pressure in the minute pore space. The developed suction pressures created by drying of the rock may be greater than the maximum lithostatic pressure that the sediment has experienced and thus can lead to its further compaction due to shrinkage and decrease of its porosity. At 50 % relative humidity, the potential capillary tension reaches 95 MPa (EINSELE, 1983). This stress value is, for example, much greater than the uniaxial strength values, which range from 10 to 30 Mpa for the investigated pelitic rocks.

Floor heave during tunneling was most likely related to the types and amount of clay minerals (especially corrensite) in anhydrite bearing rocks. The respective swelling pressure seems to be directly dependent on the corrensite content, i.e. the floor heave is almost independent of the anhydrite content of the rock (HENKE, 1976). According to FECKER (1981), the primary stress state of the rock mass is the most influential factor of six case studies of floor heave and tunnel deformations.

SELECTED ROCK MATERIAL

The investigated pelitic rock samples were selected during excavations of the Tailrace Tunnel (Ionios Flysch) and the Power Tunnel (Pindos Flysch) of the Pigai Aoos Hydroelectrical Project in northwest Greece (PPC, 1978) (Fig. 1).

The Pindos Flysch lithostratigraphic column (Dan-Priabon) in the area of Power Tunnel consists of well graded grey silt to claystone turbiditic layers, pelagic bioturbated claystones, and massive turbiditic sandstone beds. These are followed by red, well graded or massive, shales and marls at the basis and a serie with thickening upward massiv turbiditic sandstones beds at the top. Ungraded pelitic beds and debris flow conglomerates make up the sediments of the Ionios Flysch (Lower Oligocene-Burdigal) in the area of the Tailrace Tunnel.

The samples selected consist of graded siltstones (SI) and bioturbated pelagic claystones (T) from the Pindos Flysch (Power Tunnel) and ungraded pelites (IF) from the Ionios Flysch (Tailrace Tunnel).

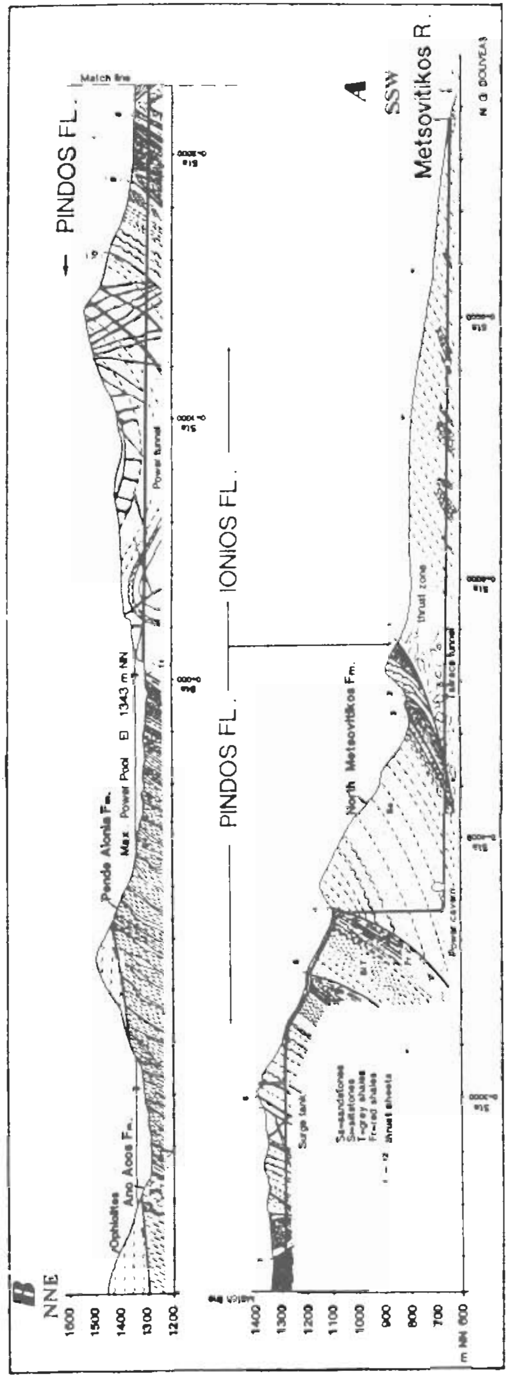


Fig. 1: Lithostratigraphy of Pindos Flysch (North Metsovitikos, Pende Alonia, and Ano Aoos Formations, DOUVEAS G.N., 1990) in the area of the hydroelectrical Projekt Pigai Aoos.

EXPERIMENTAL PROCEDURES AND RESULTS

The initial parameters of the selected rock samples

The well graded turbidites (SI) and the pelagic claystones (T) of Pindos Flysch have a considerably lower porosity, initial water content, and a lower specific surface but a higher carbonate content than the ungraded mud turbidites of the Ionios Flysch (Tab. 1).

	PINDOS FLYSCH		IONIOS FLYSCH
	(T)	(SI)	(IF)
max. water content (%)	2.38	1.56	6.4
grain density g/cm^3	2.74	2.73	2.7
wet bulk density g/cm^3	2.65	2.68	2.5
dry bulk density g/cm^3	2.59	2.64	2.3
porosity *n* (%)	6.38	4.00	14.8
calcium carbonate (%)	26.00	32.00	16.0
surface area, *Sg* m^2/g	13.80	10.70	19.3
clay minerals	illite chlorite	illite chlorite	illite chlorite corrensite

Tab. 1: Initial parameters and clay mineral fractions of the investigated rock samples

The short-term deformation behavior under uniaxial compressive stress showed that the rocks SI and T are strong to moderately strong with strength values between 11 and 30 MPa. They deform elastically to plastically (classification after DEERE and MÜLLER, 1966). The pelites (IF) have a low compressive strength and undergo plastic deformation during loading (Fig. 2).

Water equilibrium states, the water tension curves

The samples were cored perpendicular to the bedding plane. Cores of 42 mm length and 16 mm diameter were produced to determine the shrinkage or swelling character of IF, T and SI pelites under 98.8%, 92%, 85%, 45%, 35%, 5% relative humidity (r.H) conditions. This was carried out with the help of climatic simulators, i.e. six exsicators, in which various relative humidity conditions could be created by using the appropriate salt solutions under constant temperature (s. MERC, 1982).

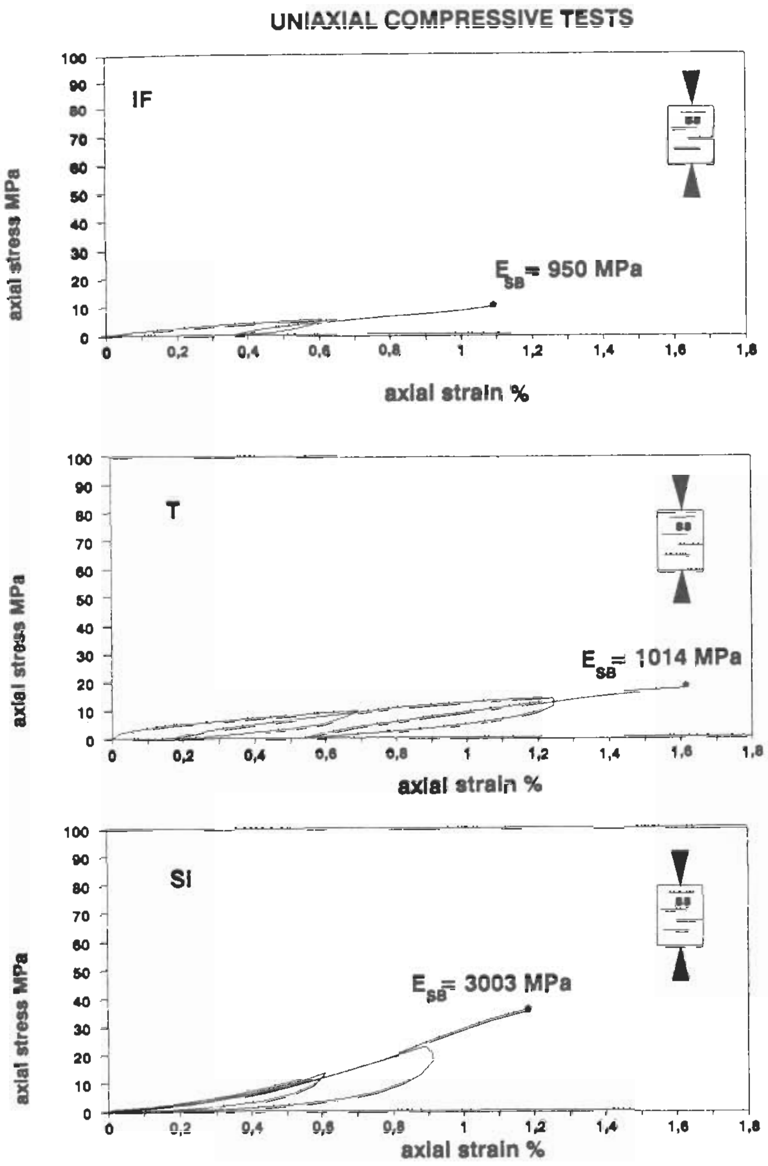


Fig. 2. Behavior of IF, T, SI samples under uniaxial compressive stress; IF: weak with plastic deformation, T: moderately strong with plastic to viscous deformation, SI: strong with elastical deformation.

Three axes, namely X, Y, and Z (Z normal to bedding plane, X and Y parallel to bedding plane and X vertical to Y) were measured to determine the shrinkage or swelling values. In addition, the changes in water content were noted. At the beginning of the tests all the cores were water-saturated. Some of the results, which are plotted in terms of time versus water content, versus shrinkage values in X, Y, Z directions, and versus volumetric shrinkage values, are shown in Fig. 3, diagr. 1-3. The left sides of the diagrams describe the shrinkage/swelling, dehydration/hydration equilibrium states according to the respective relative humidities. The right sides of the diagrams describe the process of rock deconsolidation due to repeated drying (24 h at 92% r.H) and wetting (immersing 24 h).

A distinct equilibrium state with a specific water content of each core corresponds to every humidity condition. According to the theory of sorption properties of porous media to every moisture state of air, i.e. vapor pressure, corresponds a distinct range of capillaries which hydrate or dehydrate (KLOPFER, 1974, p.21). During this process the capillary tensions decrease or increase according to the degree of saturation. The related stress values are given by EINSELE (1983; Fig. 5). During the increase of the air moisture the capillaries regain the equivalent amount of water lost during the last dehydration. After 13 cycles of rewetting/redrying, the following alterations in the IF, T and SI cores were recorded (Fig. 3, diagr. 1-3): Increase of the water content by about 8%, 6% und 2,7% of the initial values of the IF, T and SI unweathered cores, respectively. These recorded amounts of absorbed water are exchangable in 92-100 % air moisture. In addition, a volume/porosity increase i.e. swelling, deconsolidation or loosening of all cores, and especially of the cores IF, after each cycle of drying/wetting was recorded. The cores of IF began to deconsolidate with the development of the first joints due to stratification immediatelly after the first rewetting. Further drying and rewetting under 92-100 % conditions lead to the creation of more cracks parallel to stratification (Fig. 3). The anisotropical shrinkage and swelling along the three directions X, Y, and Z affects the grain to grain bonds and initiates further cracks along all directions leading to core desintegration in smaller peaces or "slacking". Figure 4 shows the process of slacking and the change of sample water saturation, which decreases due to the increase of the trapped air within the cracks as the core's loosening proceeds. In Figure 5 the diagramms 1-3 portray the water tension curves, i.e. the respective equilibrium states of core moisture balanced between 0-100 % relative humidity conditions and the pore size distribution of any sample. The IF water tension curves, Fig. 5, diagr. 1, differ from the tension curves of T and Si in that they have a higher percentage of great voids in the pore system. The IF, T and Si samples show high amounts of adsorbed water, namely 83-88 % for the IF, 91-93 % for the T, and 94-98% adsorbed water for the SI cores at 98,8 % relative humidity, i.e they are sorption sensitive (HUDEC, 1975).

CORE DECOMPACTION AND LOOSENING DUE TO WETTING AND DRYING

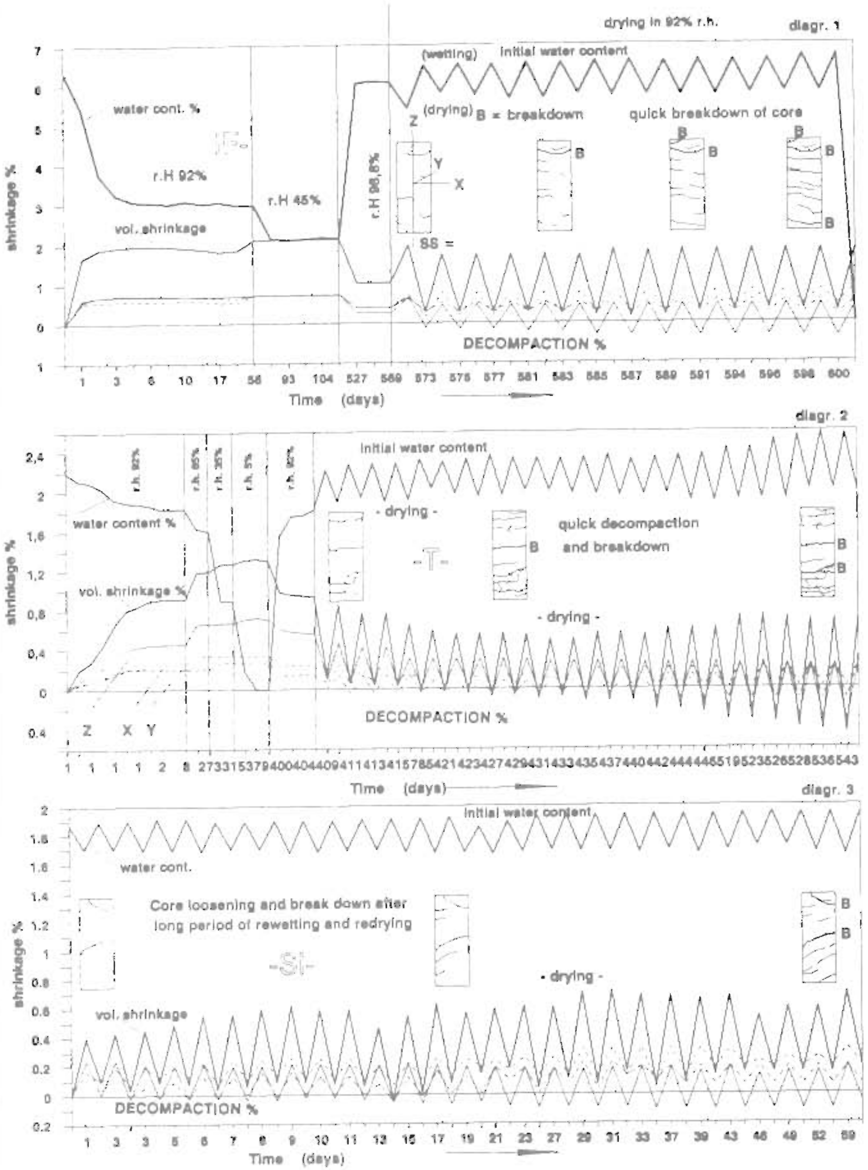


Fig. 3: Swelling and shrinkage rates of the IF, T, SI core samples under varying relative humidity conditions; note the increase of porosity/decompaction or loosening after every phase of hydration/dehydration; drying succeeds in 92 % relative humidity and saturating after immersion of sample in water for 24 h; at the beginning of tests all samples was water saturated, fresh and unweathered.

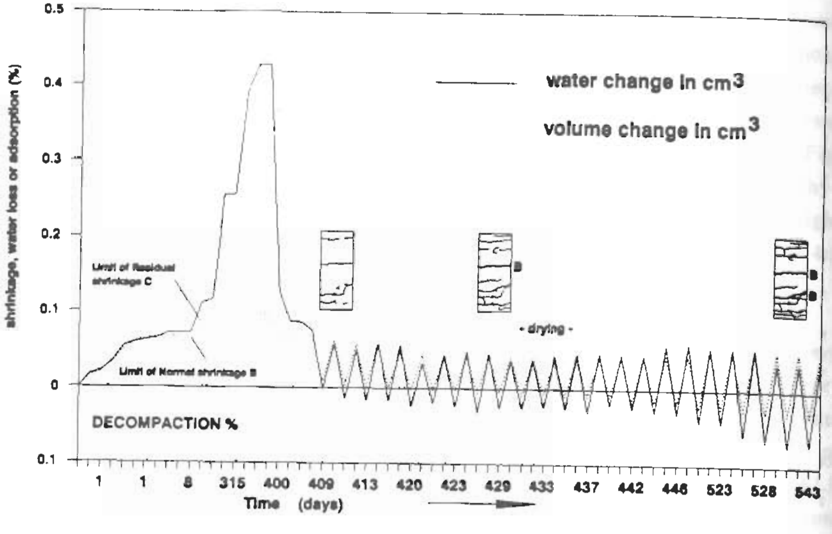
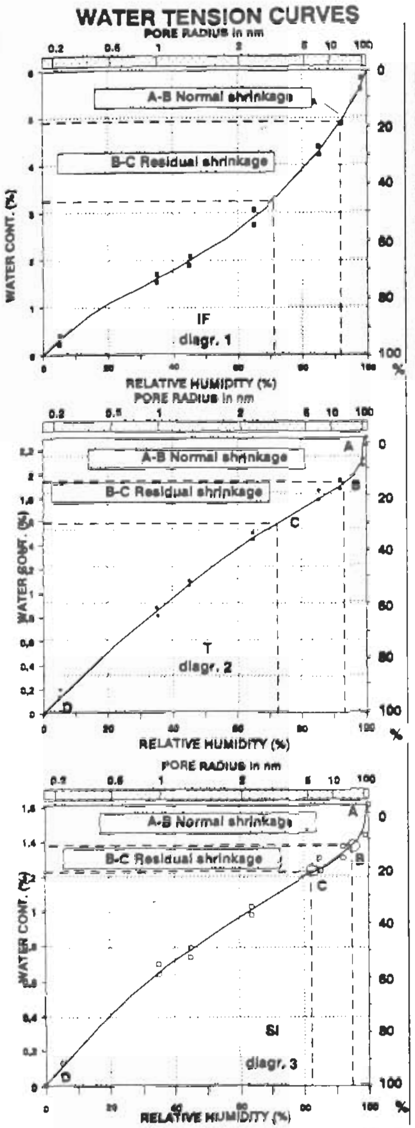
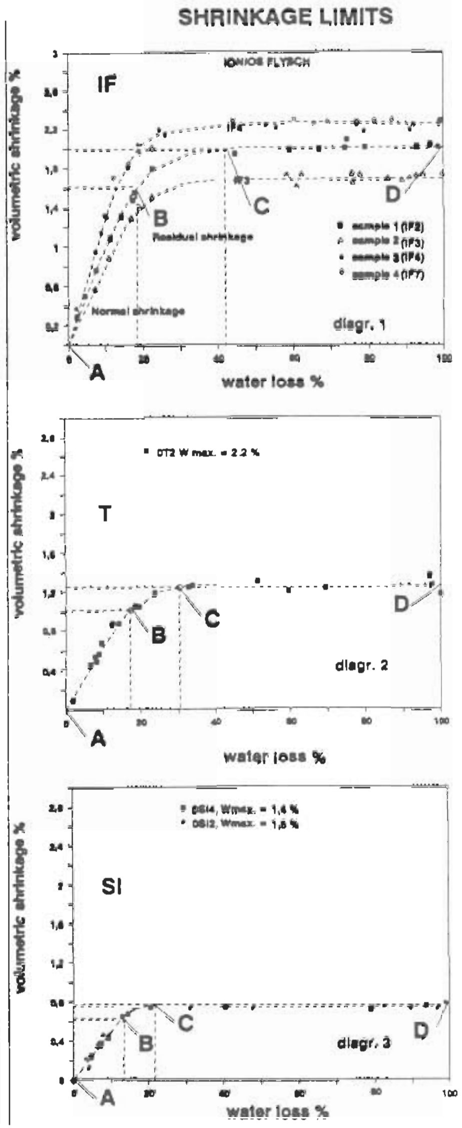


Fig. 4: Decrease of sample's water saturation by repeated drying and wetting; note the state of water saturation of the core at the limmits of "linear" and "residual shrinkage"; limits B and C.

Limiting of shrinkage/swelling process

All cores showed a maximal shrinkage limit during drying. The shrinkage process is divided into three stages: A-B, B-C, and C-D, Fig. 6, diagr. 1-3. In stage A-B (the beginning of drying), every water loss of the sample recorded in cm^3 was equal to the volumetric change as well. This means the sample retained water saturated during its dehydration in stage A-B. The relationship of the two parameters here is linear. The shrinkage rate in stage (A-B) is called **"linear shrinkage"**, with the characteristic "shrinkage limit" at point B. All cores had reached their shrinkage limit (B) after 15-18% decrease of their initial water content. Further drying gave rise to a small decrease of the core volume described as **"residual shrinkage"**, stage B-C in which the water loss is volumetrically greater than the shrinkage. Here the cores are no more water saturated and no further change of core's volume takes place hier any more (Fig. 7). Strong capillary suction pressures keep the cores in a compressive state which does not change as long as the voids and capillaries remain unsaturated. It is the reason that the core does not swell by any moisture increase in the range of relative humidities of the stage C-D (Fig.7).





A = Limit of normal shrinkage B = Limit of residual shrinkage

Fig. 5: Water tension curves showing the pore size distribution of the investigated samples.

Fig. 6: Limitation of the shrinkage/swelling process; B=limit of the "linear shrinkage", C=limit of the "residual shrinkage".

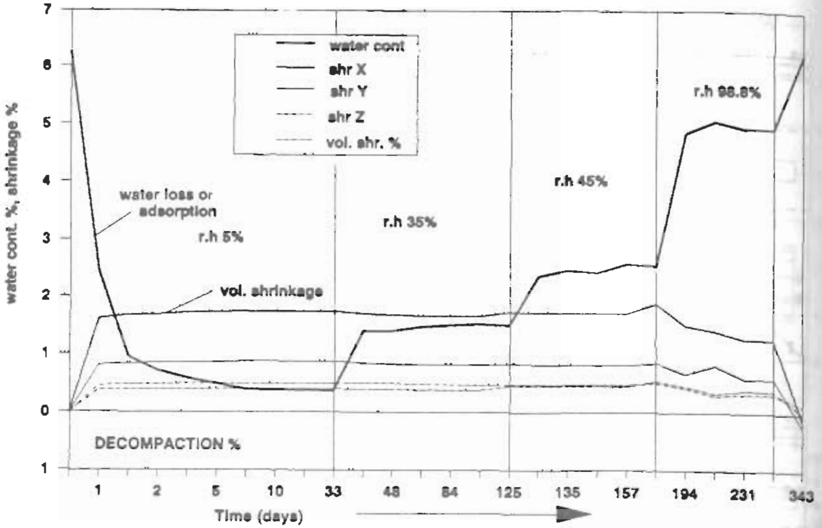


Fig. 7: Swelling of core is not possible so long the pores and capillaries remain unsaturated in the range of the relative humidities of the "residual shrinkage".

The greatest values of swelling or shrinkage occur only in a water saturated state of the cores, i.e. stage A-B and under relative humidity conditions varying between 92-100 % related to 13-18 % decrease of initial water content (Fig. 6). This proves the importance of capillary suction pressures on rock deconsolidation and disintegration. In the stage A-B, the expandable clay minerals cannot swell or shrinkage because the pores and capillaries are still water saturated. In addition, the action of expandable clay minerals, if possible in the stage A-B, could be buffered by the great pore spaces, which varies between 20-110 nm (Fig. 5). The dehydration of the expandable clay minerals can only take place after most of the great pores and capillaries begin to empty, namely in stages B-C and more possibly in C-D, i.e. under high vapor pressure or high stress conditions in the rock mass. The maximal recorded volumetric shrinkage (linear + residual shrinkage) of the IF cores was 1.7% - 2.2%, of the T cores about 1.2%, and of the SI cores about 0.8%, all given in percent of core volume in the saturated state (Fig.6).

The clay minerals characteristics during dehydration

Corrensite is the only expandable mineral included in the samples of IF pelites and was determined using X-ray diffraction techniques. The clay mineral fractions of the T and SI samples are shown in Tab.1.

The non-expandable component of corrensite is similar to the unit layer of chlorite and has a constant spacing of 14 Å. The expandable member of corrensite, a montmorillonite-like layer, has a spacing of about 10Å in an oven dry state. The spacing of both components of corrensite together under oven dry conditions is 24Å. Hydration causes corrensite to expand to 29Å (LIPPMAN, 1976). Under "water-excess" conditions corrensite attains a spacing of 33Å. The behavior of corrensite under a wide range of relative humidity values are not exactly known. But it can be supposed that corrensite, which has a interlayer spacing of ca. 9Å under water saturated conditions, cannot be dehydrated as long as pores having larger radii (20-100 nm) are still filled with water. Dehydration of corrensite becomes possible over 100 MPa ca. 50 % r.F. vapor pressure or stress values. Dehydration of corrensite is thus not possible in the range of linear shrinkage A-B. The stage C-D with low relative humidities and high vapour pressures outlines the most suitable conditions under which a dehydration of corrensite seems likely (Fig. 5, diagr.1)

The fresh unweathered IF, T, SI rock samples were immersed in water for over two years and they showed no water absorption, i.e. they were water saturated under the primary conditions in the rock mass and no disintegration. This suggests that the Ionios pelites was not in a state of dehydration before mining of Tailrace Tunnel. This means that the expandable clay minerals like corrensite are in the pelites of Ionios flysch water saturated and consequently they can not swell. On the other hand the action of capillary pressures by hydration/dehydration can lead, as shown above, to rock disintegration. The intensity of this process is mainly depended on the degree of compaction of the sediment.

CONCLUSIONS

The ungraded mud turbidites of the Ionios Flysch differ from the Pindos graded turbidites in higher porosity, carbonate content, specific surface area and in higher content of organic matter. Uniaxial compression tests show that the Ionios sediments have a low compressive strength and undergo plastic deformation during loading. The clay mineral fraction of Ionios sediments consists of expandable corrensite and non expandable illit and chlorite. The Pindos sediments contain only illite and chlorite. The Ionios sediments swell or shrink during hydration/dehydration more than the Pindos ones. The water tension curves show that both groups of sediments have a well developed pore system composed of micropores (<100 nm). The capillary suction pressures occuring under moisture conditions of the "linear schrinkage" cause 80 % of the total swelling/shrinkage values related to 13-18 % decrease of initial water content leading to rock breakdown. The "linear schrinkage" takes place under 92-100 % moisture conditions; during this remains the rock water saturated. Further drying gives rise to a small value of shrinkage described as "residual shrinkage" and leads to a decrease of water saturation of the rock. At this stage, the rock is in a compressive state due to strong capillary tension caused by the high vapour pressure which causes as well as in this stage the dehydration of the expandable clay minerals. Moisture increase releases the capillary tensions and increases the water saturation giving rise to rock swelling again. The repeating hydration/dehydration leads to rock swelling and deconsolidation, causing in this way a rockmass loosening in a depth up to ca. 60 cm under the tunnel surface. Floor heave and tunnel lining deformations, observed in the tailrace tunnel, are most likely connected to updoming processes due to lateral expansion and vertical rebound of the Ionios pelites under the floor of Metsovitikos valley.

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