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Evaluation of compressibility of glacial till contaminated with hydrocarbons on the basis of CRL tests results

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ABSTRACT

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The article presents the results of CRL research on glacial till contaminated with JET A1 aviation fuel and mineral oil 15W40. The conducted research has shown that the compressibility of fine grained soils contaminated with hydrocarbons during a constant rate of loading tests depends on the physical properties of the soil, properties of oil contaminants, their content in the soil pores as well as the adopted loading velocity. The implemented laboratory test program shows that the contamination of glacial till with hydrocarbons increases their compressibility. Moreover, this research shows that the CRL test method may be recommended in the compressibility research of fine grained soils contaminated with hydrocarbons.

Key words: CRL test; Soil compressibility; Hydrocarbons; Glacial till.

INTRODUCTION

Hydrocarbons are a group of potential contaminants, which may be a real threat to the natural environment, including the ground for engineering objects. Research conducted so far on the influence of petroleum products on the behavior of mineral soils clearly indicates that these compounds significantly modify the geological and engineering properties of contaminated soils (Ahmed et al. 2009; Kermani and Ebadi 2012; Barański 2000; Echeverri-Ramirez *et al.* 2015; Izdebska-Mucha and Trzciński 2021; Stajszczak 2021). These modifications are expressed in the change in the value of physical and mechanical parameters of polluted soil, often in a less favorable direction from the designer's point of view. The studies carried out so far using scanning electron microscopy have documented changes in the microstructure of the soil as a result of pollution by hydrocarbons (Tuncan 1997; Izdebska-Mucha and Trzciński 2007, 2011; Izdebska-Mucha *et al.* 2011; Khosravi *et al.* 2013; Stajszczak 2019). Changes in the microstructure of soils contaminated with petroleum products are accompanied by changes in physical properties, which are expressed by the grain size distribution, bulk density, consistency limits and parameters describing the pore space of soil (porosity and void ratio). Introduction of non-polar liquids into the soil pores finally causes an increase in compressibility. The observed changes very often depend on the types of contaminations and their content in the pores of soil (Srivastawa and Pandey 1997; Kaya and Fang 2000; Olchawa and Kumor 2008; Singh *et al.* 2008; Nazir 2011; Di Matteo *et al.* 2011; Karkush *et al.* 2013). This fact raises the need to continue the scientific research carried out so far by other authors, with particular emphasis on the possibility of applying research methods not used so far in the study of contaminated soils.

COMPRESSIBILITY OF FINE GRAINED SOILS – LABORATORY TEST METHODS

In engineering geology, soil compressibility is understood to be a reduction in soil volume as a result of a change in the stress state. Increases in the effective stress in the ground may be caused by the foundations of engineering objects (buildings, roads, bridges), as well as by lowering of the groundwater table (construction drainage, mine drainage). The change in the volume of soil as a result of increasing the load is caused by (Lambe and Whitman 1977; Holtz and Kovacs 1981; Wiłun 1987; Kaczyński 2017):

– reduction in the volume of the pore space due to the mutual displacement of particles and grains,
– deformation of particles and crushing of individual grains,
– reduction in the thickness of the electric double layer (cohesive soils),
– removal of air and water from the pores of the soil.

Soil compressibility depends on its physical properties. These properties are expressed i.e. by the grain size distribution, porosity, mineral composition of the clay fraction and the bulk density. The stress history (pre-consolidation) and the nature of the microstructural features of the soil (cementation) are also important.

In the laboratory, compressibility tests can be performed using two types of equipment – an edometer and a consolidometer. In soil compressibility studies, two ways of applying a load on surface of a soil sample are distinguished. These are (Head 1986):

– incremental loading (*IL test*).
– continuous loading (*CL test*).

The incremental loading test can be performed in an oedometer or in a consolidometer (slurry consolidometer, Barden Rowe cell). It should be noted, that due to the simple laboratory procedure, ease of interpretation of measurements and relatively low cost of preparing a stand for tests, the oedometer is currently the most commonly used device to assess soil compressibility during laboratory tests of soil samples (PN-88/B-04481; ASTM D2435-04; PN-EN ISO 17892-5:2017).

Due to the development of available technologies, in the second half of the 20th century, CL tests were introduced into laboratory practice (Lowe *et al.* 1969; Smith and Wahls 1969; Aboshi *et al.* 1970; Wisa *et al.* 1971). Compressibility tests with continuous loading can be performed according to one of the following variants (Rowe and Barden 1966; Head 1986; ASTM D4186-06):

– constant rate of loading (*CRL test*),
– constant rate of strain (*CRS test*).

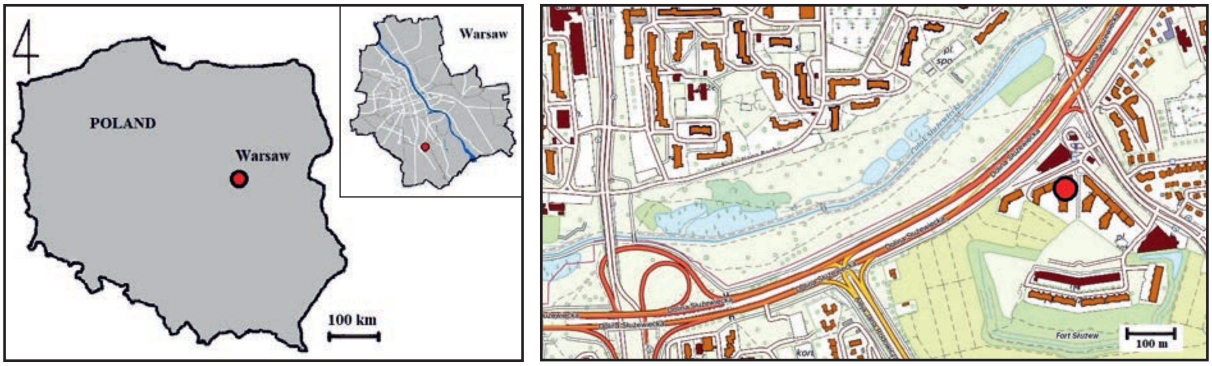
CRL tests, similar to tests with incremental loading, can be performed in a Barden-Rowe cell or in a slurry consolidometer. Tests with constant rate of strain are commonly performed in a CRS cell mounted in a load frame. In this case the use of a load frame ensures a constant rate of strain during the test. From a practical point of view, very important is the fact, that CL tests have a shorter test time than traditional tests with incremental loading. Moreover, the equipment used during the test with continuous loading allows the pore pressure to be measured, which is obligatory during performing this type of research. These factors are an unquestionable advantage of CL tests (Sinha and Bhargava 1992; Soumaya 2005; Kowalczyk 2007; Dobak 2008; Dobak *et al.* 2015; Soumaya and Kempfert 2010; Stajszczak 2019). The successful application of CL tests in the assessment of the filtration and consolidation properties of fine grained soils suggests, that this method may also be a useful tool used in the assessment of deformation characteristics of fine grained soils contaminated with hydrocarbons.

MATERIAL AND METHODS

Samples of the Odranian glacial till, which is common in Poland, were selected for laboratory tests. The samples were taken from the walls of the excavations which were made for the foundations of the Fort Służew housing estate in the Ursynów district (Warsaw) (Text-figs 1, 2). All soil samples had a natural, undisturbed structure. On the basis of visual description (according to PN-EN ISO 14688-1:2018), the collected soil samples were classified as *CLAY with sand*. Physical parameters of the tested soil were determined for intact samples and for soil pastes. The determination of natural water content, consistency limits, particle size distribution and bulk density were carried out in accordance with the recommendations given in following standards: PN-B-04481: 1998; PN-EN ISO 17892-1:2015; PN-EN ISO 17892-2:2015; PN-EN ISO 17892-12:2018. The mineral composition of the studied soil samples was estimated on the basis of derivatographic analysis (thermal analysis). Thermal analysis was performed on a TA Q600 apparatus. Interpretation of the obtained results was carried out according to the methodological recommendations of Kościówko and Wyrwicki (1996).

In order to investigate the influence of petroleum products on the physical properties of tested soils, soil pastes were prepared. Petroleum products were represented by JET A1 aviation fuel and mineral oil 15W40. The procedure of preparing the soil pastes consisted of six stages. They were as follows:

1) grinding the intact samples into smaller pieces,
2) mixing by hand and homogenization,
3) drying in room conditions,



Text-fig. 1. Location of the place where the samples of glacial till were collected for laboratory tests (red point).

4) contamination with petroleum products in the amount of 2 and 10% in relation to the mass of the soil skeleton,

5) increasing the water content of contaminated soil paste to the value corresponding to 1.0–1.1 w_L of unpolluted soil samples,

6) consolidation of soil paste under a effective stress equal 20 kPa. The time of consolidation was 4–5 weeks.

During the preparation of uncontaminated soil pastes, step 4 was omitted.

When the consolidation of the soil pastes was completed, samples for compressibility tests were collected. Compressibility tests were carried out in a Barden Rowe cell. In these tests, soil samples were loaded with a constant rate of loading (*CRL test*). During CRL tests of unpolluted and polluted samples the applied loading velocity was 25 and 100 kPa/h (Text-fig. 3). Each CRL test was stopped when the total stress applied on the sample surface reached 2000 kPa (except for the CRL test performed on a soil sample named FS Jet A1 10%, loading velocity 25 kPa/h). The CRL tests were carried out for soil pastes prepared according to the procedure described above.

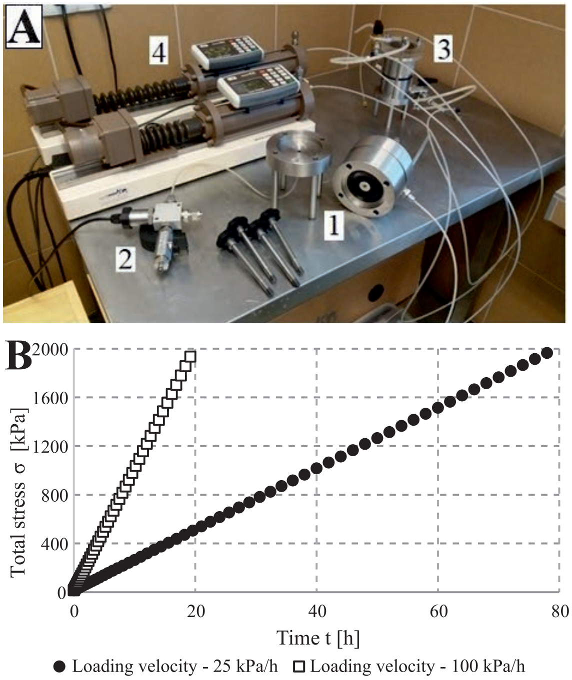
In order to evaluate the effect of the destruction of the natural soil structure on its compressibility, a CRL test of the intact sample was also performed. In this study, a saturation procedure was performed at a back pressure of 416 kPa. After completion of the saturation stage the CRL test was carried out. Adopted loading velocity was 100 kPa/h.

The procedure of preparing soil pastes makes it possible to meet the assumptions of the consolidation

Text-fig. 2. Location of sampling glacial till samples: A – general view of the excavation, B – view of the excavation wall with visible glacial till

Parameter	Formula	Unit
Effective stress	$\sigma' = \sigma - \frac{2}{3}u_b$	[kPa]
Parameter of pore water pressure	$C_{CL} = \frac{u_b}{\sigma}$	[-]
Axial strain	$\varepsilon = \frac{\Delta H}{H_i}$	[-]
Modulus of compressibility	$M_k = \frac{\Delta\sigma' \cdot H_{i-1}}{H_{i-1} - H_i}$	[MPa]
Compression index	$C_C = -\frac{\Delta e}{\Delta log\sigma'}$	[-]
Compressibility modulus ratio	$CM_R = \frac{M_{UP}}{M_P}$	[-]

Table 1. The Parameters used for the evaluation of the compressibility of soil samples during performed CRL tests. Explanations: u_b – pore pressure [kPa], σ – total stress [kPa], σ' – effective stress [kPa], H – sample height [m], e – void ratio [-], M_{UP} – modulus of compressibility determined during CRL test of unpolluted soil sample [MPa], M_P – modulus of compressibility determined during CRL test of soil sample polluted with hydrocarbons [MPa].



Text-fig. 3. Characteristic of performed Constant Rate of Loading tests. A – Stand for performing CRL tests of fine grained soils contaminated with hydrocarbons, B –The change of total stress value versus time during performed CRL tests. Explanations: 1 – Barden-Rowe cell, 2 – pore pressure transducer, 3 – interface dedicated to the tests of contaminated soils, 4 – volume and pressure controller.

theory, which takes into account that all pores are filled with water (the saturation of the tested soil sample was evaluated on the basis of the value of the pore water pressure parameter C_{CL}). Moreover, the homogeneity of the soil pastes and the complete control of the degree of contamination influenced the comparability of the obtained results positively. The implemented program of laboratory tests made it possible to assess the impact of the tested petroleum products and the adopted loading velocity on the values of the compressibility parameters of soil pastes prepared from glacial till from the Warsaw area. The parameters used for the evaluation of the compressibility and saturation of the tested soil samples are presented in Table 1.

The petroleum products used in the research have different physical and chemical properties (viscosity, density). Thanks to this, it was possible to take into account this variability in the analysis of the changes taking place in the physical and deformation properties of tested soil pastes after contamination. The physical parameters of the petroleum products used during laboratory tests are presented in Table 2.

RESULTS

Physical properties of tested soil

The results of the laboratory tests indicate that glacial till from the Warsaw area (Ursynów district) formed during Middle-Polish glaciations in a natural state should be considered as fine grained soil (PN-EN ISO 14688-2:2018). The material transported across the ice sheet in terms of particle size distribution is unsorted. For this reason, in the glacial till from the Fort Służew region (Warsaw), both the silt and sand fractions occur in similar amounts, with a slight dominance of the clay fraction (Table 3). The grain size distribution of the cohesive soils has a direct influence on their physical parameters. The natural water content of intact samples ranges from 15.0 to 19.0% and is about two times lower than the water content determined for soil pastes. On the basis of the values of the liquid limit it can be stated that the tested glacial till has medium plasticity. The high values of the consistency index (I_C: 0.89–1.06) documented for samples with a natural structure allow the classification of their consistency as *stiff* and *very stiff*. As mentioned above the values of water content determined for soil pastes are higher than values obtained for intact samples. For this reason the consistency of soil pastes was described as *soft* and *very soft* (PN-EN ISO 14688-2:2018). It was found that prepared soil pastes, in relation to intact samples, have lower values of the bulk density and higher values of parameters describing pore space of soil (porosity and void ratio). The observed differences are caused by the destruction of the natural structure of the glacial till

Characteristic	Aviation fuel JET A1	Mineral oil 15W40	Water
Color	light yellow	brown-yellow	colorless
Physical state at room temperature	liquid		
Density [g/cm^3]	0.77–0.84	0.88	1.00
Kinematic viscosity [mm^2/s]	1.2–1.7 temperature 20–40ºC	13.5–16.3 temperature 100ºC	1.0 temperature 20ºC
Flash-point [ºC]	> 38	>215	–
Water solubility	insoluble and not miscible		–
Dielectric constant	~2		~80

Table 2. Selected physical parameters of petroleum products used during CRL tests.

during the preparation of soil pastes. Moreover the adopted axial stress (σ_c: 20 kPa) during initial consolidation of soil pastes was lower than the pre-consolidation pressure which occurs in natural conditions (σ'_p: 200 kPa: Stajszczak 2022).

In the implemented laboratory test program, contamination with petroleum products had a significant impact on the values of selected physical parameters of tested soil. After contamination with hydrocarbons, all samples show a decrease in the clay fraction content and an increase in the content of silt and sand fractions. The documented changes in the grain size distribution of the glacial till are related to changes in the pore space characteristics. All samples of soil pastes after contamination with JET A1 aviation fuel and mineral oil show an increase in the value of porosity and void ratio. In the case of the void ratio values, it is from 0.03 to 0.09. This corresponds to changes in porosity of tested soil in the range of 0.12–0.43 (Table 2). Increase of pore space after contamination with hydrocarbons causes a decrease in the proportion of soil solids in its volume. For this reason, after contamination of soil samples with aviation fuel and mineral oil, a decrease in the bulk density was observed. The changes in values of the described parameter were in the range of 0.05–0.19 Mg/m^3. It should be noted that soil pastes contaminated with aviation fuel have a lower bulk density than soil pastes contaminated with mineral oil (Table 3).

Constant rate of loading test results

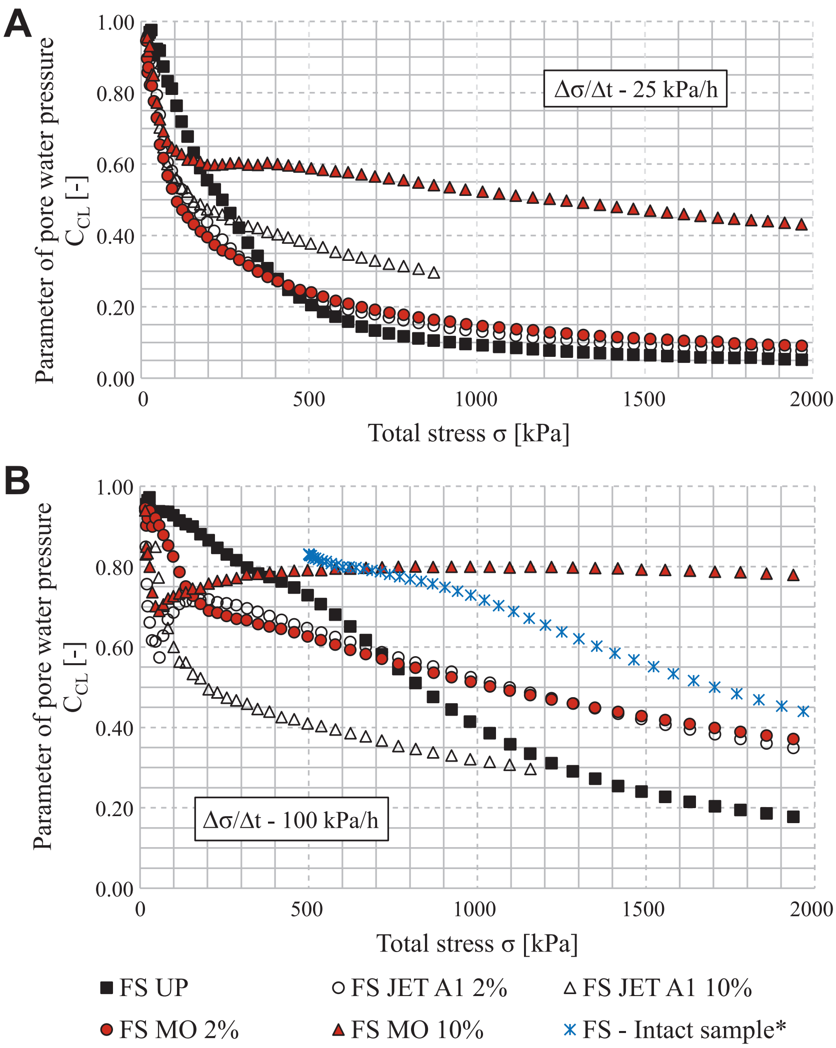
The values of the parameter of pore water pressure C_{CL} obtained at the start of the CRL test of soil pastes ranged from 0.94 to 1.00, which indicates full saturation of the tested soil samples. The C_{CL} parameter at the beginning of the CRL test of intact samples is lower than at the beginning of CRL tests of soil pastes. This fact indicates incomplete saturation of the pores of the intact sample with the liquid phase and a more significant share of the soil skeleton in the transfer of applied total stress (Text-fig. 4).

Based on performed laboratory tests, it was found that the values of axial strain obtained during CRL tests of fine grained soils contaminated with hydrocarbons will depend on:

- physical properties of tested soil and its pre-consolidation,
- type of hydrocarbon products used for soil contamination,
- content of petroleum products in the pores of tested soil samples.

Parameter	Intact sample	Soil paste		
		Unpolluted	Polluted with JET A1 aviation fuel	Polluted with mineral oil 15W40
w [%]	15.3–18.9	36.8–39.7	42.9–48.4	31.7–39.2
w_p [%]	15.1–18.0		–	–
w_L [%]	40.3–46.2		–	–
I_L [-]	-0.06–0.11	0.74–0.85	–	–
I_C [-]	0.89–1.06	0.15–0.26	–	–
ρ_s [Mg/m^3]	2.66			
ρ [Mg/m^3]	2.10–2.14	1.83–1.86	1.67–1.75	1.70–1.78
n[-]	0.30–0.33	0.49–0.51	0.54–0.58	0.51–0.52
e [-]	0.43–0.50	0.96–1.04	1.16–1.39	1.04–1.09
Sr [-]	0.97–1.00	1.00	1.00	1.00
fi [%]	29		21–26	22–27
fπ [%]	35		37–42	37–44
fp [%]	36		37–38	34–36
Hydrocarbons content in the pores of soil [%]	0		2 and 10	2 and 10
Name of soil acc. to PN-EN ISO 14688-1:2018	sandy CLAY		fine silty. sandy CLAY	fine silty. sandy CLAY
Mineral composition of Ordanian glacial till *				
Beidelite	17.6			
Kaolinite	3.2			
Illite	10.6			
Carbonates	5.6			
Quarz and others	63			

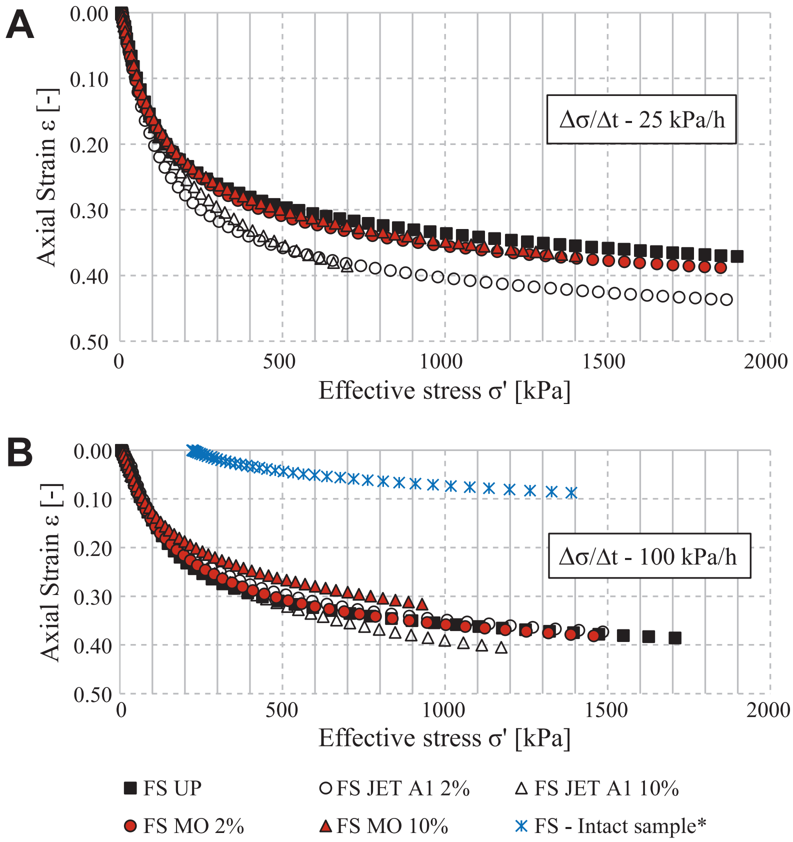
Table 3. Physical parameters of tested soil samples. Explanations: w – moisture content , w_P – plastic limit, w_L – liquid limit, I_L – liquidity index, I_C – consistency index, ρ_s – particle density, ρ – bulk density, n – porosity, e – void ratio, fi – clay fraction, fπ – silt fraction, fp–sand fraction, Sr – degree of saturation. * acc. to Stajszczak & Dobak 2021



Text-fig. 4. The values of parameter of pore water pressure obtained during CRL tests of ground pastes and intact sample before and after contamination with hydrocarbons. A – results of CRL tests performed with loading velocity 25 kPa/h, B – results of CRL tests performed with loading velocity 100 kPa/h, FS – ground paste prepared from glacial till from Warsaw area, UP – unpolluted soil sample, JET A1 – soil paste contaminated with JET A1 aviation fuel, MO – soil paste contaminated with mineral oil 15W40; *acc. to Stajszczak et al. 2020.

The highest values of axial strain, which were documented during CRL tests of uncontaminated soil samples are in a range from 0.37–0.39. After contamination with hydrocarbons the compressibility of soil pastes prepared from glacial till increases. Maximum values of the described parameter obtained for soil samples contaminated with JET A1 aviation fuel are from 0.40 to 0.44. These values are 1.1–1.2 times higher than the values of axial strain obtained for soil pastes contaminated with mineral oil. The influence of petroleum products on the values of axial strain of tested soil samples can be clearly observed for CRL tests carried out at a loading velocity of 25 kPa/h (Text-fig. 5A).

The axial strain of cohesive soil samples during a constant rate of loading test has a direct influence on the values of the modulus of compressibility. For all soil samples the lowest values of the compressibility modulus were documented in the initial stage of the CRL test. As the total stress increases, the value of the compressibility modulus gradually increases (Text-fig. 6). This Fact indicates a gradual decrease in the deformability of tested soil samples during a CRL test. The highest values of the compressibility modulus M_{max} were determined during tests of soil samples not contaminated with hydrocarbons and they are in the range 19.6–23.0 MPa. After contamination with hydrocarbons, the obtained maximum values of

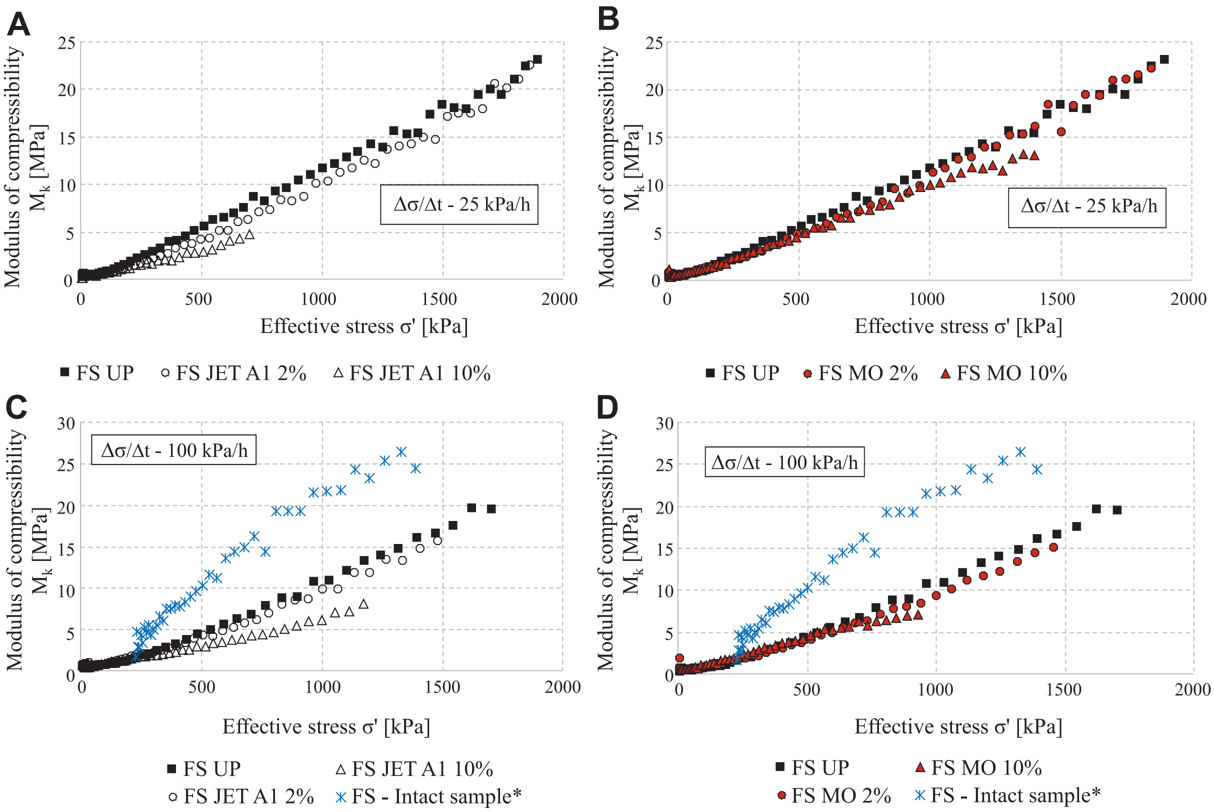


Text-fig. 5. The values of axial strain obtained during CRL tests of ground pastes and intact sample before and after contamination with hydrocarbons. A – results of CRL tests performed with loading velocity 25 kPa/h, B – results of CRL tests performed with loading velocity 100 kPa/h, FS – ground paste prepared from glacial till from Warsaw area, UP – unpolluted soil sample, JET A1 – soil paste contaminated with JET A1 aviation fuel, MO – soil paste contaminated with mineral oil 15W40; *acc. to Stajszczak et al. 2020.

the compressibility modulus are 1.1–2.0 times lower than those obtained during CRL tests of uncontaminated soil samples. It should be noted that these values decrease with increase in the content of aviation fuel and mineral oil in the pores of the tested soil. In the case of applied loading velocity, similar conclusions can be made. During CRL tests performed with a loading velocity of 100 kPa/h the maximum values of the modulus of compressibility are 1.2–1.9 times lower than those documented during tests performed with a loading velocity of 25 kPa/h (Text-fig. 6).

The evaluation of the compressibility of fine-grained soils can also be made by determining the values of the compressibility index *Cc* (PN-EN ISO 17892-5). This parameter takes into account changes in the values of the void ratio caused by an increase in the effective stress and for each soil sample assumes a constant value. In the implemented program of laboratory tests, the values of the compressibility index were determined for the values of effective stress corresponding to the primary compressibility of tested soil samples. It was assumed that the primary compressibility of tested soil pastes occurs when the effective axial stress is higher than 20 kPa (value of initial consolidation stress applied during preparation of soil pastes) and the relationship between effective stress and void ratio is linear (Text-fig. 7).

Based on the results of CRL tests it was found that values of the compression index of uncontaminated soil pastes are in a range from 0.246 to 0.262. In the implemented laboratory test program the influence of the loading velocity on the values of the discussed parameter is insignificant. The fourfold increase in the loading velocity resulted in a reduction in the value of the compressibility index by 0.016. Significant changes in the values of the compression index were observed after contamination of tested soil samples with petroleum products. After contamination with mineral oil and aviation fuel, the value of *Cc* parameter increases. The values of the compression index of soil pastes contaminated with JET A1 aviation fuel are in the range from 0,310 to 0,604. These values are



Text-fig. 6. The values of modulus of compressibility obtained during CRL tests of ground pastes and intact sample before and after contamination with hydrocarbons. A and B – results of CRL tests performed with loading velocity 25 kPa/h, C and D – results of CRL tests performed with loading velocity 100 kPa/h, FS – ground paste prepared from glacial till from Warsaw area, UP – unpolluted soil sample, JET A1 – soil paste contaminated with JET A1 aviation fuel, MO – soil paste contaminated with mineral oil 15W40; *acc. to Stajszczak et al. 2020.

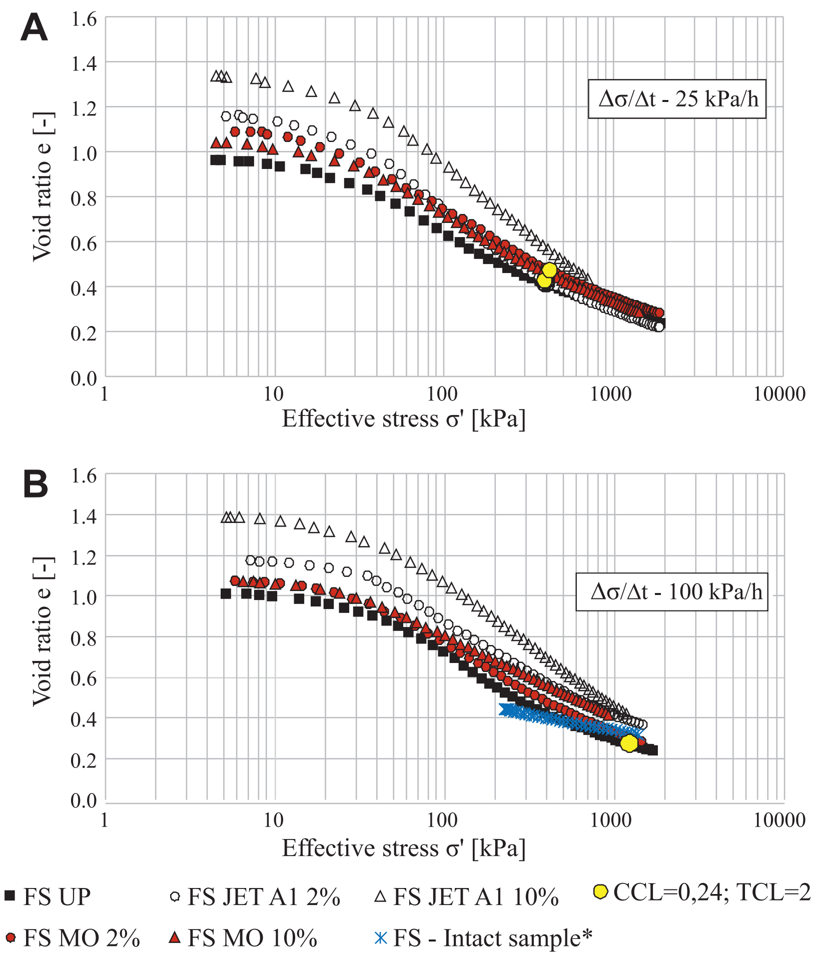
from 1,1 to 1,5 times higher than values of the discussed parameter obtained during CRL tests of soil samples contaminated with mineral oil.

The content of petroleum product in the pores of the soil plays an important role. As observed, the increase in the content of pollutants in the pores of glacial till from 0 to 10 percent caused the increase in the values of Cc parameter from 1.1 to 2.4 times. (Text-fig. 8).

DISCUSSION

Physical properties of tested soil

The results of laboratory tests of glacial till from the Warsaw region confirm the influence of petroleum products on the geological and engineering properties of cohesive soils presented in the literature (Meegoda and Ratnaweera 1994; Barański 2000; Chen *et al.* 2000; Khamehchiyan *et al.* 2007; Gupta *et al.* 2009; Ahmed *et al.* 2009; Nasehi *et al.* 2016; Hangshemo and Arabani 2022). The tested glacial till, after contamination with JET A1 aviation fuel and 15W40 mineral oil, shows changes in the characteristics of grain size distribution, which is accompanied by changes in the values of parameters describing pore space of soil (porosity *n* and void ratio *e*). Changes in the grain size distribution of fine grained soils after contamination with hydrocarbons are caused by the processes that take place on the border of the solid phase of soil (mineral skeleton) and the liquid phase (water, petroleum product). As is known, the electric charge of clay particles has an influence on the distribution of molecules and ions present in the solution filling the pore space of the soil medium, thus leading to the formation of an electrical double layer (Birdi 2003). The research carried out so far shows that the presence of nonpolar liquids with a low dielectric constant in the soil pores leads to a reduction in the thickness of the electrical double layer surrounding the particles of clay minerals (Kaya and Fang 2000, 2005). By reducing the thickness of

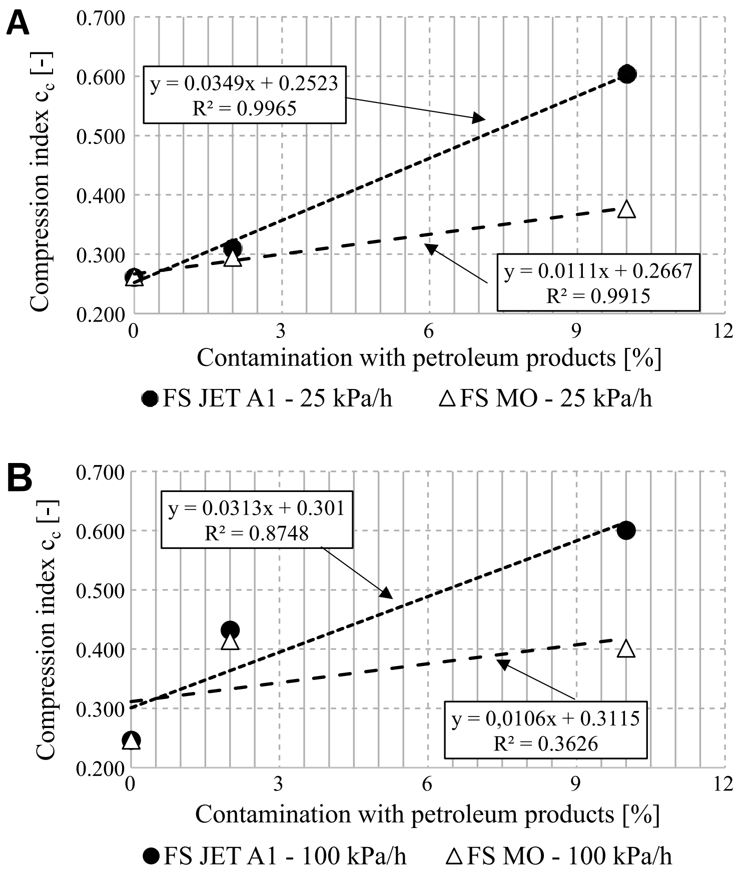


Text-fig. 7. Compressibility curves obtained during CRL tests of ground pastes and intact sample before and after contamination with hydrocarbons. A – results of CRL tests performed with loading velocity 25 kPa/h, B – results of CRL tests performed with loading velocity 100 kPa/h, FS – ground paste prepared from glacial till from Warsaw area, UP – unpolluted soil sample, JET A1 – soil paste contaminated with JET A1 aviation fuel, MO – soil paste contaminated with mineral oil 15W40, C_{CL} – parameter of pore water pressure, T_{CL} – relative consolidation time; *acc. to Stajszczak et al. 2020

the electrical double layer, the attractive Van der Waals forces, which act at short distances between the individual particles of the mineral skeleton, begin to outweigh the repulsive electrostatic forces. In this way in the environment of non-polar liquids, the flocculation process of clay particles is initiated. Its advancement is higher when the value of the dielectric constant of solution filling the pore space of soil is lower (Kaya and Fang 2005). The reduction in the thickness of the electrical double layer due to hydrocarbon contamination directly leads to the aggregation of clay mineral particles into larger aggregates. This process leads to a change in the grain size distribution characteristics, which was documented in the course of the performed laboratory tests (Table 3).

The changes of the soil microstructure in the discussed case were indirectly documented by the changes in the values of the bulk density. In performed laboratory tests the values of bulk density of all prepared soil pastes, after contamination with aviation fuel and mineral oil, are lower than those determined for non-contaminated soil samples. The decrease in the bulk density of tested glacial till after contamination with mineral oil 15W40 and JET A1 aviation fuel can be explained by the lower density of petroleum products in comparison to the density of water. It should be noted that the bulk density of the prepared soil pastes, after contamination with JET A1 aviation fuel, is lower than that determined for soil samples contaminated with 15W40 mineral oil. This fact can be explained by the lower density of JET A1 aviation fuel in comparison to the density of mineral oil 15W40 (Table 2).

The second factor which will have an influence



Text-fig. 8. The values of compression index obtained during CRL tests of ground pastes before and after contamination with hydrocarbons. A – results of CRL tests performed with loading velocity 25 kPa/h, B – results of CRL tests performed with loading velocity 100 kPa/h, FS – ground paste prepared from glacial till from Warsaw area, UP – unpolluted soil sample, JET A1 – soil paste contaminated with JET A1 aviation fuel, MO – soil paste contaminated with mineral oil 15W40.

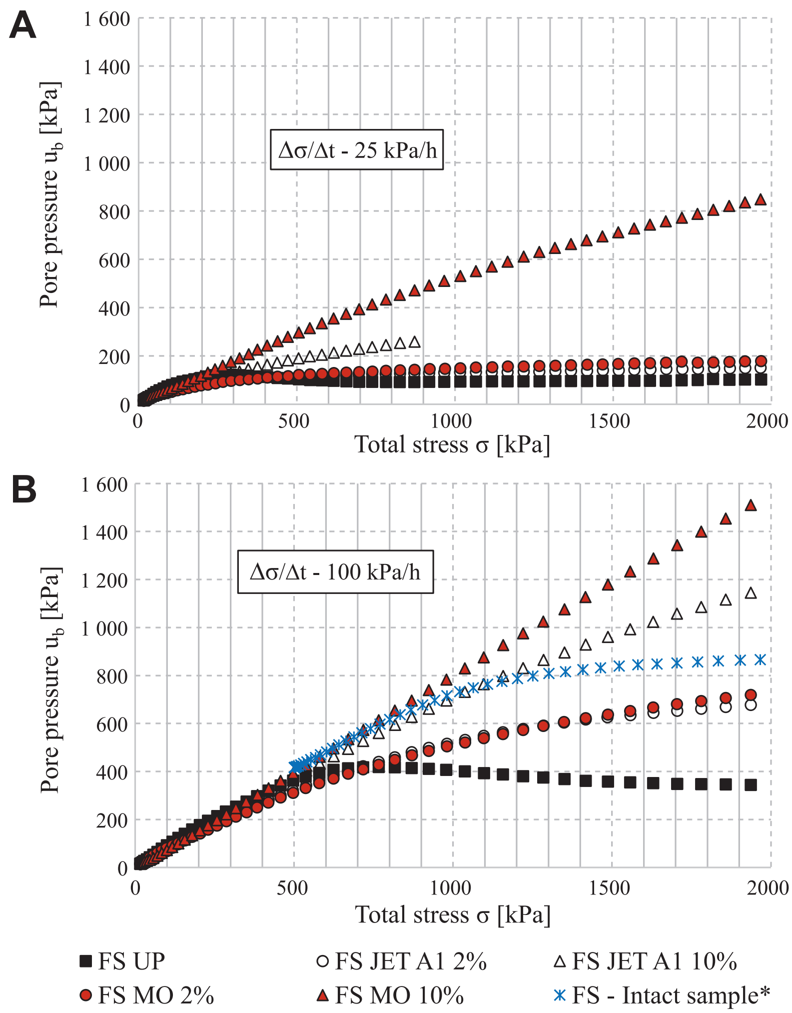
on the changes in the bulk density of fine grained soils contaminated with hydrocarbons is the change in its porosity caused by the flocculation of clay minerals. In the conducted laboratory tests the void ratio and porosity of glacial till, after contamination soil samples with petroleum products, increases with the increase in the content of JET A1 aviation fuel and mineral oil 15W40.

The influence of hydrocarbon contamination on the compressibility of fine grained soil during CRL test

These documented changes in the physical properties of glacial till after contamination with hydrocarbons has a direct influence on the course of constant rate of loading tests. A common feature of the behavior of fine-grained soils during CRL tests is a continuous, most often non-linear, increase in the values of the axial strain and compressibility modulus as a function of applied stress. In the implemented laboratory test program applied axial stress was the most important factor having an influence on the deformation characteristics of the tested fine grained soil. The axial strain of soil samples uncontaminated and contaminated with hydrocarbons under conditions of constant rate of loading increases with different velocity. Therefore, it is worth presenting both e–σ and M_0–σ diagrams in the soil compressibility assessment on the basis of CRL tests.

The second most important quantitative factor shaping the differentiation in the compressibility of the cohesive soils are the features conditioned by its grain size distribution, genesis, consistency and structure. In the case of the implemented laboratory research program, this point should also take into account the presence or absence of petroleum pollutants, their type and content in the soil pores.

The third factor determining the variability of the compressibility characteristics in the CRL tests



Text-fig. 9. The values of pore pressure recorded during CRL tests of ground pastes and intact sample before and after contamination with hydrocarbons. A – results of CRL tests performed with loading velocity 25 kPa/h, B – results of CRL tests performed with loading velocity 100 kPa/h, FS – ground paste prepared from glacial till from Warsaw area, UP – unpolluted soil sample, JET A1 – soil paste contaminated with JET A1 aviation fuel, MO – soil paste contaminated with mineral oil 15W40; *acc. to Stajszczak *et al.* 2020.

is the applied loading velocity. A consequence of the selection of higher loading rates is the mobilization of higher pore pressure values, and consequently the registration of lower values of axial strain in relation to the conditions of full pore pressure dissipation (Text-fig. 9).

The conducted CRL tests on soil pastes prepared from glacial till, which was collected in the Warsaw region proves that contamination with petroleum products can increase the compressibility of the fine grained soils. The increase in the compressibility of prepared soil samples after contamination with hydrocarbons was expressed by a reduction in the maximum values of the compressibility modulus M_{omax} (Text-fig. 6). This reduction corresponds to the increase in the value of the compressibility index Cc and the axial stain ε_{max} documented at the end of the CRL test (Text-figs 5 and 8). During the CRL tests the values of the compressibility modulus of soil pastes contaminated with petroleum products, similarly to the tests of unpolluted soil samples, increased with the increase of the total stress value. Thus, it can be concluded that the behavior of fine grained soils contaminated with hydrocarbons during CL tests will be consistent with the behavior of unpolluted soils. The only differences were documented in the quantitative characteristics (Text-fig. 6A, B). The results of the analyses presented in Text-fig. 10 indicate that the presence of hydrocarbons in the pore space of the soil may increase its compressibility even twice. However, it should be noted that the reconstruction of the soil structure as a result of the constant rate of loading, apart from its inherent properties, will depend on the pore pressure u_b generated during the CRL test. The data included in the literature and the results of the presented research prove that the pore pressure values recorded during CRL tests depend on the properties of the tested soil, the loading velocity, the physical properties of the petroleum products and its content in the pores of the soil sample (Dobak 1999; Stajszczak 2019, 2021). During a CRL test intensive mobilization of pore pressure usually leads to an increase in soil stiffness. In the performed CRL tests, the temporary increase in the stiffness of the contaminated soil samples took place in the initial phase of the CRL tests and was expressed with values of the M_{UP}/M_P ratio (compressibility modulus ratio) lower than one (Text-fig. 10). In the advanced stage of the CRL test, the mobilization of the pore pressure is usually lower than at the beginning of the test, which causes an increase in the share of the soil skeleton in the transfer of the applied total stress.

As presented in Text-fig. 10 in the advanced phase of the CRL test, soil samples contaminated with hydrocarbons are more compressible, than unpolluted soil samples. This fact is documented by a consistent increase in the value of the M_{UP}/M_P ratio.

The role of pore pressure in the evaluation of the compressibility of fine-grained soils contaminated with hydrocarbons

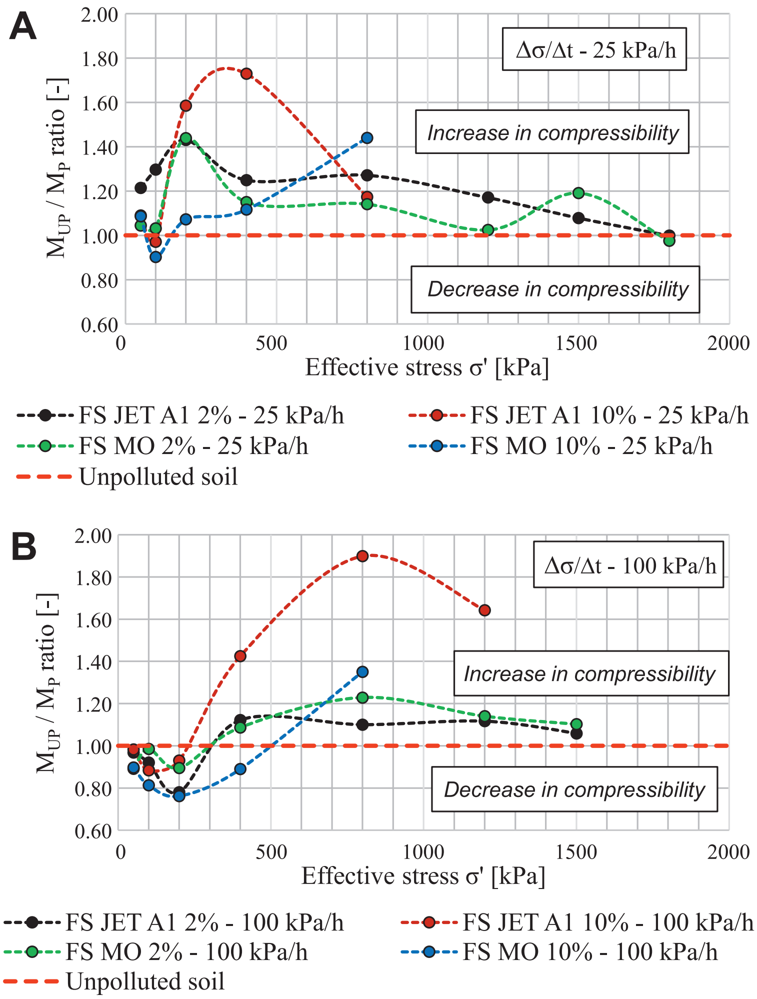
The Values of M_{UP}/M_P ratio higher than 1 (increase in compressibility of soil) in the advanced stage of the CRL test result from higher pore pressure values being mobilized after contamination of the soil samples with hydrocarbons. As noted by Wiłun (1987), the formation of a large hydraulic gradient during incremental loading tests may cause rapid destruction of the soil structure, increasing its compressibility. In the performed CRL tests, the measure of the hydraulic gradient was the measured value of the pore pressure u_b. It should be stated, that during CRL tests of fine-grained soils contaminated with hydrocarbons recorded pore pressure values will increase with increasing of (Text-fig. 9):
– the loading velocity,
– the content of oil product in the soil pores,
– the density and viscosity of the polluting phase.

Therefore, based on the available knowledge, it can be concluded that the destruction of the soil structure as a result of the generation of high values of the hydraulic gradient in the implemented CRL test program could be the reason for the documentation here of lower values of the compressibility modulus after contamination of soil pastes with the mineral oil 15W40 and JET A1 aviation fuel. This fact is confirmed by the analyzes of the u_b curves presented in Text-fig. 9. With the increase in the content of JET A1 aviation fuel and 15W40 mineral oil in the soil pores, increase the maximum pore pressure values recorded during the CRL test is observed. This trend is maintained at loading velocities of 25 and 100 kPa/h. During a CRL test of soils not contaminated with hydrocarbons, the same effect can be obtained by increasing the loading velocity. The higher values of the u_b parameter documented after contamination of glacial till with hydrocarbons indicate a deterioration of the soil permeability. The reduction in permeability of tested soil samples after contamination with hydrocarbons results from the excluding of some of the pores from the filtration process by petroleum products which are more viscous than water (Stajszczak 2021). As shown in Table 2, the viscosity of mineral oil is higher than the viscosity of aviation fuel. For this reason, the values of pore pressure and hydraulic gradient recorded during CRL tests of soil samples contaminated with mineral oil are the highest. This fact is observed at all of applied loading velocities.

The influence of physical properties of oil products on the compressibility of fine grained soils contaminated with hydrocarbons

The second factor, next to loading velocity, which will affect the compressibility of fine grained soils after contamination with hydrocarbons are the physical properties of the pollutant. This is measured by the recorded pore pressure values and, associated with them, the values of the hydraulic gradient. The documented values of axial strain, compressibility modulus and compression index indicate, that the increase in the compressibility of glacial till after contamination with JET A1 aviation fuel is higher than in case of contamination with mineral oil 15W40. This fact should be explained by the different value of the viscosity of different petroleum products. As can be seen in table 2, the viscosity of 15W40 mineral oil is about 10 times higher than viscosity of JET A1 aviation fuel. Consequently, mineral oil was less mobile in the soil pores during CL consolidation than JET A1 aviation fuel. This reduced to some extent the reconstruction of the soil structure and limited also changes in soil compressibility caused by generating high values of the hydraulic gradient.

Changes in the compressibility of fine-grained soils caused by contamination with hydrocarbons



Text-fig. 10. The values of M_{UP}/M_P ratio calculated on the basis of CRL test results of ground pastes. A – CRL tests performed with loading velocity of 25 kPa/h, B – CRL tests performed with loading velocity of 100 kPa/h, FS – ground paste prepared from glacial till from Warsaw area, M_{UP} – modulus of compressibility determined during CRL test of unpolluted soil sample, M_P – modulus of compressibility determined during CRL test of soil sample polluted with hydrocarbons, JET A1 – soil paste contaminated with JET A1 aviation fuel, MO – soil paste contaminated with mineral oil 15W40.

are also confirmed by analysis of the compressibility curves. The introduction of aviation fuel and mineral oil into the pores of glacial till during the performed CRL tests caused a shift in the compressibility curve to the right. As can be observed, this shift increases with increasing:

– content of hydrocarbons in the pores of the soil,
– loading velocity during the CRL test.

These factors, in addition to the physical properties of the fine-grained soil, will have an influence on the pore pressure values obtained during a CRL test. As mentioned above, the deterioration of permeability of soil pastes after contamination with JET A1 aviation fuel and 15W40 mineral oil caused the increase in the maximum pore pressure values which were recorded during CRL tests. Excluding some of the pores from the filtration process as a result of contamination with hydrocarbons delayed the beginning of the steady phase of CL consolidation, which is defined by the values of the pore pressure parameter C_{CL}<0,24 and the relative consolidation time T_{CL}>2 (Dobak 2008). As the CRL test progresses the observed differences in the shift of the compressibility curves are gradually reduced and the e-logσ' relationship takes a linear trend. In the performed CRL tests of glacial till contaminated with JET A1 aviation fuel and 15W40 mineral oil, the linear trend of the e-logσ' relationship occurs in the steady phase of CL consolidation. Moreover, as can be observed in Text-fig. 7, at the beginning of the CRL test, the values of the void ratio documented for soil samples contaminated with JET A1 aviation fuel are higher than the values of the void ratio documented for soil samples contaminated with mineral oil. However, this trend is reversed in the steady phase of CL consolidation, when C_{CL}<0.24 and T_{CL}>2. This fact confirms the hypothesis that any increase in the viscosity of the petroleum product present in the soil pores during CRL tests will counteract the changes in the microstructure of the fine-grained soil occurring as a result of generating high values of the hydraulic gradients.

CONCLUSIONS:

The article attempts to assess the impact of JET A1 aviation fuel and 15W40 mineral oil on changes in the compressibility of glacial till from the Warsaw region. For this purpose compressibility tests of soil pastes were performed. The compressibility tests were carried out in a consolidometer with a constant rate of loading. Based on the results of CRL tests, the following conclusions can be drawn:

1. During the CRL test, the compressibility of fine-grained soils reduces gradually. This fact is documented by an increase in the value of the compressibility modulus and a gradual decrease in the rate of strain. The values of the compressibility modulus and maximum strain of fine-grained soils contaminated with hydrocarbons during CRL tests will depend on the properties of the fine-grained soil, its structure, loading velocity, as well type and content of the oil product in the soil pores.

2. Contamination of glacial till with JET A1 aviation fuel and 15W40 mineral oil causes an increasing in its compressibility. In the implemented CRL test program, the increase in compressibility of soil samples contaminated with hydrocarbons, in comparison to uncontaminated soil samples, was expressed by an increase in the values of the maximum axial strain by 1.1–1.2 times and a decrease in the maximum values of the compressibility modulus by 1.1–2.0 times.

3. After contamination of glacial till with JET A1 aviation fuel and 15W40 mineral oil, the values of the compression index increase in the range 0.033–0.354. It should be noted that a more significant increase in soil compressibility occurs after contamination soil samples with JET A1 aviation fuel. This fact is confirmed by the values of the compression index obtained for soil samples contaminated with aviation fuel. They are 1.1–1.6 times higher than the values of this parameter determined for soil samples contaminated with mineral oil 15W40.

4. The documented increase in the compressibility of glacial till after contamination with hydrocarbons should be explained by changes in porosity caused by flocculation of clay minerals and decrease in soil permeability as a result of a reduction in effective porosity, as well as an increase in the maximum pore pressure and hydraulic gradient values, which were recorded during each CRL test. During the CRL tests, these factors caused a reconstruction of the soil structure and resulted an increase in compressibility of soil pastes prepared from glacial till. However, it should be noted that an increase in the viscosity of the petroleum product contaminating the fine grained soil will limit the changes in the structure taking place under the conditions of constant rate of loading.

5. The CRL test method should be considered as a useful tool for assessing the compressibility of fine-grained soils contaminated with hydrocarbons. In order to ensure the credibility of the obtained data, the loading velocity should be carefully selected each time, taking into account the possibility of pore pressure dissipation. Based on the implemented program of laboratory tests, it is recommended to use, during CRL tests of fine grained soils, a loading velocity not higher than 25 kPa/h.

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