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Determination of swell index and swelling pressure from suction tests – a case study of Neogene clays from Warsaw (Poland)

Emilia WÓJCIK[1,] * and Ireneusz GAWRIUCZENKOW[1]

[1] University of Warsaw, Faculty of Geology, Institute of Hydrogeology and Engineering Geology, Żwirki i Wigury 93, 02-089 Warszawa, Poland

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The paper presents the results of swell index, swelling pressure and soil suction tests carried out on Neogene clays from Warsaw, depending on the water content, clay fraction, liquid limit, plasticity index, cation exchange capacity, and content of clay minerals and beidellite. These clays are considered expansive soils in Poland, as they are vulnerable to water content variations in the active zone, which result in their volume change and, in consequence, cause damage of foundations and other construction elements. A number of physical, chemical and mineral properties were determined for these clays. The swelling tests were carried out on samples precompacted in *Proctor* apparatus, at various initial values of water content. The analyses have shown exponential relation of swell index, swelling pressure and suction *versus* water content. In addition, the investigated relationship between the suction and swell characteristics of tested clays shows good correlation as a power function between these parameters. In addition, validity of correlations between fitting parameters of obtained relationships and soil index properties, such as clay fraction, liquid limit, plasticity index, cation exchange capacity, and content of clay minerals and beidellite, have been demonstrated. The empirical relations are characterized by high values of the correlation coefficient. A very high fit has also been found for a proposed relationship between the swell index and swelling pressure for tested clays.

Key words: expansive soils, swell index, swelling pressure, soil suction, Neogene clays.

INTRODUCTION

The current development of technology and knowledge allows constructing any building in practically all groundwater conditions, and provides a good recognition of the subsoil and geodynamic processes that may occur within them. Comprehensive investigations of the soil characteristics allows for an economic design by using a full range of soil properties. In case of cohesive soils, due to their specific properties, the key is to estimate the susceptibility of soil to volume changes. The presence of expansive soils in many regions of the world is connected with the corresponding geological situation (clay-rich soils and rocks), climatic conditions (arid and semi-arid regions), hydrology, geomorphology and vegetation. The problem can be observed especially in arid and semi-arid regions. High volumetric deformations, which expansive soils may be subjected to, constitute a real threat to the stability of structures, foundations, pavements, landfills, tunnels, embankments, pipes as well as to the light buildings and roads (Cuisinier and Masrouri, 2005; Zhan et al., 2007; Sawangsuriya et al., 2011; Sudjianto et al., 2011). The costs around the world associated with the removal of damage in structures raised on expansive soils are estimated at billions of dollars.

A crucial issue in foundation design is primarily to identify the type of soil and its response to changes in water content in order to determine their expansive properties. The part of soil profile, which is subjected to the environmental influences, is called the active zone. In this area, the soil is vulnerable to water content variations. The phenomenon of soil expansion is interesting for investigations, especially in terms of how far the effects of water content change and suction variation are related to the behaviour of expansive soils, resulting in volumetric swelling. Thus, the key aspects of behaviour of expansive soils are to determine:

– soil properties (e.g., mineral composition),
– suction and water content variations,
– swelling characteristics: swelling potential, which is defined as the degree up to which a soil will swell, and swelling pressure.

The expansive soils are commonly known across the world. In Europe, they are present, among others, in the UK, Greece, Romania, Norway, Spain and Germany (Stavridakis, 2006). In Poland, cohesive soils occur widely (Fig. 1) and they are characterized by diverse properties, such as potential expansiveness, degree of expansion, and swelling potential. Considering their expansion properties, clays may be set in the following order: bentonite and bentonite clays together with weathered and non-weathered Miocene clays of the Fore-Carpathian region,

* Corresponding author, e-mail: wojcike@uw.edu.pl

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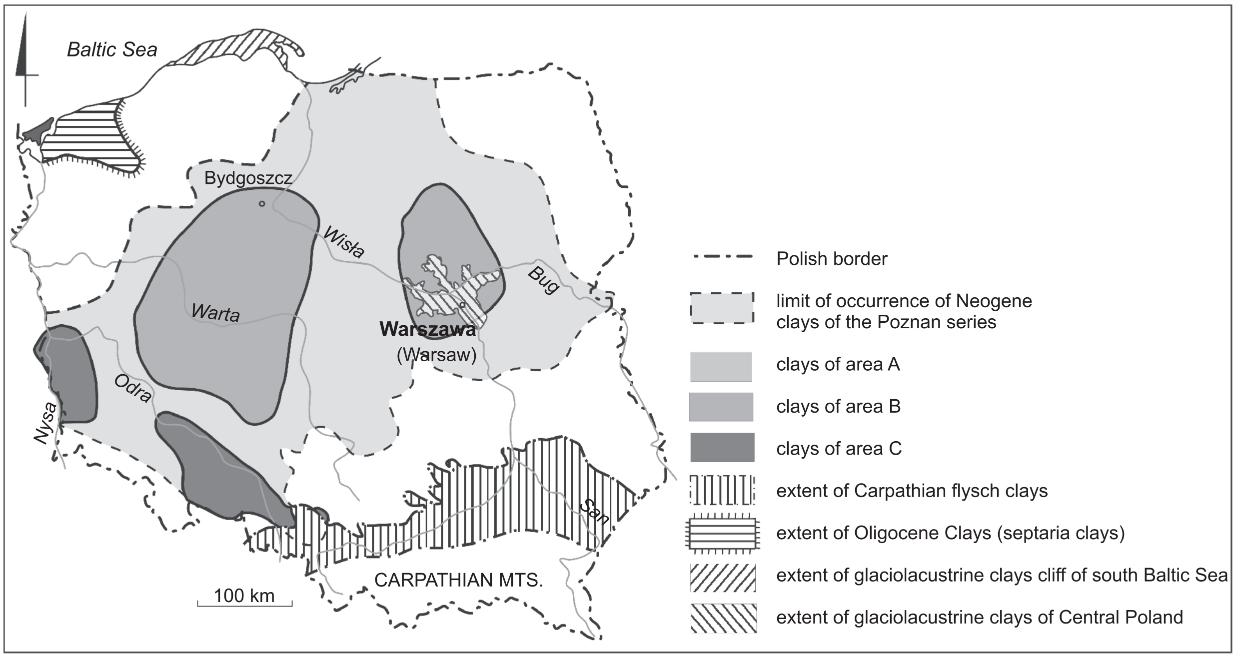


Fig. 1. Map of occurrence of the expansive soils in Poland

strongly overconsolidated Neogene (Mio-Pliocene) clays commonly known as the Poznań Formation, Oligocene septaria clays of the Szczecin area, glacio-limnic clays of the southern Baltic cliff, and finally Mid-Polish Quaternary hollow clays. Glacial tills and loess are considered moderately expansive soils (Kaczyński and Grabowska-Olszewska, 1997).

This paper refers to the Poznań Formation clays of Neogene age, occurring over a wide area of the country (e.g., Duczmal-Czernikiewicz, 2013), often near the surface or under differently thick Quaternary deposits. In Warsaw, the average thickness of Neogene clays exceeds 30 m, whereas in areas of glaciotectonic deformations the thickness can reach 150 m (Frankowski and Wysokiński, 2000). The top of Neogene clays is not a leveled (flat) surface, but numerous elevations and depressions are observed there. Their orientation is mainly NNW–SSE and their extreme relief variations exceed even 100 m. The genesis is associated with glaciotectonic and erosion processes. Locally, the Neogene clays are exposed at the surface (e.g., Central Warsaw Elevation) or occur at shallow depths under Quaternary and man-made sediments (Żoliborz Warsaw District, Stare Babice near Warsaw). These soils are the subsoil of many constructions and, if they occur, extended and careful soil recognition and appropriate foundation system design is recommended.

Warsaw is a rapidly expanding city, where not only skyscrapers, and residential and commercial buildings are raised, but also a high-speed underground rail is being developed. It can be expected that both in Poland and worldwide the problems related to expansive soils will be still relevant in the future. It is associated with the development of engineering activity and the challenges that man faces with (e.g., geotechnical design in urbanized areas or under extreme conditions, at great depths). In connection with the construction of the metro line in Warsaw, numerous publications have appeared concerning the variability of Neogene clays parameters (e.g., Stamatello and Rossman, 1955; Pinińska and Dobak, 1987; Kaczyński, 2001, 2002, 2003; Izdebska-Mucha and Wójcik, 2014).

The paper provides the results of a comprehensive study of the swelling Neogene clays. The most important issue was to determine the relationship between suction and swelling properties of clays obtained from boreholes drilled in the centre of Warsaw. In addition, an attempt was made to determine the influence of particular index parameters of soil (e.g., clay content, liquid limit, plasticity index, cation exchange capacity, clay minerals content, and beidellite content) on the examined parameters. The purpose of the study was also to verify if there was a strong correlation between the fitting parameter in empirical relationships and a soil type and its properties.

MATERIALS AND METHODS

The natural clays for this study come from Warsaw, central Poland, Mazowsze province. This is the area of shallow occurrence of Neogene clays of the Poznań series, which are characterized by expansive properties (Kaczyński and Grabowska-Olszewska, 1997; Barański and Wójcik, 2007, 2008; Kumor, 2008, 2016). The Poznań series (clayey and sandy-clayey sediments) formed in a wide, shallow inland reservoir that covered almost the whole area of the Polish Lowlands and continued as far as the boundary of the Sudetes. It consists of three lithostratigraphic strata, which differ from each other in the sedimentary environment, geochemical conditions, and related different mineral composition of the clay fraction. The Poznań clays were deposited from the Middle Miocene to the Late Pliocene (Piwocki et al., 2004).

The following properties were determined for six clay samples: particle-size distribution (BS 1377: Part 2, 1990), specific density, bulk density (BS 1377: Part 2, 1990) and particle density by the pycnometer method (AccuPyc 1330), and Atterberg limits: liquid limit and plastic limit (according to BS 1377: Part 2, 1990). In addition, identification of the specific surface area was obtained by the methylene blue adsorption method (according to PN-88/B-04481). Mineral composition was determined by thermal analysis, using a *Q600* apparatus manufactured by TA Instrument. The following conditions were used: weight of sample from 44–67 mg, sensitivity adjusted automatically by the apparatus, heating speed 10 C/min, and air atmosphere. In order to determine the quantitative mineral composition, derivatograms of the particle fraction less than 2 m were obtained for each sample. The fraction was separated using a sedimentation method. Identification and quantitative determination of the proportion of clay minerals was based on the knowledge of dehydration (dh), dehydroxylation (dh_o), the range of temperatures at which they were observed, and the presence or absence of a kaolinite peak (Kościówko and Wyrwicki, 1996).

For a complete characterization of swelling and suction of tested clays, and to determine the effect of water content on these parameters, the samples were formed in a particular way. To eliminate the heterogeneity of natural soil samples, each sample was crumbled and dried at 105°C, and then rubbed through a sieve with a mesh size of 0.063 mm. Such prepared powder was mixed with an adequate amount of deionized water in order to obtain samples with different initial water content, i.e.: 15, 20, 25 and 30%. Since the method of compaction does not play a significant role in the process of swelling (Niedzielski, 1993), the samples were compacted dynamically in *Proctor* apparatus. Then the specimen was cut out of the sample for swell, swelling pressure and suction tests. The assumed initial water content was controlled by standard measurements in the weighing bottles.

One of possible ways of swelling prediction is empirical relationships based on different soil properties. Hanumantha Rao et al. (2011) provided a comprehensive overview of the correlations between swelling and physical parameters of the soil. The basic properties directly characterizing a swelling soil are swell index and swelling pressure. There are many methods of swelling studies depending on the purpose of work and availability of test equipment. In the literature, different methodologies and interpretations can be found concerning the determination of swelling parameters. In this study, the uniaxial swelling test was performed in accordance with ASTM D 4546-90 (Method A) by means of a soil swelling-metre adapted to the test. The samples, ~8–12 mm in height and 65 mm in diameter, were placed in the oedometric ring and then in a swelling measurement device. After that, the sensor was set, and deionized water was poured into the container so that the sample saturation started from the bottom and continued throughout the whole test. The samples were subjected to the vertical pressure of ~1.5 kPa by a covering cup. The observations were continued until complete swelling of the soil was reached, manifested by the lack of changes in the sensor indications during three consecutive readings. The swelling test was conducted for six natural soil samples. Additionally, for each clay sample, analyses were made in four repetitions for the following initial water contents: 15, 20, 25 and 30%. A total number of 30 swell tests were performed. Swell index was calculated according to the following formula:

$$\varepsilon_p = \frac{h - h_0}{h_0} \cdot 100\%$$

where: ε_p – swell index (percent swell; %), h – sample height after swelling (mm), h_0 – initial sample height (mm).

Free swell ratio (FSR) method gives information about soil expansivity and nature of clay mineralogy. According to Sridharan and Prakash (2000) it is defined as the ratio of equilibrium sediment of the volume of 10g of oven-dried soil, passing through a 425 μm sieve in a distilled water (V_d) to that in a non-polar (kerosene – V_k) liquid:

$$FSR = \frac{V_d}{V_k}$$

where: FSR – free swell ratio (-), V_d – volume of 10 g of soil after sedimentation in distilled water (cm^3), V_k – volume of 10 g of soil after sedimentation in kerosene (cm^3).

Swelling pressure tests were performed in an *h-200A* apparatus manufactured by Geonor, Norway. All tests were carried out in accordance with ASTM D 2435-90 (Method C), at a sample constant volume, maintained by the apparatus by applying a vertical pressure on the sample after saturation with water. That prevented the soil sample from swelling, and thus from increasing its volume. Swelling pressure tests were carried out for both natural and model samples, compacted in *Proctor* apparatus to the maximum possible bulk density and with the initial water content of 15, 20, 25 and 30%. The specimens were cut out from the sample to a diameter of about 50 mm and to a height of ~1.98 mm. Then the specimens were inserted into the ring and – in a special container – to the Geonor apparatus (Fig. 2). The sample was loaded initially with a pressure of 8.5 kPa. Then the height of the sample was controlled by the engine to keep the height at the constant level (with a accuracy equal to 0.01 mm). In the control unit the clock was set to a standby mode. After preparing the apparatus, the test was run together with real-time clock. Then, the sample was saturated with water, and the saturation continued from the bottom. The first several readings were taken manually, and then automatic reading at a specific time interval (every hour) was switched on. After reaching the stability of swelling pressure, i.e. lack of changes in three consecutive readings, the study was completed and the final parameters, such as water content, bulk density and degree of saturation of the study, were determined.

The suction test was performed by the filter paper method (FPM) in accordance with ASTM D 5298-94. Total suction is a sum of the osmotic and matrix (capillary) suction. Osmotic suc-

Fig. 2. Swelling pressure apparatus *h-200A Geonor*

tion is a result of the presence of dissolved salts in the liquid occurring in the pore space. Osmotic suction leads to physical changes in the soil, but is totally independent of water content and stress state (external load). Matrix suction is a result of the existing capillary phenomenon in the zone of capillary action. The value of the matrix suction depends primarily on the type of clay mineral composition of the soil, the initial water content, and the stress state. Matrix suction (u_a–u_w), next to net tension, is one of the main variables of stress state in unsaturated soils and is used in the analyses of their volume change (Fredlund and Rahardjo, 1993). In this paper, matrix suction was determined by the filter paper method. Before the test, the filter paper was placed into an oven overnight to eliminate any water contained in it. The dried filter paper was transferred to a desiccator for a few minutes to cool down, all the time using tweezers to avoid any water reappearance. Matrix suction was determined based on the water content of the middle filter paper amongst the three filter papers used in the test. It is best, if the two external filter papers have a slightly larger diameter than the central paper to protect it from possible contamination and ensure direct contact with the two cylindrical soil samples with well-levelled surface, between which a triple layer of paper is stacked keeping the contact with specimen. Each soil sample was closed together with filter papers in a sealed container. Then, all containers were placed in an air-conditioned room with a constant temperature of ~20°C in a chamber allowing minimizing any changes until an equilibrium between the water content of soil sample, filter paper, and air was achieved. In case of matrix suction, equilibration time should last at least 7 days (Ridley and Wray, 1995). After reaching the equilibrium state, the filter paper was removed from the container and immediately placed into a metal container and weighed on a precision balance with an accuracy of 0.0001 g. The filter paper was then dried in an oven at 105°C for a minimum of 4 hours. The weight of the warm containers with filter paper was determined at this stage. The value of suction was read from the relation obtained during filter paper calibration at particular water content. In this study, Whatman filter paper no. 42 was used. The filter paper-based method is among the group of indirect test methods. Its advantage is its simplicity and inexpensiveness, and the measurement range is wide.

RESULTS AND DISCUSSION

The tested samples represent various facies of Neogene clays, which, together with the changes of sedimentation conditions, changed their colour from black to yellow. For the purpose of this study, grey, yellow and green clays were investigated. According to the Unified Soil Classification System (USCS, following the requirements of ASTM D 2487-06), the tested soils can be classified as CH and CL clay (Table 1). Potentially expansive soils can be recognized in the laboratory by their plastic properties. It is commonly believed that clay soils of high plasticity, generally those with plasticity index >30% and liquid limits >50%, usually have high inherent swelling capacity. In Figure 3, different classification schemes, proposed by earlier researches, are employed to identify the swelling degree of the soil examined in this study. It can be observed that plasticity and swelling of the clays vary from medium to very high, and their potential expansiveness from high to very high.

Knowledge of the mineral composition is very useful to indicate probable ranges of physical-mechanical properties and their variability and sensitivity to changes due to environmental conditions. Table 2 shows the test results of mineral composition of the clays that are characterized by a high contribution of clay minerals from 39–67%. The dominant mineral is beidellite (smectite group). It is indicated on clay fraction derivatographs by the ratio of dehydration (dh = 10–11%) at a temperature of 25–220 C with a maximum response at 100 C towards dehydroxylation (dh_o = 5–6%) at a temperature of 390–800 C with a maximum response at 510 C. The amount of beidellite in tested soils ranges from 30 to almost 57%. The second clay mineral occurring in the soils is kaolinite. Its amount ranges from 7–13%. In most samples, illite was also found (most probably as the mineral of beidellite mixed layer) from trace amounts to ~6%. Endothermic reactions on derivatographs, obtained for raw samples and their fractions at temperatures from 220–300 C with a maximum at ~290 C, indicated goethite admixtures. Larger mass losses along the TG curve for clay fraction than for a raw sample were noted. It indicates that goethite is fine-grained and concentrated on the clay fraction. Its amount is estimated to range from 1–7%. Based on the exothermic reaction along the DTA curve at a temperature of ~380–420°C, a small admixture (~ 0.7%) of organic matter was found in sample no. 26. The completion of the mineral composition of the samples was quartz (at 575 C, a peak associated with polymorphic transformation from beta-quartz to alpha-quartz was observed on the raw sample's DTA curve) and thermally non-active minerals, constituting from 25 to almost 59% of composition.

The research on swelling of natural samples indicated that for the 16–28.5% water content (values observed *in situ*) the swell index varied from 3 to ~13%, whereas the swelling pressure ranged from 86–157 kPa. According to the classifications of swell soils by Olson (1973) and Sorochan (1974), which use swell index as a reference, the swelling was classified from low to very high. In this group, the highest values of swell index and swelling pressure were recorded for soil sample no. 28. This sample was characterized by a high quantity of beidellite (Table 2). Soil samples nos. 39 and 42 have a similar grain-size distri-

Table 1

Physical properties of tested clays

Soil no.	Percent fractions			Soil class USCS	Soil parameters				
	Sand	Silt	Clay		Liquid limit LL [%]	Plastic limit PL [%]	Plasticity index PI [%]	Specific gravity ρ_s[Mg/m^3]	CEC [meq/100g]
26	2.3	44.0	53.7	CH	57.6	21.0	36.6	2.70	20.25
28	0.5	42.4	57.1	CH	70.6	24.4	46.2	2.70	28.62
32	14.2	49.2	36.6	CL	46.2	19.2	27.0	2.71	15.86
33	12.8	48.8	38.8	CL	51.5	19.5	32.0	2.70	15.44
39	0.7	38.7	60.7	CH	74.7	25.7	49.0	2.78	29.56
42	0.3	35.8	63.9	CH	82.2	33.1	49.1	2.75	32.10

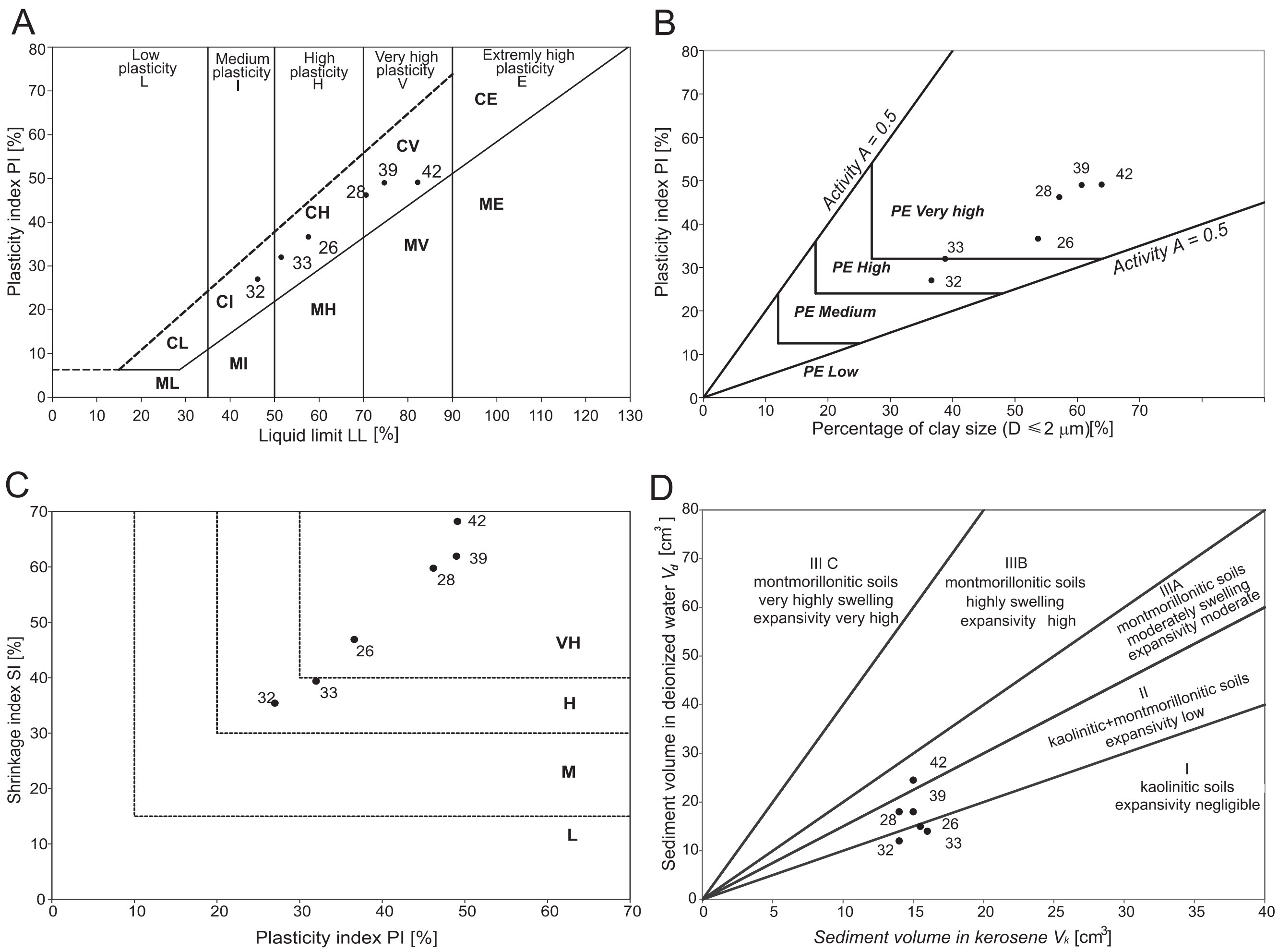


Fig. 3. Classification of soils used in the present study based on classification schemes proposed by: A – Casagrande chart by Head (1992); B – Van der Merwe (1964); C – Raman (1967); D – Prakash and Sridharan (2004)

A – CL – clays of low plasticity, CI – clays of medium plasticity, CH – clays of high plasticity, CV – clays of very high plasticity, CV – clays of extremely high plasticity, ML – silts of low plasticity, MI – silts of medium plasticity, MH – silts of high plasticity, MV – silts of very high plasticity, MV – silts of extremely high plasticity; **C** – L – low expansivity, M – medium expansivity, H – high expansivity, VH – very high expansivity

bution as no. 28, but a higher content of beidellite, and the swell index twice lower due to differences in natural water content, which is a key factor in the swelling process. Analysing the swelling potential S (Fig. 4) of tested clays, the samples can be divided into two groups: with a potential of >25% and a very high degree of expansion DE – soils nos. 28, 39 and 42, and with a potential of 5–25% and a high degree of expansion DE – soils nos. 26, 32 and 33. This indicates that the clays may have a negative impact on the foundation constructed within them, especially under conditions where water content may vary due to environmental factors.

The study has confirmed the common relationship that greater swelling occurs at lower initial water content of the sample. Chen (1988) stated that expansive soils with a natural water content <15% pose the greatest threat to buildings, because they can significantly increase its volume by absorbing water, while the same soil with water content >30% cannot be subjected to swelling. In Poland, the substrate composed of clays with the initial water content *w* <35% and the swell index ε_p >5% is considered as swelling, while that with the values of *w* <15% and ε_p >10% is treated as strongly swelling (ITB 296, 1990). The results of tests for water content values between 15 and 30% are shown in Figure 5A.

Table 2

Mineral composition of tested clays

No.	Percentage of individual components						
	clay minerals	including:			goethite	organic matter	quartz and other
		beidellite	kaolinite	illite			
26	46.9	39.9	7.0	ak	–	0.7	52.4
28	56.9	44.1	12.8	5.0	–	–	43.1
32	40.1	32.2	7.5	0.3	1.1	–	58.8
33	38.9	30.2	6.8	1.9	3.4	–	57.8
39	64.2	51.0	7.5	5.7	2.1	–	33.7
42	67.2	56.5	10.1	0.6	7.5	–	25.3

The soils show different values of swell index, ranging from ~2–53%. The analysed soils can be divided into three groups of different soil susceptibility to swelling, depending on the percentage of clay fraction and mineral composition, which is reflected in the nature of obtained relationships.

Soils nos. 26 and 28, grey in colour, are characterized by the clay fraction content from 54–57%, sand fraction content between 0.5 and 2.3%, and significant silt fraction content from

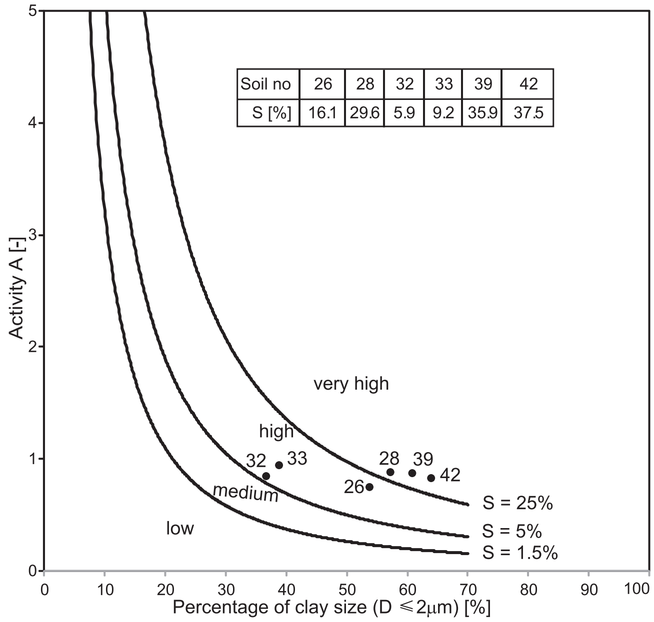


Fig. 4. The studied clays on the classification chart for swelling potential (Seed et al., 1962)

42.4–44%. The diversity in the swell index values results from the significant differences in the mineral composition of the clay fraction. Soil no. 28 is characterized by high amount of clay minerals (57%) of which beidellite accounts for ~44% of composition. This results in higher values of swell index (~5–22%) in comparison to soil no. 26. The greatest differences were observed on samples with a water content of 15% (Fig. 5A, Tables 1 and 2). At 15% of water content, soil no. 28 reached the swell index values similar to the yellow soils nos. 39 and 42. The latter are characterized by the highest amount of clay fraction among the analysed soil samples, i.e. from 61–64%, and by the lowest value of sandy fraction content – not exceeding 1%. The amount of clay minerals and beidellite is similar, reaching 64.2–67.2% and 51.0–56.5%, respectively (Tables 1 and 2). This results in the ~53% swell index values at 15% water content. The third group is represented by soils nos. 32 and 33 – yellow and green, clearly silty (~49% of silty fraction), with a low amount of clay fraction (37–39%), and the lowest content of clay minerals (39–40%) and beidellite (30–32%) (Fig. 5A, Tables 1 and 2). Therefore, the swell index values are the lowest in the entire set of soils.

According to Alexander (1993) the swelling pressure values can be classified in terms of threat to the construction, as follows: <150 kPa noncritical, 150–170 kPa marginal, 180–250 kPa critical, >250 kPa very critical. The test results for swelling pressure on the model soils with predetermined water content between 15 and 30% are shown in Figure 5B. The obtained values indicate that the soils were characterized by high swelling pressure values even at high water content of ~30%. The values of nearly 60–123 kPa were obtained for soils nos. 28, 39 and 42, which can generate problems even for a small housing. For the remaining soils at water content of ~30%, the obtained swelling pressure values were ~22 kPa. At 15% water content, swelling pressure increases significantly, reaching values from 300–600 kPa. This may bring serious consequences for the construction and maintenance of even large public buildings. According to the classification, this can be critical to their safety. Even the samples with lower content of clay minerals and beidellite showed a swelling pressure of up to 300 kPa at the same water content level.

The course of received relationships between the initial water content and swell index was best reflected by an exponential function. For soils nos. 39 and 42, the relationship between the parameters was better reflected by a linear function. For the analysed samples the regression coefficient R^2 was >0.95 for exponential relationships and >0.99 for the linear ones (Fig. 5A). Similarly, the course of received relationship between water content and swelling pressure was best reflected by exponential functions, and the regression coefficient R^2 is >0.94 in this case (Fig. 5B).

The analysis of the relationship of swell index and swelling pressure against water content of Neogene clays from the Poznań Formation can be found in the publications of Gorączko and Kumor (2011). The tested clays were from Bydgoszcz (area B), from the central part of the sedimentary basin (Wichrowski, 1981) with the most fully developed succession, and they were characterized by similar physical parameters in relation to those described in this paper.

For natural soil samples (dried uniformly at room temperature) with different initial water contents ranging from 19–41%, the swell index values ranged from 5–60%. For clays with a water content level close to natural, the swelling pressure values were in the range of 100–400 kPa, whereas for clays desiccated to a water content close to the shrinkage limit, the swelling pressure values reached 2000 kPa. The above-mentioned authors indicated a linear relationship between the water content and swell index, and an exponential function in case of water content and swelling pressure. They also claimed that only in a narrow range of water content, linear approximation could be applied with sufficient accuracy. Exponential character of the correlation relationship was also confirmed by Niedzielski (1993) in the investigations on undisturbed samples of Poznań clays and varved clays.

Moreover, at the initial water content exceeding the plastic limit, the influence of the water content changes on the values of swelling parameters (swell index and swelling pressure) is lower than for the water content values close to the shrinkage limit, below which changes in volume are no longer observed. It has been confirmed by tests carried out with the assumption of the exponential nature of the obtained values. In the future, it is planned to extend the scope of the research to water content values close to the air-dry state. This will allow observing the magnitude of the impact on the building after hydrating such desiccated soils. Based on the empirical relationship of McDowell (1959), the end of swelling can be estimated according to the equation $0.47w_L + 2$. The calculations indicate that further analysis of the swelling parameters in clays characterized by water content above 30% would make sense only for soils nos. 28, 39 and 42. Their assumed water content is 35.2, 37.1 and 40.6%, respectively, as calculated from the formula, and the soils should swell at the water content of 30%. This hypothesis finds confirmation in the results of the swell index, obtained in this report (Fig. 5A).

Many methods have been developed to estimate the swell and shrink potential of soils. As mentioned above, they can be divided into:

- indirect (the use of the relationship of physical, chemical and mineralogical soil properties with swelling–shrinkage characteristics),
- direct methods involving actual measurements of swelling (e.g., swell index test and swelling pressure test) and shrinkage (e.g., CLOD index C_w).

Between the factors influencing the swelling properties of expansive soils, not only the stress state, but also the soil characteristics (particle-size distribution and mineral composition) and environmental influences (changes of water content)

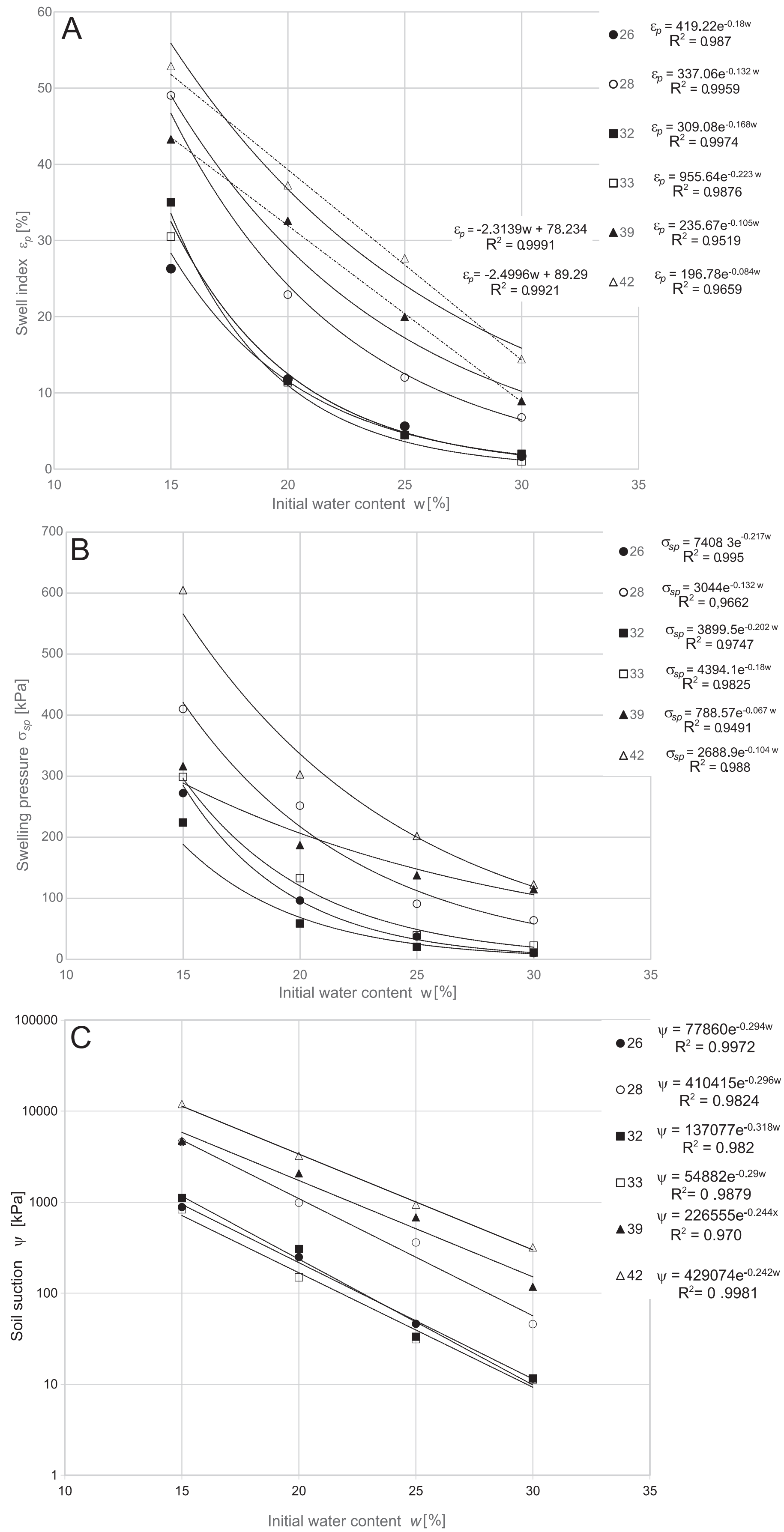


Fig. 5. The effect of initial water content on: A – swell index, B – swelling pressure, C – soil suction

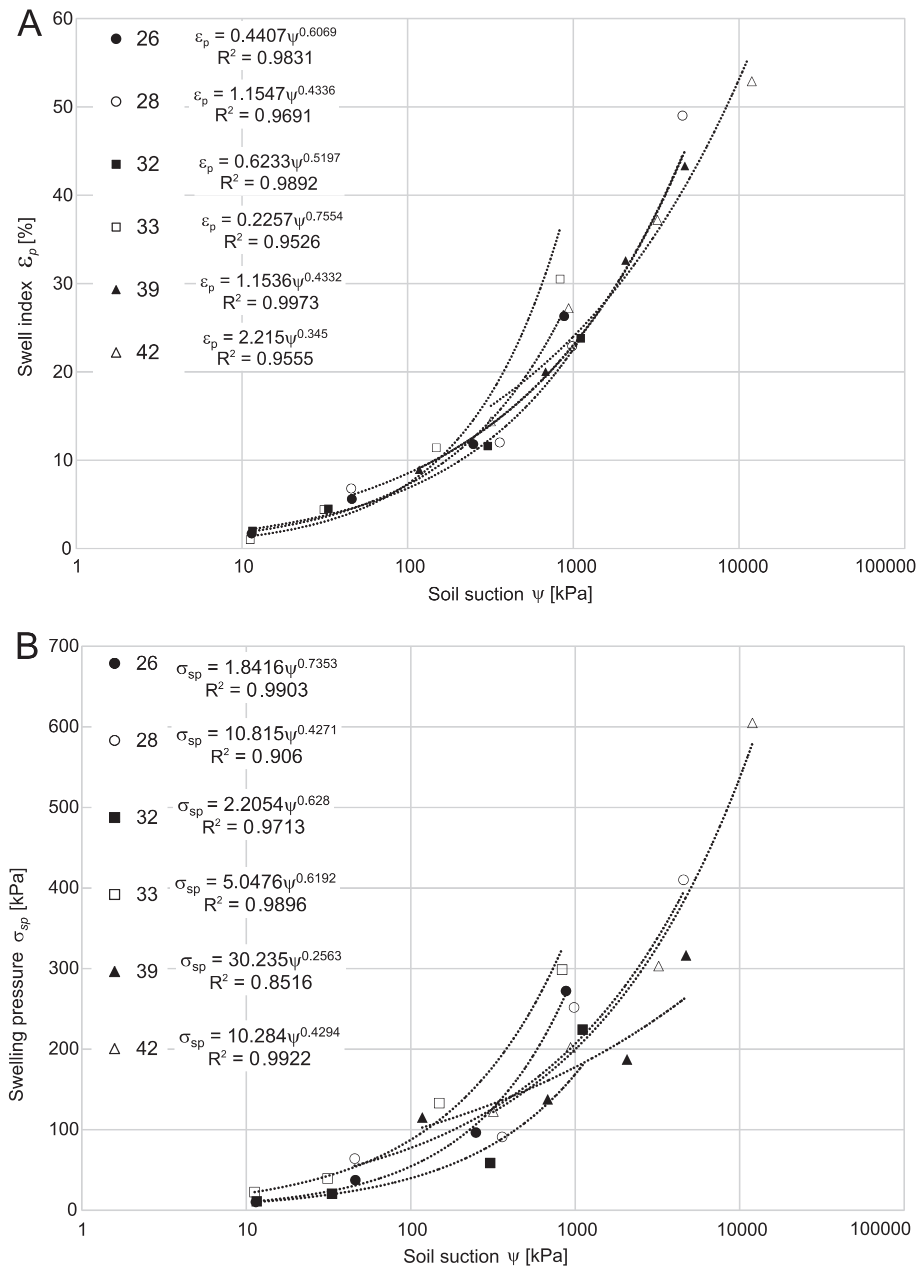


Fig. 6A – the relationship between swell index and soil suction;
B – the relationship between swelling pressure and soil suction

should be mentioned. A fundamental physical property of unsaturated soils that indicates the intensity or energy level with which a soil sample attracts water is soil suction. This extremely vulnerable indicator, which incorporates overall physical, chemical and mineralogical properties of the soil, describes the potential with which a given soil at a given water content adsorbs and retains pore water. Therefore, soil suction measurements can be alternative for determining swelling properties of soils.

The results of soil suction tests carried out on six types of clays of different initial water contents are shown in Figure 5C. They indicate that there is a correlation between these parameters, according to which the higher the initial water content is, the lower suction value is obtained. Soils nos. 42, 39 and 28, containing more clay fraction than the other soil types (57.1–63.9%) and >57% of clay minerals in the clay fraction, are characterized by higher suction and located in the upper part of the graph. The subsequent analysis was made to relate the values of swelling parameters of Neogene clays with the suction values for water contents of 15, 20, 25 and 30%. Figure 6A illustrates the relation between soil suction in kPa and swell index, whereas Figure 6B presents the correlation between suction and swelling pressure for tested clays. The study has demonstrated that the character of correlation relationships between swelling and suction parameters takes the form of a power function: $\varepsilon_p = A1\Psi^{B1}$ and $\sigma_{sp} = A2\Psi^{B2}$. The linear nature of the correlations between these parameters is also stated in Uzundurukan et al. (2014) for compacted clayey soils. However, a different form of the empirical relation was a result of the adoption of different units for suction (this parameter was expressed in log kPa). The relationship between swelling properties and the initial soil suction was also studied by Hanumantha Rao et al. (2011). These authors looked for the relationship be-

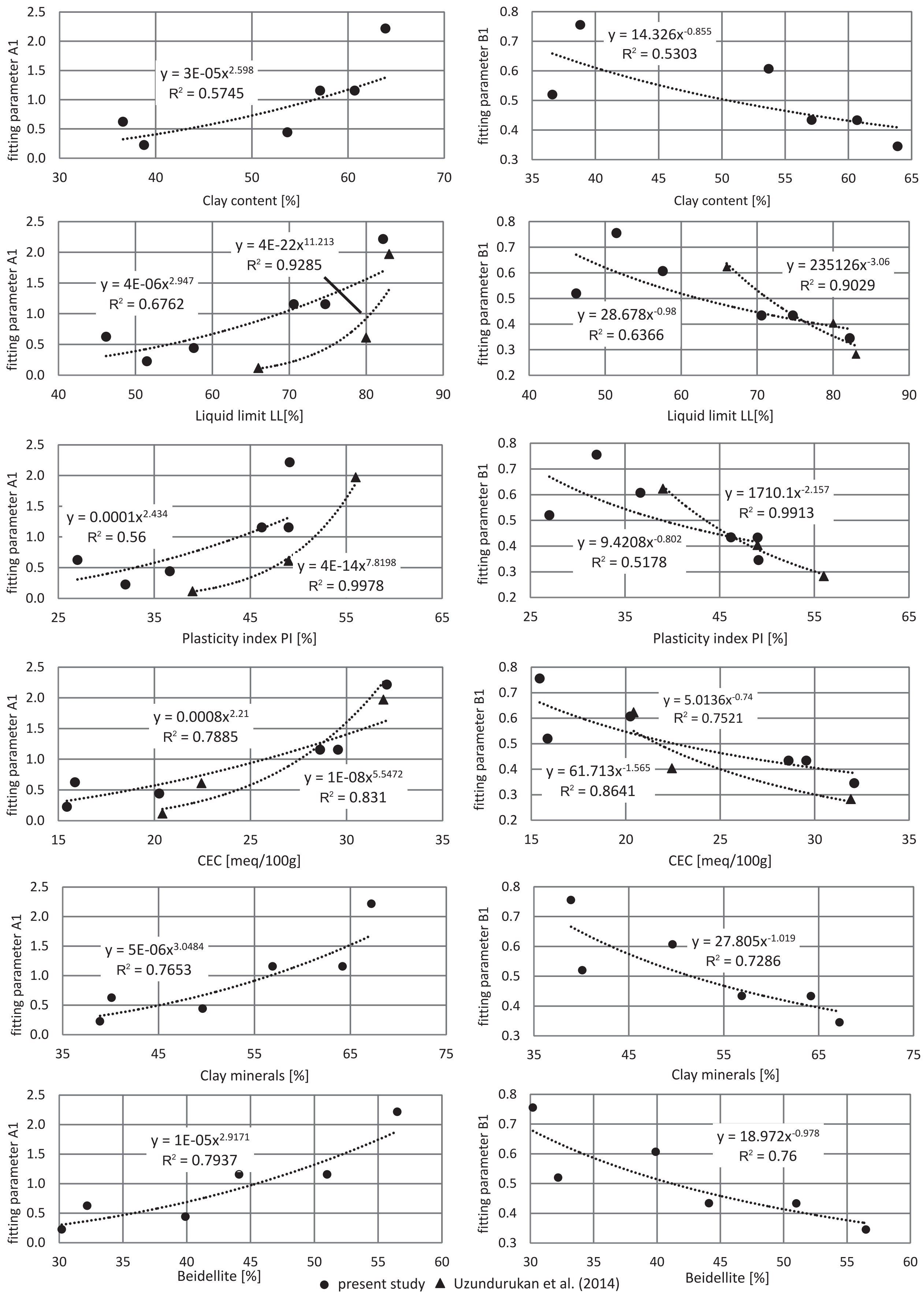
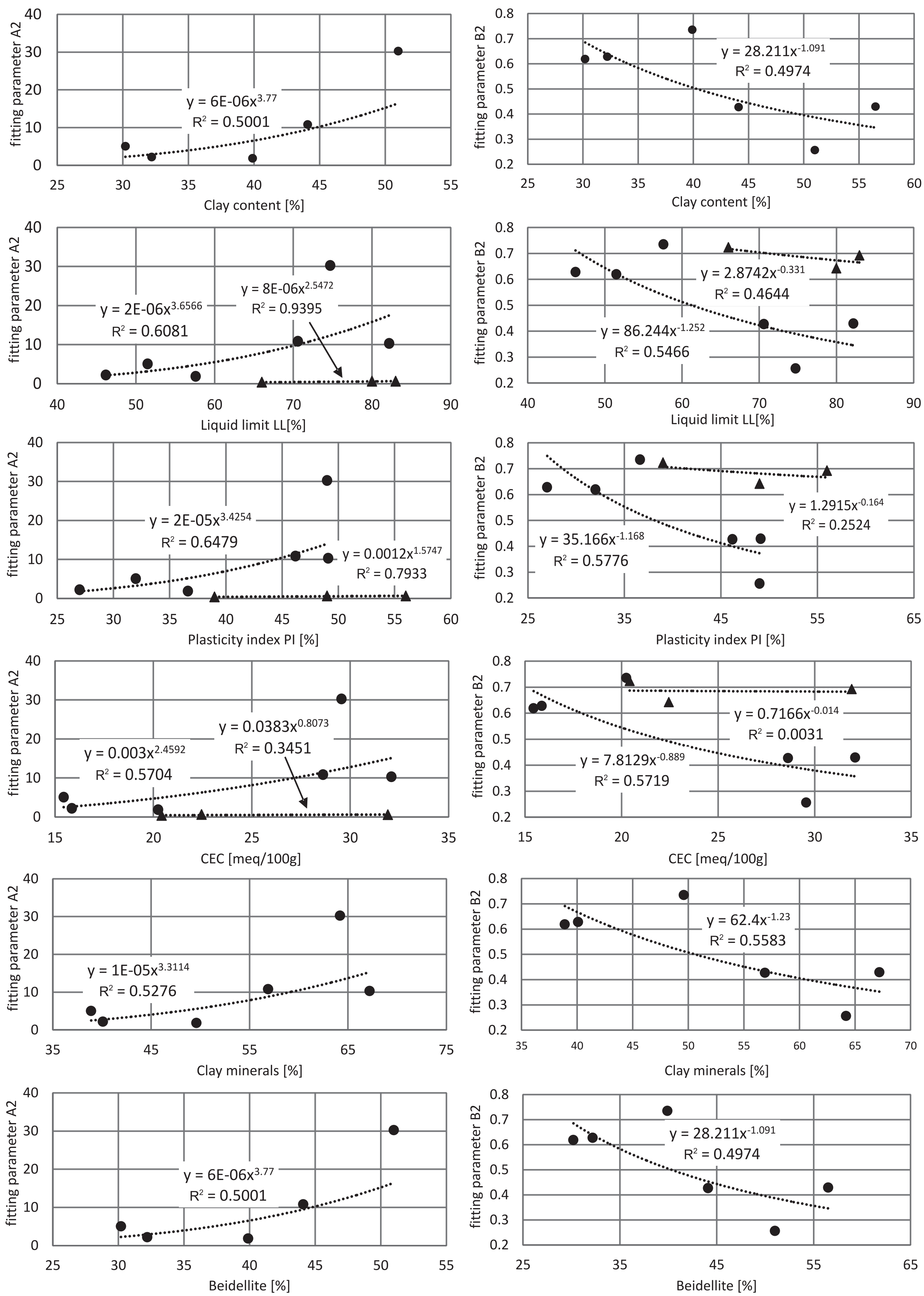


Fig. 7. Variation of fitting parameters (A – A1 and B1; B – A2 and B2) with a – clay content [%],



b – liquid limit LL[%], c – plasticity index PI [%], d – CEC [meq/100g], d – clay minerals[%], e – beidellite [%]

tween swell [%], swell pressure [kPa] and FSI [%] with the suction corresponding to the specimen compacted at ρ_{dmax} at the optimum water content OMC.

Based on the swelling and suction test results, an additional analysis was also performed, referring to the relation of A1, B1 and A2, B2 coefficients in the equations of power function towards the index parameters of soils, including: clay fraction content, plastic limit, plasticity index, CEC, clay minerals content, and beidellite content, which have been determined for tested clays. Figure 7A presents the variation of fitting parameters A1 and B1 with soil parameters, whereas Figure 7B shows a similar parametric analysis of A2 and B2 coefficients. The results presented in each figure include also data taken from Uzundurukan et al. (2014). By analysing the results, it was found that the relation between the index parameters of the clay soil and the coefficients in the equations (best describing the relationship of swell index *versus* soil suction, and swelling pressure *versus* soil suction) is described as a power function. With the increasing percentage of the clay fraction, plastic limit, plasticity index, CEC, clay minerals content, and beidellite content, the A1 and A2 values (fitting parameter) are higher, whereas the B1 and B2 values (exponent) are lower.

Higher values of the regression coefficient R^2 are found in the analysis of the relationship between swell index and soil suction than between swelling pressure and soil suction. Determining the statistical significance of the impact of these factors is a complex task, because each of them can variably influence the swelling process. The issues, described in the paper, require further experimental studies, extended to other types of clays with different mineral composition, to develop and validate the relationship that is general in nature.

In addition, the measured ε_p values are also plotted in Figure 8 against the swell pressure σ_{sp} values for the data from the experiments. In the Neogene clays, this relationship has the form of a linear function. In the investigated range of water content, a strong exponential relationship is also noted. High coefficients of correlation confirmed the strong correlation between σ_{sp} and ε_p, and the trend lines overlap to the value of 200 kPa. Higher discrepancies are noted together with the increase of determined parameters. Thanks to this relationship, it is possible to predict the swelling pressure on the basis of the indicator as a substitute for long-lasting, advanced laboratory tests. Similar studies on the relationships between the swelling pressure and swelling index are discussed in the papers of Sridharan and Gurtug (2004), Gunes (2009), Erzin and Gunes (2011, 2013). Erzin and Gunes (2013), who studied a mixture of kaolinite (K) and bentonite (B) (95% K + 5% B, 90% K + 10% B, 85% K + 15% B i 80% K + 20% B), confirmed the same character of empirical relationships and a high correlation between these parameters (R^2 = 0.77). The course of received relationship corresponds to the results obtained for Neogene clays, especially for the swelling pressure <300 kPa (Fig. 8).

SUMMARY

Each subsoil, regardless of its geographical location, is naturally subjected to changes due to a variety of environmental factors, both natural or anthropogenic. In urban areas, geotechnical design is generally considered as a difficult engineering task, especially when expansive soils occur in the profile. Therefore, a key aspect for engineering practice is to determine the volume changes occurring due to natural water content oscillations that may cause numerous damages and failures to buildings. The laboratory assessment of volume changes can be undertaken by a number of methods. Empirical methods that assess volume changes in terms of simple soil properties, such as liquid limit, plasticity index or activity, are useful, but they are accepted as simple indicator methods. Moreover, they do not take into account *in situ* conditions (e.g., moisture content, soil suction, soil structure, and climate). Oedometer methods represent more direct methods of assessing volume changes, nevertheless they are time-consuming and expensive. Soil suction methods provide high sensitivity; they are relatively simple and quick, and thus inexpensive.

This report presents:

– the effect of the initial water content on the swell index, swelling pressure, and soil suction,
– the relationship between soil suction and swelling properties,
– variations of the fitting parameter in relation to the soil index properties,
– the relationship between the swell index and swelling pressure values for the soils from the soil-structure interaction zone, representing the largest complex of expansive soils in Poland.

The study shows that the fluctuation of water content ranging from 15–30%, which is approximately equal to *in situ* conditions, causes the change of swell index in the range from 1–53%, and of swelling pressure in the range from 10–605 kPa. This indicates that the initial water content is one of the crucial parameters affecting the range of deformation observed in clay. The results of this study indicate the exponential nature of the relationship between the initial water content and swell index and swelling pressure, with a high correlation coefficient (R^2 >0.95).

Soil mineralogy plays a significant role in the swelling properties of expansive soils. The potential for volume change of clay soils is governed by the type and amount of clay minerals present. It was observed that these soils are characterized by a high content of the clay fraction and a high content of minerals from the smectite group. Soils containing high proportions of the clay fraction – yellow clays (soils nos. 39 and 42) and beidellite (soils nos. 39, 42 and 28) – reached the highest values of the swelling and suction parameters.

As suggested by Bell and Maud (1995), suction tests should be carried out for the assessment of potential expansion. Additional tests, based on suction measurements of the soils discussed in this study, were undertaken for a better understanding of the influence of water content changes on swelling properties. This survey has demonstrated that lower soil suction was obtained at higher initial water contents. The tested soils were characterized by diverse values of suction, depending on the soil type, particle-size distribution, and mineral composition. The nature of the correlation between these parameters was exponential. Attempts were also made to relate the swelling properties with soil suction. Figure 6A and B show that the swelling properties exhibit a well-defined correlation with soil suction, having the form of an exponential function. Therefore, swelling properties can be determined by measuring suction. These methods of volume change assessment are recommended for further studies. Additional analysis, carried out to obtain a correlation equation relating the fitting parameters A1, B1 and A2, B2 to the soil index properties, has indicated that the relation between soil suction and swelling properties clearly depends on the nature of the different clays.

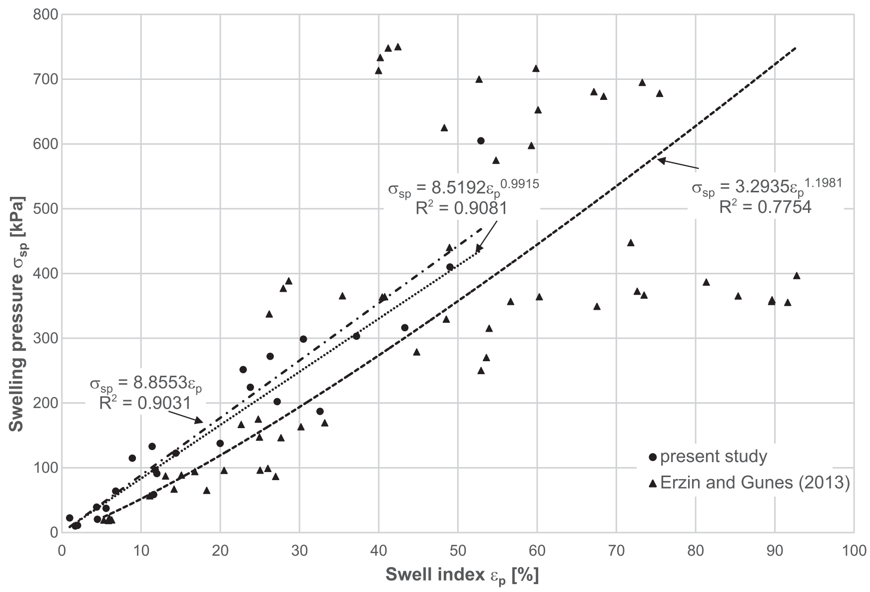


Fig. 8. The relationship between swell index and swelling pressure

The relationship between the swell index and the swelling pressure for the investigated Neogene clays is linear and can be used in the prediction of swelling pressure, based on an easily determined parameter such as swell index.

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