# MEASUREMENT OF CHANGES OF STIFFNESS DUE TO SATURATION ON CRUSHED GRAVEL MADE FROM WEAK ROCK

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**Abstract**

Crushed gravel derived from weak rocks can be susceptible to degradation of its material properties. Saturation of this gravel can lead to significant changes. This article focuses on the laboratory measurement of crushed claystone from Czech Republic under 1D compression conditions. The tests involved varying initial water content, and samples were saturated at specific loads. Parameters of interest included the vertical deformation of the sample and changes in stiffness during loading and due saturation of the sample. The measurements revealed, that the saturation of this crushed gravel has a significantly affects its stiffness, leading to high compaction of the loaded sample. This process could potentially have a substantial negative impact on ground construction using this material.

**Keywords**

Weak rocks, crushed gravel, slaking effect, degradation of material properties

# 1 INTRODUCTION

It is common practice to construct earth structures, such as embankments, using materials readily available near the construction site. For embankments, the most available material often comes from a nearby cut on the same road under construction which means that the material for the embankment is predetermined by the location.

In the Czech Republic a common type of rock is weak rock, such as claystone and mudstone, predominantly found in western Bohemia and the Carpathian Mountains. These materials are commonly used for construction of earth structures.

However, weak rocks, such as claystone and mudstone, may be susceptible to degradation, especially due to changes in void ratio or during wetting-drying cycles. Franklin [1] extensively studied this phenomenon on rock fragments. More recently, Afifi [2] studied the behaviour of weak rocks during saturation on test blocks and found that the duration of submersion significantly affects the change in mechanical properties.

Kikumoto [3] conducted tests on crushed weak rocks from Japan, focusing on 1D compression tests and observing changes in particle size distribution due to several wetting and drying cycles. He demonstrated that these cycles cause significant increase in vertical deformation of the sample under load and alter its mechanical properties.

The primary objective of the laboratory tests carried out in this research is to qualitatively determine the mechanical behaviour of crushed material made of weak rocks from the Czech Republic during loading, saturation and subsequent loading after saturation. Another factor that has been varied was the initial water content of the crushed material before its first load. The insights gained from this study can be applied, e.g. in the settlement analysis of embankments built from similar materials.

## Tested soil types

In this study, samples of claystone from two locations, approximately 1 km apart, were tested. The first group of samples is from Záhořanské geological stratum and due to its larger availability, it was predominantly used in the majority of the tests. The second group of samples comes from Bohdalecké geological stratum.

All claystone samples were obtained from shallow excavations with a depth of approximately 1 m. Additionally, one test was conducted on quartz fluvial sand, which was not expected to undergo volumetric changes due to wetting-drying cycles. This test served as a reference for comparison with the tests conducted on claystones.

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# 2 METHODOLOGY

For the purpose of the 1D compression tests, claystone samples taken from the site were mechanically crushed to the fraction with grain diameter between 0 and 4 mm. The material prepared in this manner, was not further sorted or otherwise modified as its preparation corresponds to the workflow in practise. The maximum grain size corresponds to the requirement of standard ČSN EN 1997-2 [4] stating that the maximum grain size must be smaller than 20% of heigh of the sample.

Crushed gravel made from Záhořanské claystone, available in larger amount, was tested with three different initial water contents to determine the influence of this factor. The first moisture content level was the in-situ value of 2%. The other initial values of water content were 5% and 10%. Crushed gravel made from Bohdalecké geological stratum was tested only with one initial water content of 10% due to limited amount of available material. The original water content of Bohdalecké claystone was 4%. The sample prepared from quartz fluvial sand was tested with its original initial water content of 0.5%.

After adjusting the water content, the crushed gravel was compacted in the 1D compression ring. Compaction was carried out to reach the density index $Id = 0.5$ according to the formula (1).

$$I_D = \frac{e_{max} - e}{e_{max} - e_{min}} \tag{1}$$

where $I_D$ is density index, $e_{max}$ is the maximum void ratio, $e_{min}$ is the minimum void ratio and $e$ is the actual void ratio.

The minimum and maximum void ratios were estimated to be 0.60 and 0.97, respectively. The density of solid particles was estimated to be 2700 kg/m³. It means that a ring for the 1D compression test with a diameter of 50 mm and a height of 20 mm must contain approximately 60 g of crushed gravel. Compaction was carried out in 2 layers each with a height of 10 mm to ensure uniform density across the sample's height.

After compacting the crushed gravel with the selected water content into a ring for 1D compression test, the sample with the 1D compression box was placed into the loading frame. Subsequentl, one of two types of loading sequence scheme was performed. In the first scheme, a sample was instantaneously loaded to the final stress of 300 kPa in all tests. The final stress level roughly corresponds to the value at the base of an embankment with a height of 17 m. In the second scheme, the final stress was applied in several loading stages, during which a constant load was maintained. The advantage of the second scheme is that vertical deformations were measured at different stress levels. However, the second scheme takes longer, with each load step lasting 15 hours long to allow the vertical deformations to settle. This implies that the water content may change more compared to the first loading scheme.

Once the final stress was reached, the time for stabilisation of vertical deformations was allowed, and then the sample was saturated without any change in vertical stress. After saturation, vertical deformations were measured for a few days. Subsequently, more loading steps were added to determine the behaviour of saturated sample in comparison with its behaviour before saturation. The maximum vertical stress applied during the test ranged between 500 kPa and 3400 kPa. Finally, the sample was unloaded in several loading steps.

Vertical deformation and vertical stress were directly measured during the tests. Stiffness and its changes were evaluated by means of the compression index according to Formula (2), which defines the slope of a measured stress-void ratio curve with effective stress axis in logarithmic scale according to the standard ČSN EN ISO 17892-5 [5].

$$C_C = \frac{-\Delta e}{\Delta \log \sigma'_v} \tag{2}$$

where $C_c$ is compression index, $e$ is void ratio and $\sigma'_v$ is vertical effective stress.

# 3 RESULTS

The measured data from all laboratory tests are presented in figures Fig. 1–Fig. 5. The first symbol in the test designation indicates the geological stratum (Z – Záhořanské, B – Bohdalecké), the second one defines the initial water content, and the last one indicates the number of repetitions of a particular test. Fig. 1–Fig. 3 contain measured data from tests on samples from Záhořanské geological stratum, Fig. 4 shows measured data from tests on samples from Bohdalecké geological stratum, and the results from the reference test on quartz fluvial sand are presented in Fig. 5.

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Changes in vertical strain due to water saturation are summarised in Tab. 1. Compression indexes $C_{c,1}$ at the initial loading from 50 kPa to 100 kPa are stated in Tab. 2, and in Tab. 3 compression indexes $C_{c,2}$ for further loading after saturation are provided.

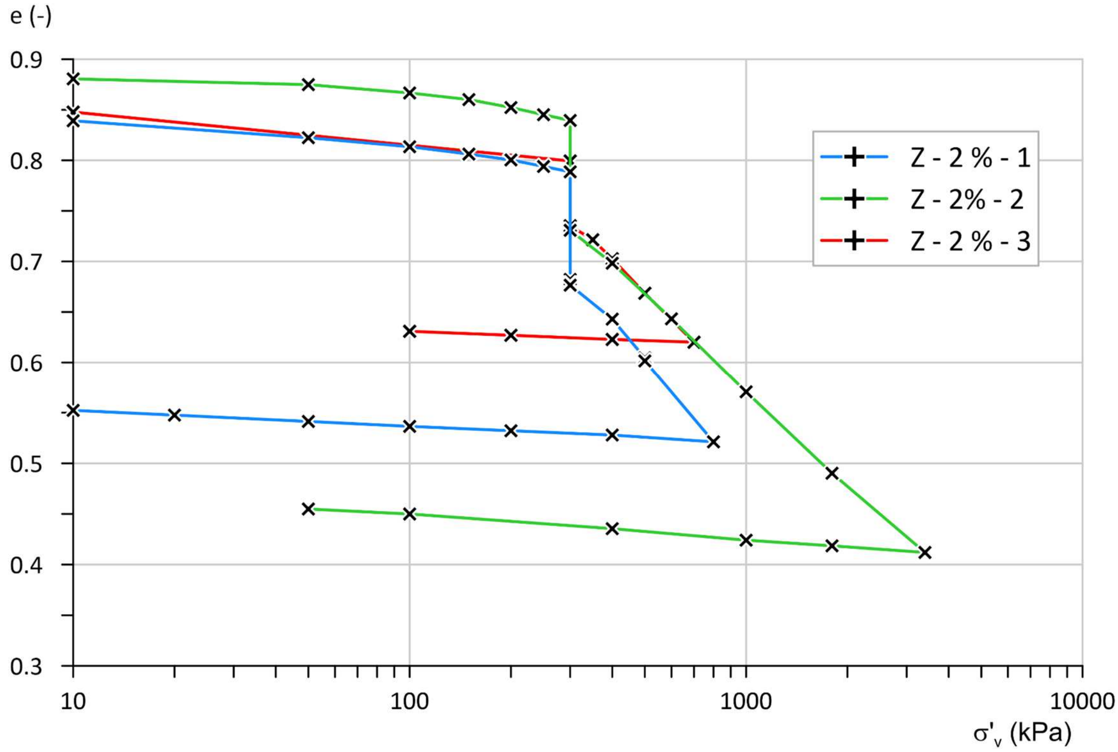


Fig. 1 Plot of void ratio versus vertical effective stress for samples from Záhořanské geological stratum with the initial water content of 2% (designated as Z – 2%).

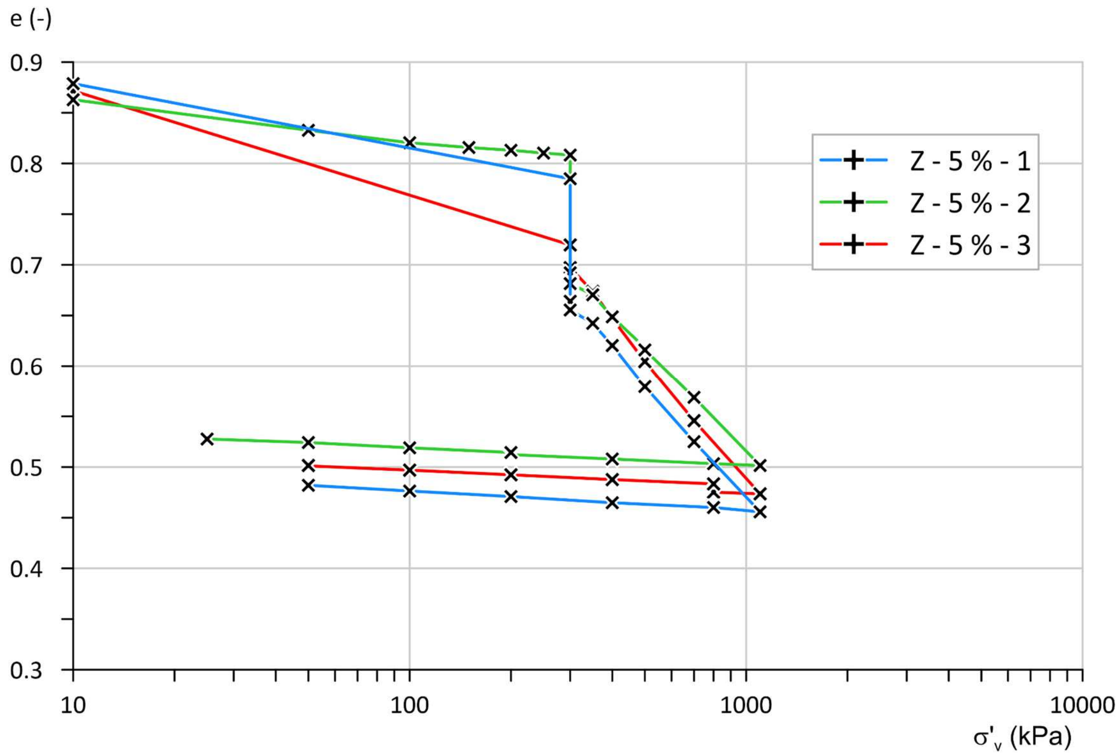


Fig. 2 Plot of void ratio versus vertical effective stress for samples from Záhořanské geological stratum with the initial water content of 5% (designated as Z – 5%).

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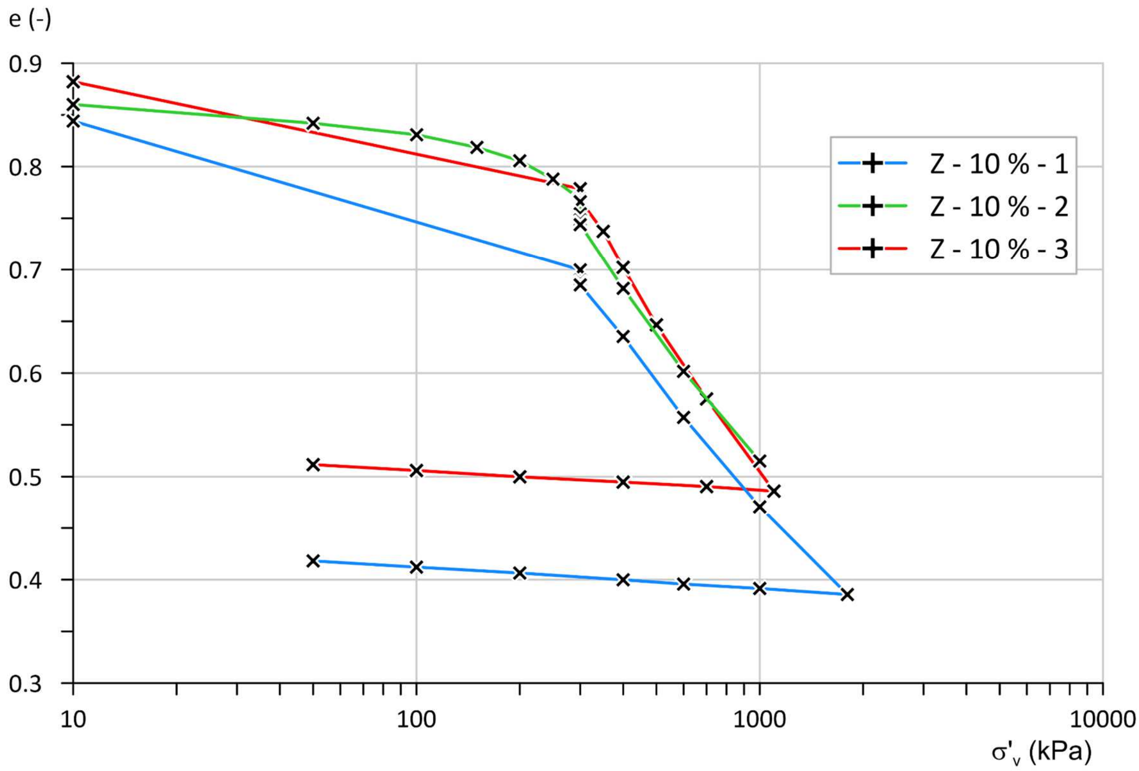


Fig. 3 Plot of void ratio versus vertical effective stress for samples from Záhořanské geological stratum with the initial water content of 10% (designated as Z – 10%).

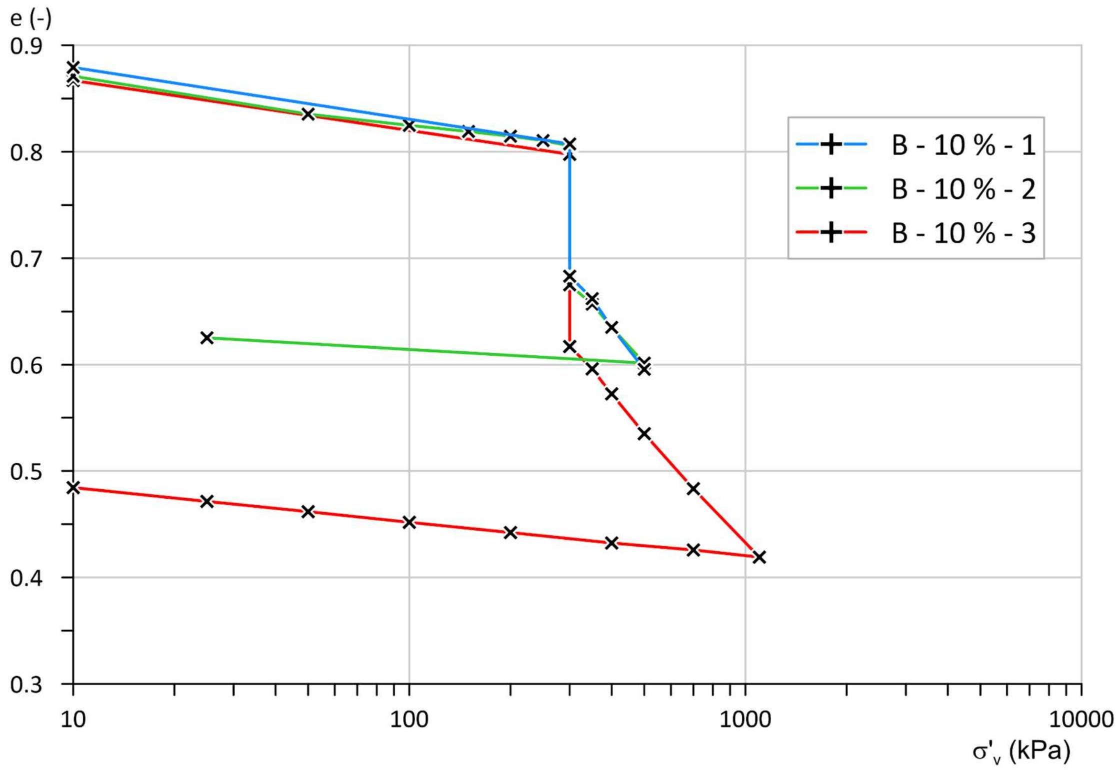


Fig. 4 Plot of void ratio versus vertical effective stress for samples from Bohdalecké geological stratum with the initial water content of 10% (designated as B – 10%).

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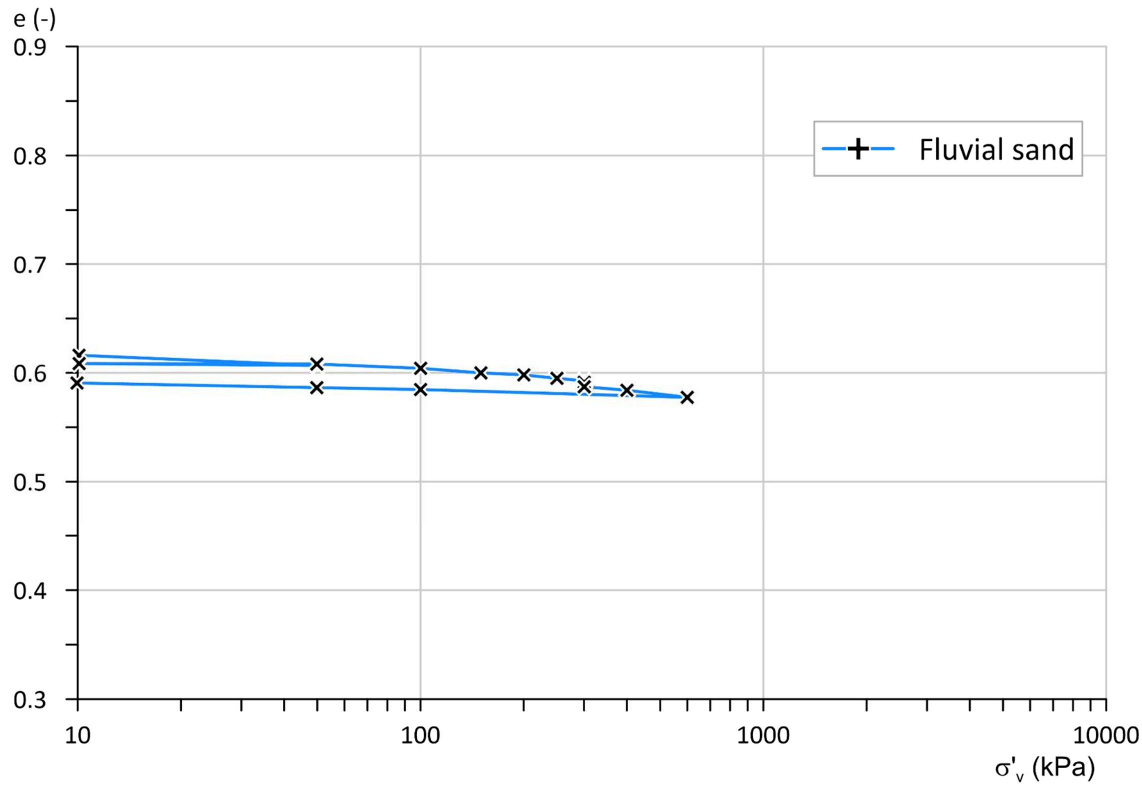


Fig. 5 Plot of void ratio versus vertical effective stress for dry sample from fluvial sand.

Tab. 1 Change of vertical strain Δε (%) for each tested sample due to the saturation.

| Sample Nr. | Z – 2% | Z – 5% | Z – 10% | B – 10% | Fluvial sand |
|---|---|---|---|---|---|
| 1 | 6.1 | 6.9 | 0.7 | 6.6 | 0.3 |
| 2 | 5.7 | 6.8 | 1.3 | 6.9 | - |
| 3 | 3.5 | 1.2 | 0.6 | 9.7 | - |

Tab. 2 Compression index $C_{c,1}$ (-) for tested samples for initial loading from 50 kPa to 100 kPa.

| Sample Nr. | Z – 2% | Z – 5% | Z – 10% | B – 10% | Fluvial sand |
|---|---|---|---|---|---|
| 1 | 0.030 | - | - | - | 0.023 |
| 2 | 0.027 | 0.017 | 0.037 | 0.035 | - |
| 3 | - | - | - | - | - |

Tab. 3 Compression index $C_{c,2}$ (-) for each tested sample for loading after the saturation.

| Sample Nr. | Z – 2% | Z – 5% | Z – 10% | B – 10% | Fluvial sand |
|---|---|---|---|---|---|
| 1 | 0.409 | 0.373 | 0.412 | 0.425 | 0.037 |
| 2 | 0.307 | 0.342 | 0.418 | 0.356 | - |
| 3 | 0.339 | 0.394 | 0.488 | 0.347 | - |

# 4 DISCUSSION

All tested samples exhibited qualitatively similar behaviour during loading, saturation and unloading as presented in Fig. 6. The typical behaviour and has 4 major phases (marked as phases A to D).

Phase A corresponding to loading from 0 to 300 kPa with the initial water content, displaying a highly non-linear response. The detailed behaviour of the sample in this phase was measured only when loading was carried out in multiple stages. The slope of the measured stress-void ration curves in logarithmic scale (compression index) increases with the increasing stress level. This might be caused by several reasons:

A) slaking effect manifested in the gradual degradation (crushing) of interparticle contacts,

B) gradual approaching to the NCL line.

The detailed behaviour of the sample in this phase was measured only when loading was carried out in multiple stages.

Phase B correspond to the full saturation of the sample at a constant stress of 300 kPa. The samples responded to saturation with a rapid increase in deformation. The rate of deformation decreased quickly with time and most of the deformation occurred within a few minutes after saturation. Volumetric changes were measurable even after a few days after saturation.

In phase C, the samples were loaded above 300 kPa in several steps and were fully saturated throughout this phase. The behaviour of samples in this phase was substantially different compared to the first phase. Firstly, linear void ratio-stress curves in logarithmic scale were measured resulting in the constant values of compression index. Secondly, the compression indexes from this phase were significantly higher than those from the first phase, indicating that the stiffness of the sample is lower.

In phase D, unloading took place and the samples were fully saturated. The slope of the curve in the stress-void ratio plot was constant during the entire phase. The compression index is much smaller than in loading phase C, suggesting that the sample is much stiffer. This behaviour corresponds to the typical behaviour of fully saturated soils, where the stiffness during unloading is significantly higher than the stiffness during loading in phase C.

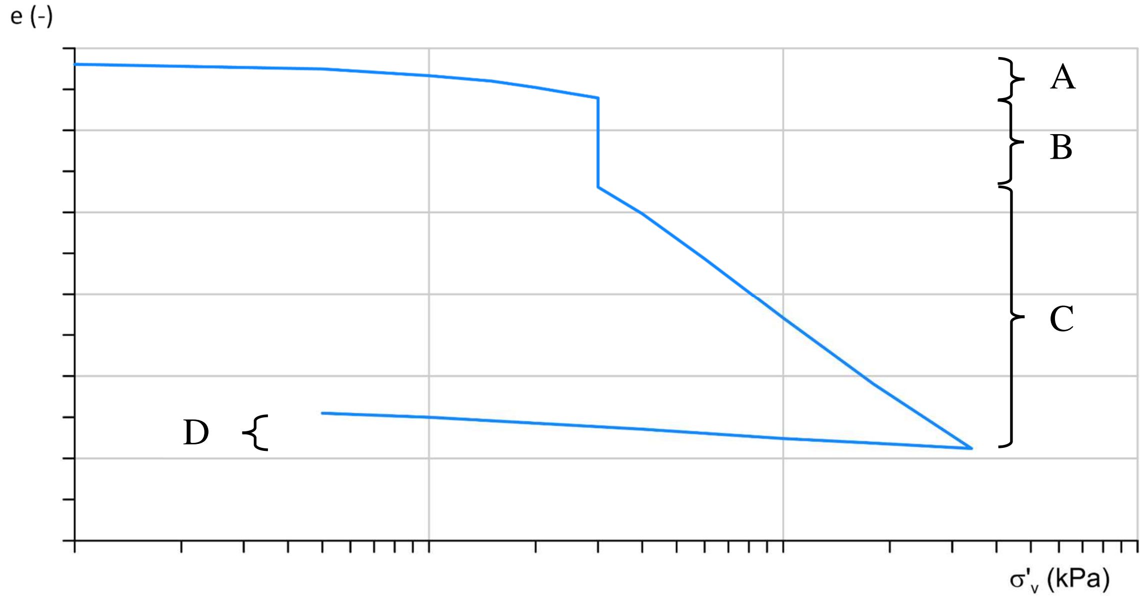


Fig. 6 Typical behaviour of tested samples with 4 major phases of test.

The behaviour of individual samples differs slightly from each other from a quantitatively. The curve non-linearity in phase A is most significant for the sample from Záhořanské geological stratum with an initial water content of 10% (tests designated as Z – 10%), for which the value of compression index changed from 0.037 to 0.243 before saturation. For samples with lower initial water contents, the compression Index changed approximately from 0.030 to 0.070. On the other hand, volumetric changes during saturation (phase B) were greatest for the samples from Záhořanské geological stratum with an original water content (tests designated as Z – 2%) or with an initial water content of 5% (tests designated as Z – 5%), as shown in Tab. 1. The changes in vertical strain ranged between 5.7% to 6.9% for most of the samples from these two groups. The differences in vertical strain changes in phase B between samples Z – 2% and Z – 5% were small but several times higher than in samples Z – 10%. Compression index $C_{c,2}$ for further loading in phase C ranged between 0.330 and 0.420 as shown in Tab. 3. The significant difference was between compression index $C_{c,1}$, during loading from 50 kPa to 100 kPa, as shown in Tab. 2, and compression index $C_{c,2}$ when loading after saturation in phase C as it increased more than 10 times. Compression index during unloading in phase D ranged between 0.015 and 0.027. In general, the total volumetric changes of the samples from Záhořanské geological stratum were comparable regardless of the initial water content. The difference was that with the increasing initial water content, a larger portion of volumetric changes took place during the initial loading (phase A).

The samples prepared from Bohdalecké geological stratum were tested only with an initial water content of 10%. Contrary to the samples from Záhořanské geological stratum with the same initial water content, only minor changes in compression index during phase A were detected. On the other hand, significantly higher volumetric changes were measured in the following phase B during saturation.

The comparison of the behaviour of samples prepared from crushed claystone with the behaviour of the sample prepared from quartz fluvial sand shows that fluvial sand is much stiffer. The change of the compression index before and after saturation for the sample made of fluvial sand was only small, ranging from 0.026 to 0.037. The change in vertical strain due to saturation was only 0.3% for sample made of fluvial sand.

Fig. 1 to Fig. 4, Tab. 1 and Tab. 3 show that in each group of samples, one sample behaving differently from the others in the same group can be found. This applies to initial void ratio, changes in vertical strain due to the saturation or to the compression index, hence the slope of the curve, during loading after saturation. These differences between samples in one group were probably caused by slight variations in the initial weight of the samples when compacted or in the amount of water added for water content adjustment. Another reason for variations in the behaviour of samples in one group may be possible local inhomogeneities in the mechanical properties of the claystone from which the laboratory samples were crushed.

# 5 CONCLUSION

The 1D compression test conducted on samples of crushed claystone revealed the material's high sensitivity to changes in water content and its response to full saturation under load. The behaviour under load depends on its initial water content. In samples with lower initial water content, a greater portion of vertical deformation occurred due to saturation and the deformation during loading up to the stress of 300 kPa was smaller compared to samples with higher water content. However, total vertical deformations from the beginning of the tests to the end of the saturation phase were similar. The compression index measured after saturation (phase C) ranged for most tests from 0.330 to 0.420.

From a qualitative standpoint, the samples from two different locations exhibited similar behaviour. However, in a quantitative comparison of the tests with the same initial water content, larger volumetric changes during water saturation (phase B) and smaller ones the during initial loading (phase A) were measured for samples from the Bohdalecké geological stratum.

Total vertical strains due to full saturation reached values between 5.7% and 6.9%. These are significant values, especially when considering settlements of infrastructure at the top of high embankment. Nevertheless, it is important to note that the tests were carried out on samples with a lower grain size than those found in real constructions, so the value of vertical strain can differ. However, qualitatively similar behaviour can be expected.

The reference test conducted on quartz sand confirmed that negligible volumetric and stiffness changes were detected in such a type of coarse-grained soil.

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