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Void Index and Suction Stress for Reconstituted Clay Samples from Syria

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- ✓ consolidation
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- ✓ liquid limit,
- ✓ void index.
- ✓ void ratio

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Abstract

Mostly, clay soil may exist in the nature either on river banks or beside different water resources thus, it may expose to the effect of water levels changes. Another reason of water exposing is a heavy rainfall. When it occurs, a remarkable effect appears and reflect on the settlement values, because of clay consolidation. Therefore, it is so important to study clay soil at high values of water content in order to understand its behavior and expect the value of settlement by time. This research aims to normalize the relation between the changes in water content of the soil on site, and its impact on settlement phenomena. So, some reconstituted clay samples with high initial water contents in range (0.74 LL-1.3LL) were formed in the laboratory, and the necessary curves and equations that correlate between variables were deducted. By consequence, a relation between void index (I_v), void ratio (e) and suction stress (σ_s'), for these samples of clay were found.

NOTATION

$C_c^* = (e^*_{100} - e^*_{1000})$
e = void ratio
e0 = initial void ratio
e^*_{100} = void ratio of reconstituted clays at $\sigma v' = 100$kPa
e^*_{1000} = void ratio of reconstituted clays at $\sigma v' = 1000$kPa
eL= void ratio at liquid limit
ICL = intrinsic compression line
Iv = void index
PI = plasticity index
LL = liquid limit
PL = plastic limit
$\sigma v'$ = effective vertical stress
$\sigma s'$ = suction pressure

1. Introduction

Many researches concentrated on the differences between the behavior of natural clay soil samples and reconstituted one. These differences are due to the natural structure of the soil during or after sedimentation, where the clay structure can be unstable, because of the microstructure for different types of clay mineral and this acts on its physical and mechanical properties and in turn will lead to significant effects on soil compaction and strength [1]. The composition and arrangement of soil is expressed by the term "soil structure", in addition it includes the concept of mechanical behavior in natural state which is different from the state of reconstituting [2] Cotecchia et al. discusses the microstructural features a high plasticity natural clay achieves through its geological history and reconstituted one, by applying one-dimensional (1D) compression in the laboratory (lab) [3]. *Graham and Li* [4] applied one-dimension consolidation Oedometer test for natural and reconstituted clay soil samples. The results showed there is a similarity in the soil behavior for both type of samples. NCL's and CSL's for the two-test series are approximately parallel. However, the reconstituted clay soil samples appear to be stiffer in terms of both compression moduli and shear moduli. The bulk moduli are generally similar. The pore-water pressures in the natural clay are much higher than corresponding reconstituted values, particularly for over consolidated samples. *Burland* [2], who has great achievements in this domain, had reconstituted samples of clay soil with specific water content to reach the liquid limits equal or more, i.e. in the range of (1.0LL-1.5LL), then it was tested in Oedometer apparatus. It is essential to distinguish between the properties of natural samples and the reconstituted one so it was used *Void Index* I_v as a normalizing parameter that is given by the following equations *Burland* [2]:

$$I_v = \frac{e - e^*_{100}}{e^*_{100} - e^*_{1000}} = \frac{e - e^*_{100}}{C^*_c} \qquad (1)$$

$$I_v = 2.45 - 1.285\ \log \sigma'_v + 0.015\ (\log \sigma'_v)^3 \qquad (2)$$

Based on this intrinsic concept, *Void Index* I_v, important contributions have been made by several studies to develop an accurate comparison of the mechanical behavior between naturally sediment soils and reconstituted one. The results of some Oedometer tests also showed that the initial water content of the samples significantly affects the intrinsic parameters set by Burland. *Sorensen et al* [5] performed tests on triaxial test equipment with strain-controlled loading and found that over consolidation does not affect the axial strain rate of reconstituted clay (London clay). Soils may exhibit a concept called “pre-stressed pressure” upon compaction, which is observed to increase with the increase in the absorption value in most of the fine unsaturated soils. This concept has been named by *Hong et al* [6] *suction pressure*, and it has been shown that its value can have an effect on the intrinsic compression line (ICL) found by Burland. The value of this pressure is calculated based on the extrapolation of the compression curve to the ratio of voids drawn in the experiment. They also considered that the void ratio at the liquid limit (e_l) has an influential value in simulating the nature through the relationship between the initial void ratio (e_0) and the suction pressure of the reconstituted soil samples at different values of the corresponding liquid limit [7].

Hong et al [7,8] had worked with three types of high plasticity clay soils by preparing reconstituted samples in range (70 - 200) % of its liquid limit values. *Yin & Miao* [9] had applied an extensive Oedometer test on various remolded and reconstituted soils with distinct liquid limits and initial water contents to verify the validity of modified expressions of Burland.

Habibbeygi et al [10] had used the intrinsic concept from Burland on Australian clay. All compression curves of reconstituted Baldivis clay were an inverse S-shape similar to those of natural clays. However, the behavior is completely affected by the initial water content at stresses lower than the remolded yield stress (σ'_{yr}). The relationship between σ'_{yr} and normalized initial water content can be presented by the following power equation:

$$\sigma'_{yr} = \frac{33.5}{\left(\frac{W}{LL}\right)^{-1.96}} \qquad (3)$$

Habibbeygi [11] worked on four models that were developed to predict intrinsic constants based on some simple physical parameters as well as clay mineralogy of a reconstituted clay sample. Dahal & Zhen [12] carried out an experimental study on undisturbed, remolded and reconstituted soil samples to determine the compression behavior. The study revealed that the undisturbed soil sample has the highest compression index among all samples while the remolded sample has the lowest compression index. Yin et al. [13] had found a new intrinsic compression line (BSi-ICL) suitable for biogenic silica-kaolin clay mixtures which is developed based on the intrinsic compressibility concept of Burland [2], and it is considered as an extension of Burland's ICL. Moreover, Gaspar et al., [14] studied the effects of structure both undisturbed and compacted specimens by applying many consolidation tests for reconstituted sample. The results were be similar for both compacted and undisturbed samples, measured values were lower than that of the reconstituted specimen. Besides, Lieske et al. [15] investigated the effect of the microstructural of clay samples for both undisturbed and remolded one through Oedometer compression tests that were carried out in a high-pressure on those samples.

2. Methodology

This research is approaching the real changes in water levels in clay soil and their impact on its compressibility through finding relationships express values of deformations that will occur in the soil structure upon applying static loads. Defining the velocity and acceleration of these deformations as result of different moisture levels to match the changes that could happen in the sites upon construction. The methodology of this research was done by reconstituting clay samples from south of Syria with relatively high moisture levels (these moistures are taken as percentages from the liquid limit of the soil).

2.1 Experiments

The laboratory tests that were applied on clay soil drop within two main groups as follow:

I) Physical properties tests:

- Specific gravity **ASTM D854**
- Grain size distribution: Sieve Analysis **ASTM D 6913M-17** and Hydrometer Analysis **ASTM D 7928-16**
- Atterberg Limits: **ASTM D 4318**

According grain size distribution tests (Sieve Analysis & Hydrometer), **Figure 1** shows the percent of different size as: sand 1.76%, silt 35.69%, and clay 62.55%. Specific gravity 2.72, liquid limit 54%, plastic limit 25%, plasticity index 29%. So, the soil is classified according USCS, CH - high plasticity clay.

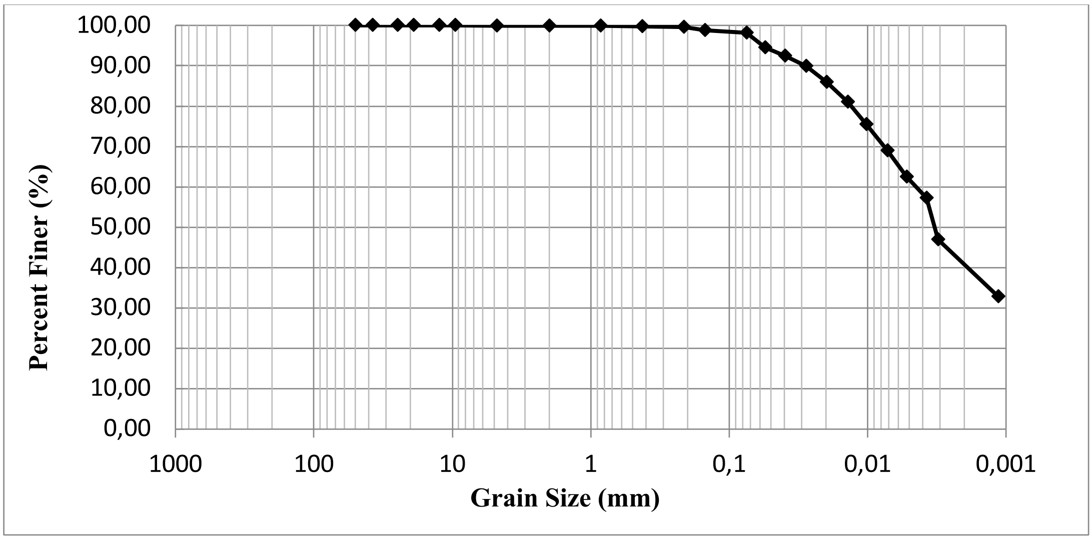


Figure 1: Grain size distribution of clay soil sample

II) Consolidation Tests ASTM D2435:

Consolidation is a property of soil in which the volume of soil decreases by decreasing the porosity coefficient after applying external loads. The compressibility differs according to the type of soil, whether it is soft or coarse, as the consolidation of soft soil is affected by time, due to the slow drainage of the water from the pores. One-Dimensional consolidation test -Oedometer- was carried on undisturbed samples and reconstituted samples under static load.

III) Reconstituted Samples Preparation:

The method of preparing reconstituted samples has not specific standard, however many researches such as *Burland* [2], *Hong et al* [7,8] *Yin and Miao* [16] have depended on the following methodology (in this research it was prepared in the range (0.74LL-1.3 LL):

- The sample of soil was dried to 105°C, then it was mixed with different percent of water, these percent were defined as percent of liquid limit in the range of 0.74LL to 1.3 LL as following in **Table 1**:

Table 1: water content of reconstituted sample

Liquid Limit (%) (of natural sample)	**Percent (%)**	**Water content (%)** (reconstituted sample)
54	74	40
54	93	50
54	111	60
54	130	70

- After adding the water content with the previous percentage (illustrated in table), it was placed in the ring with diameter 75mm of the Oedometer instrument. From stress approximately 5 kPa up to stress 20kPa. After this value, the unloading stage begin. **Figure 2** illustrate scheme for reconstituting steps:

Figure 2: scheme of reconstituting steps of clay sample

After unloading stage end (end of the preloading stage), the sample was taken to other ring with dimension 50 mm to begin with consolidation test, i.e. the ending of reconstituting process.

3. Results and Discussion

3.1 Results

After finalizing the laboratory tests some data should be analyzed. **Figure 3** presents the results of the (preloading stage), whereas, **Figure 4** and **Figure 5** illustrate the results of Oedometer test for reconstituting samples, effective stress versus void ratio and effective stress versus ln(1+e), respectively.

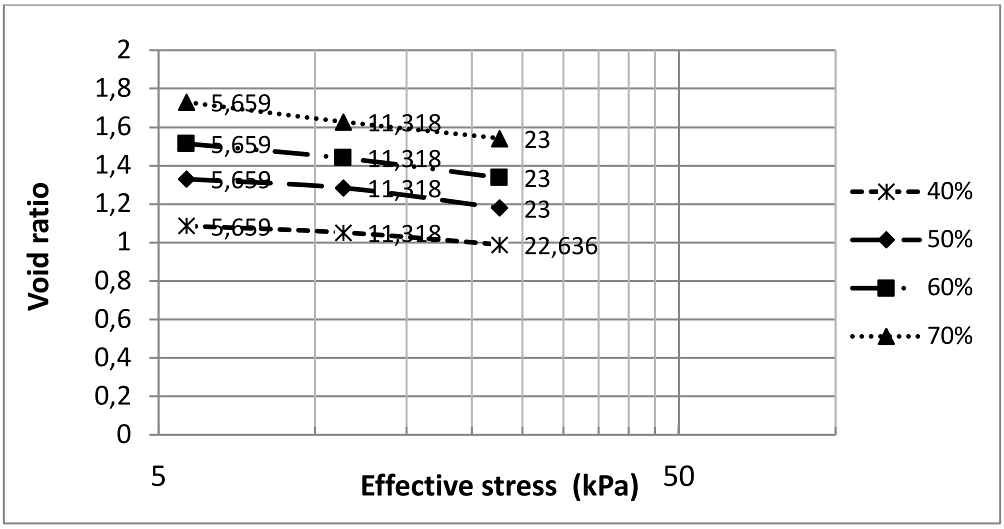


Figure 3: effective stress vs void ratio (preloading stage)

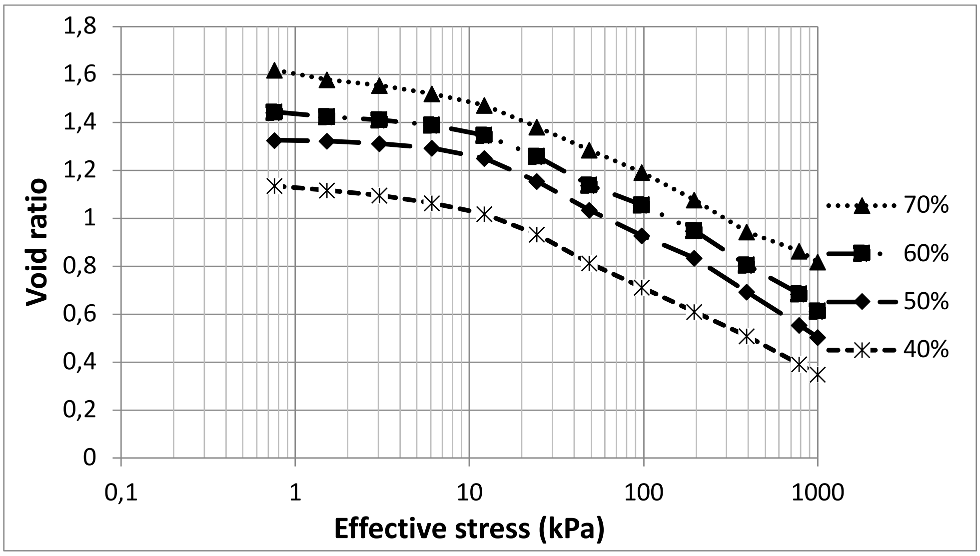


Figure 4: The effective stress (log σ'_v) vs void ratio after Oedometer test for reconstituting samples

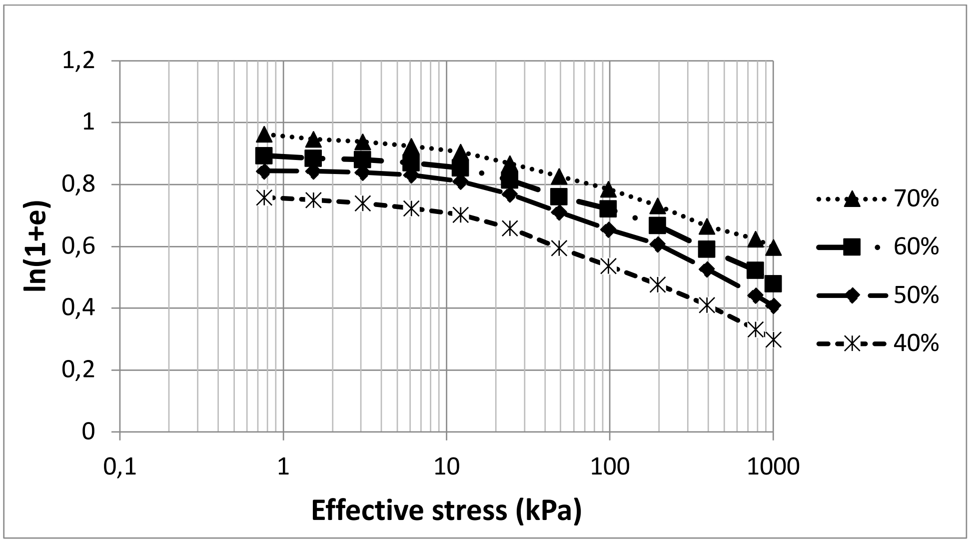


Figure 5: The effective stress vs ln(1+e)

After analyzing the curves of consolidation, **Table 2**, shows the value of void ratio for samples in both situations in (reconstituting stage) and in (consolidation stage).

Table 2: void ratio values for samples in both situation (reconstituting) and (consolidation)

Water content	Reconstituting		Consolidation	
	start	end	start	end
40%	1.0861	0.9893	1.1354	0.3491
50%	1.3297	1.1793	1.326	0.504
60%	1.5139	1.3373	1.433	0.652
70%	1.7301	1.5420	1.619	0.818

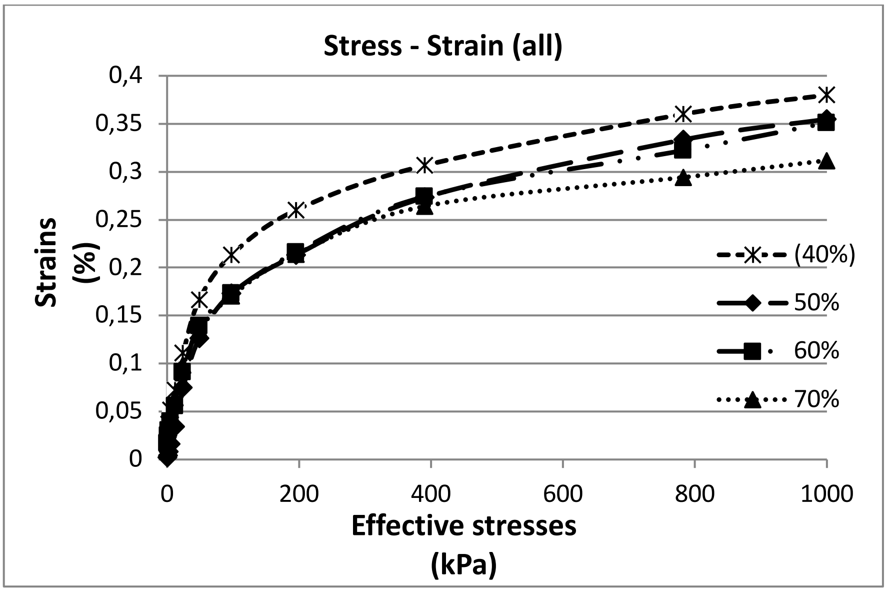


Figure 6: Stress vs strain after consolidation

Figure 6 presents the relation between stress and strain for all reconstituted samples. It is clear that all samples pass from elasticity to elastic-plastic to plastic deformation. The elasticity situation is founded, approximately, at the same limits for all samples, however the limits are different. The velocity and acceleration of strain versus time were studied and thus their behavior, it was demonstrated through **Figure 7** and **Figure 8**:

By reviewing the previous observations, and by following the graphs of changing velocity with time, it could be summerized the following observations:

According the general equation: $\acute{\sigma} = \sigma - u$, there is an increase in velocities within a certain time, and this means that the velocity of the water leaving the sample is directly proportional to the load, meaning that there is no obstacle to the exit of water. The following stage, there is a slowdown in the velocity and this is resulting from the difficulty of leaving the water, which it could be justified for several internal reasons (including rearranging the atoms, closing the water path, ... etc.), this leads to maintain the value of the pore water pressure for a longer period of time and therefore there is no decrease in the value of the stress, i.e. the effective stress and velocity keep its values, then the water re-exit at a high velocity and a low value of the pore water pressure. The same trend was observed with accelerations.

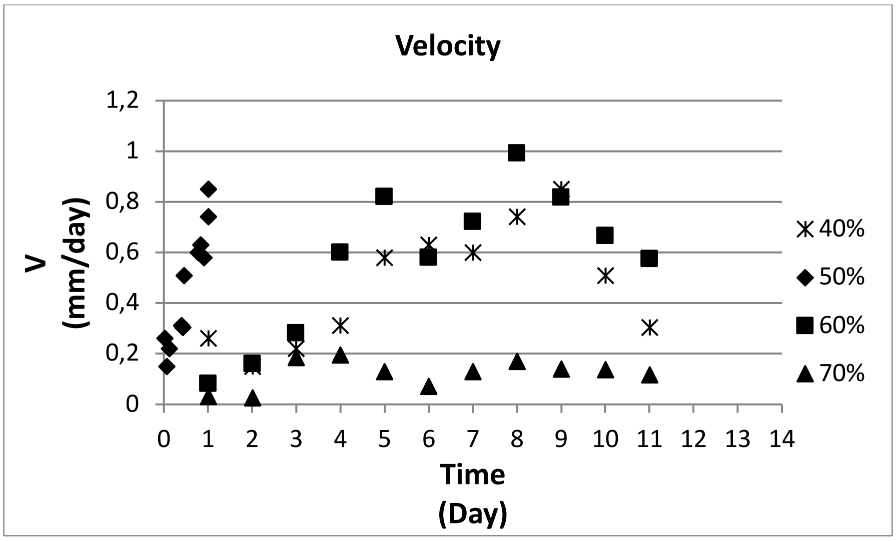


Figure 7: velocity of deformation

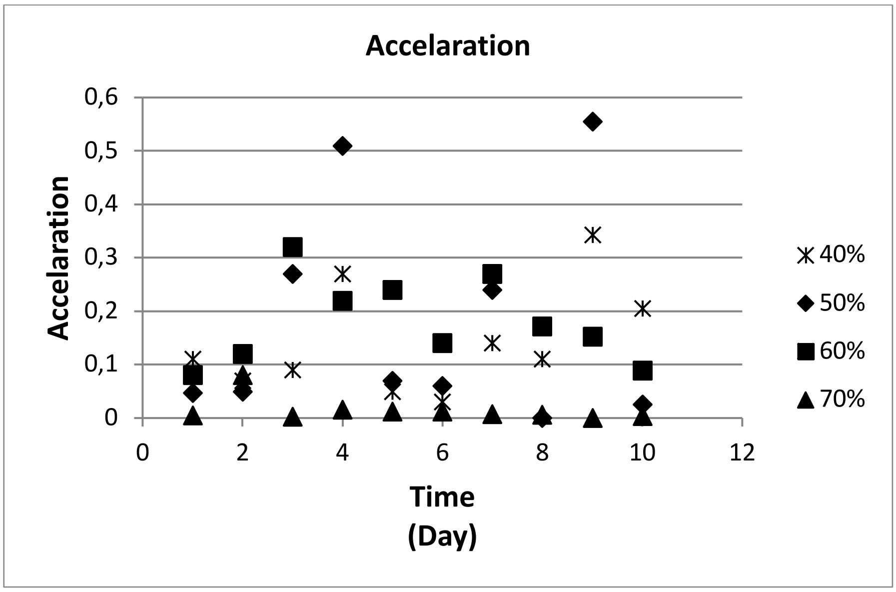


Figure 8: acceleration of deformation

Therefore, it is clear that the pore water pressure changes could be calculated without setting indicators to measure them, but this matter requires a deep mathematical analysis outside the scope of this research.

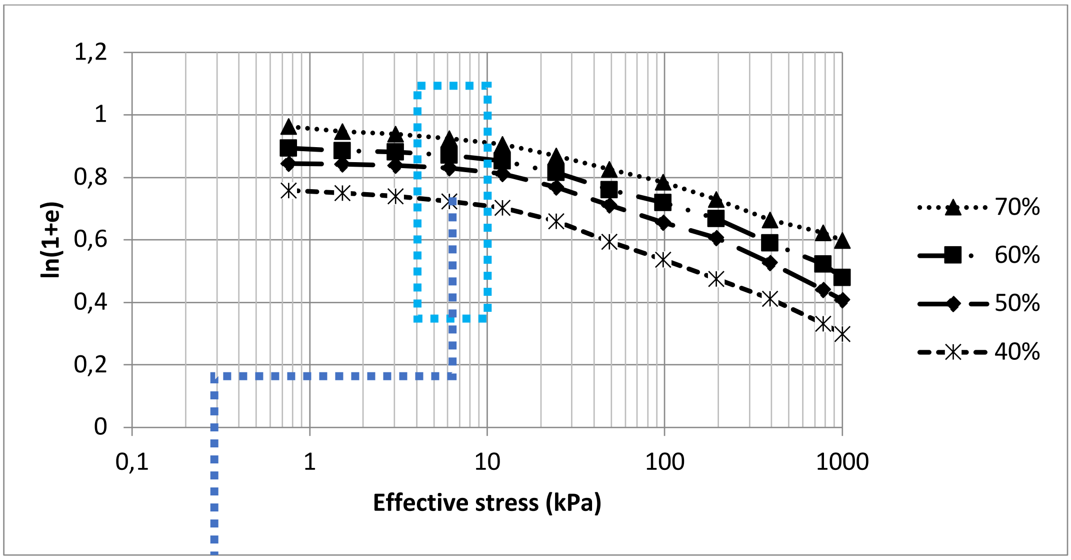
Also, it is not easy to draw a curve or straight asymptotic to these points in general, and the reason for this is because each group of points expresses a specific situation (elasticity - elasticity, plasticity, plasticity) and this requires working according to the **theory of least squares** for each of them separately until reaching a specific function that includes it completely, and this also depends on a very accurate mathematical analysis

3.2 Discussion

Relation between effective stresses, void index and void ratio:

Experiments that were carried out on the reconstituted samples showed the extent to which the shape of the consolidation curves is affected by the value of the suction pressure σ'_s. it was found that when loads, that are applied to the sample, do not give large values of effective stress, the consolidation curves will take a different shape comparing with the curves that result when the effective stress exceed the value of suction pressure [17-20]. By reviewing *Hong et al* [7] and depending on Figure 5, suction stress could be defined as shown in **Figure 9** where e_L could be calculated from the relation *Braja,* [21]*:*

$$e_L = G_s * \left(\frac{LL}{100}\right) \qquad (4)$$



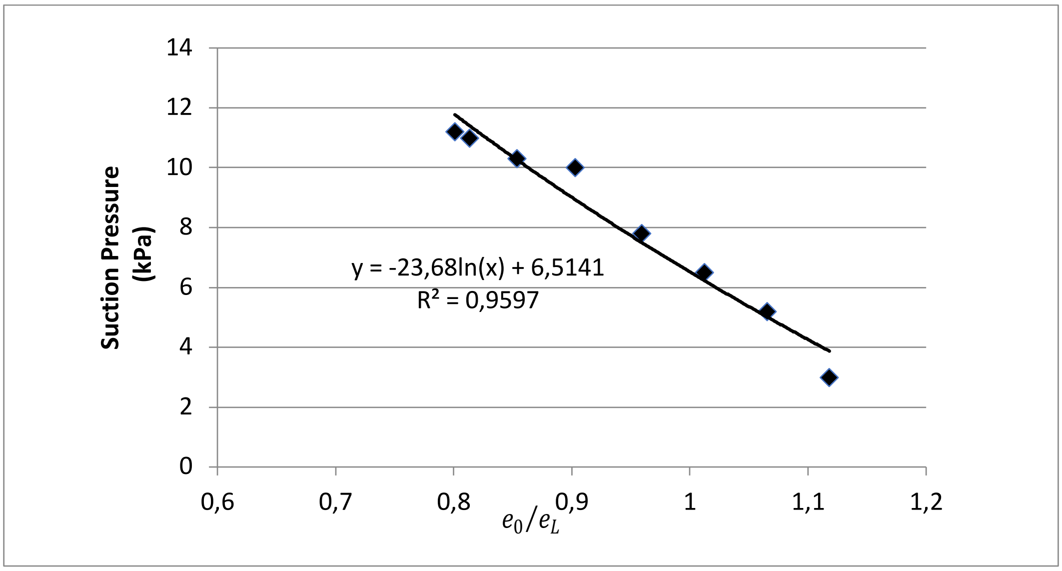


Figure 9: suction pressure vs e_0/e_L

Accordingly, it is probably to find the value of the suction stress and associate it with the ratio e_0/e_L and get the following equation:

$$\sigma'_s = -23.68 \ln\left({}^{e_0}/_{e_L}\right) + 6.5141 \qquad (5)$$

This indicates that the difference in the value of the initial void ratio had an effect on the analysis. Upon analyzing the relation between void ratio and effective stress as seen from **Figure 10** the linear relationship between both parameters in case the values of effective stress are less than the value of the suction stress and could extract the following relation:

$$e = -0.0052\,\sigma' + e_o \qquad (6)$$

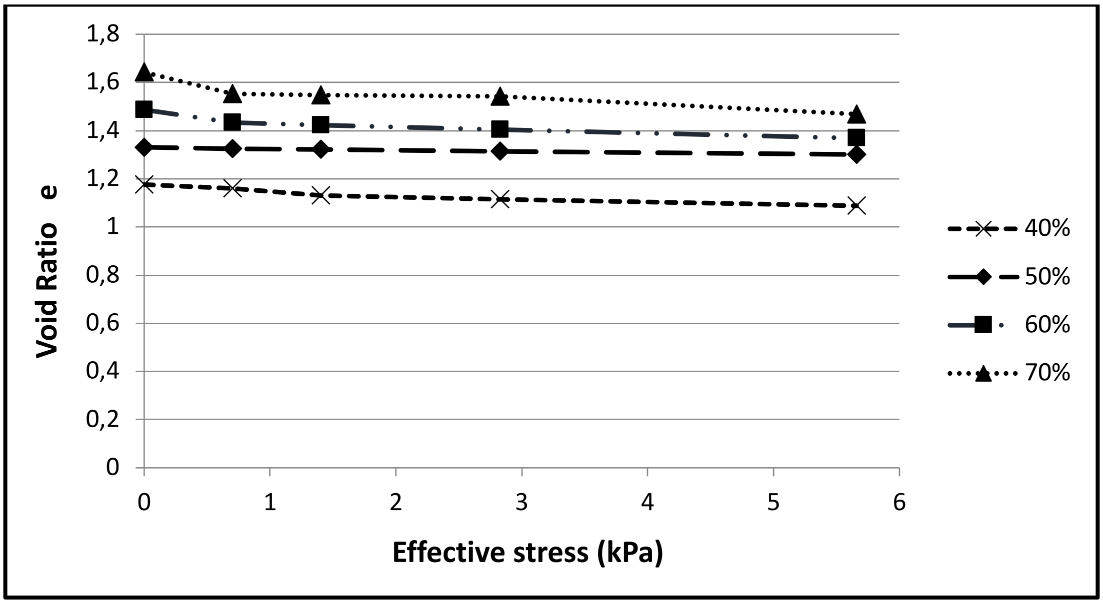


Figure 10: effective stress vs void ratio (σ′<σ′ₛ kPa)

While when the values of the effective stresses exceeded the value of the suction stress, the relation between the void ratio and the effective stresses was no longer the same as before as **Figure 11**, and depending on the concept of the void index (I_v), whose values are calculated according to the relationship (1) mentioned previously.

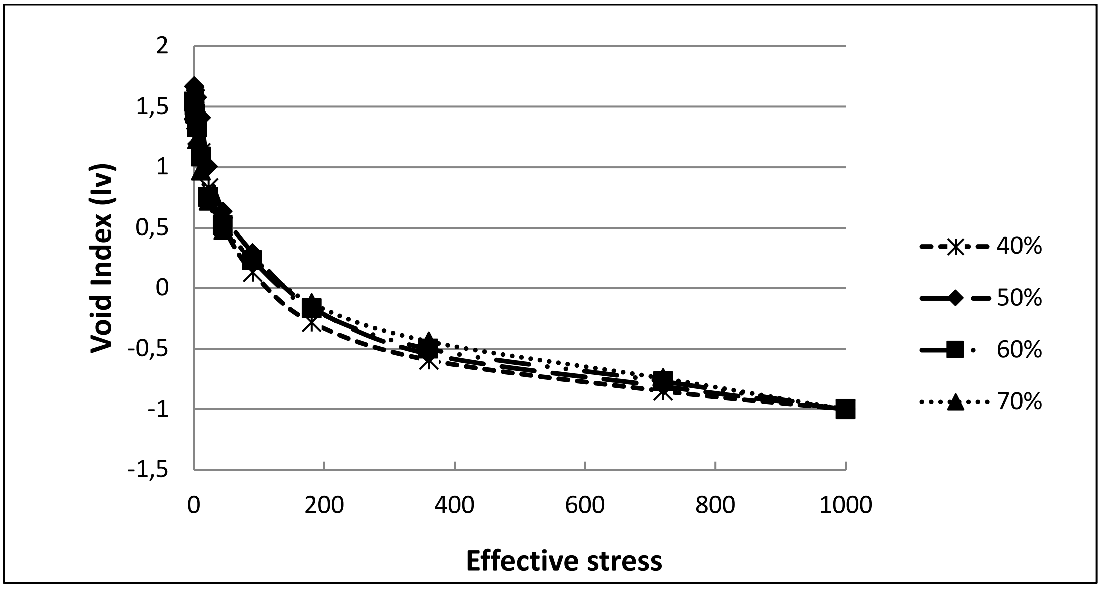


Figure 11: effective stress vs void index Iv ($\sigma' > \sigma'_s$ kPa)

In this study the relation between (I_v) and the effective stresses that express the "Intrinsic Compression Line" (ICL), which is illustrated in **Figure12**, can be written linearly as follows:

$$I_v = 2.661 - 1.221\log(\sigma') \qquad (7)$$

Hence, the both relationships (6) and (7) are written in general as follows:

$$e = \begin{cases} -0.0052\,\sigma' + e_o & \sigma' < \sigma'_s \\ c_c^*[2.661 - 1.221\log(\sigma')] + e_{100}^* & \sigma' \geq \sigma'_s \end{cases} \qquad (8)$$

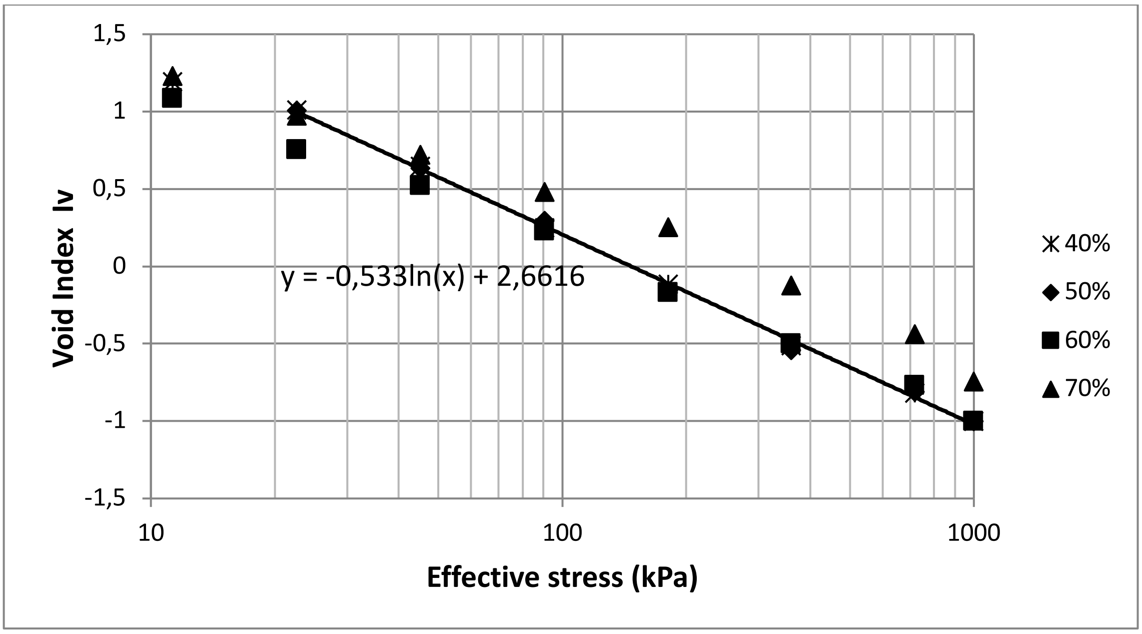


Figure12: effective stress vs void index Iv

Conclusion:

All the studies that were carried out after Terzaghi found the theory of one-dimensional compression of soft soils, clarified how necessary it is to go and expand the concept of compressibility more. Therefore, as void index is a normalizing parameter to help in correlating the compression properties of various clays, it was so interesting to apply this parameter and study some types of clay in south of Syria to validate using this parameter for other types. It was obvious that results of this research coincide with other researches.

Suction stress begins to develop within the soil structure during or after its deposition, where it is responsible of small value of compression that occurs to the soil when applied stress are less than its value, i.e. within the pre-plastic state, but the soil pressure will continue to increase until it moves from the non-plastic state to the plastic state in case that the value of the stresses that are applied is greater than the value of the suction stress of the soil. The consolidation curves between e-log and σ`, which showed an "s" shape, can be expressed according to two flow lines drawn within a diagram ln(1+e) versus log $\sigma`_v$, where intersection point of these lines is suction stress of this soil.

Recommendations:

It is recommended to develop an instrument for reconstituting the soil samples with high moisture contents before applying Oedometer test on these samples.

Conflict of Interest: **There are no conflicts of interest.**
Compliance with Ethical Standards*:* This article does not contain any studies involving human or animal subjects.

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