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RESEARCH ARTICLE

Investigation of the Effect of Different Saturation Methods on the Undrained Shear Strength of a Clayey Soil Compacted with Standard and Modified Proctor Energies

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Abstract

In this study, unconsolidated-undrained (UU) shear strengths of a clayey soil that is subject to saturation separately by using vacuum saturation method and falling head method were investigated. In the study, a soil with CL class according to Unified Soil Classification System was used. The soil samples prepared by being compacted in a rigid-wall permeameter mechanism were subject to a saturation process for periods varying from 1 week to 4 weeks. In the saturation by using falling head method, maximum 4 m hydraulic load was applied to the samples. In saturation by using vacuum method, minimum - 70 kPa vacuum was used. After the saturation process, the samples were subject to UU type triaxial tests. Depending on the saturation method and duration, a decrease of approximately 2 - 3 times was observed in UU shear strength parameters (c_u and ϕ_u) of the samples, which are subject to the saturation process, compared to the unsaturated samples. In the samples compacted with Standard Proctor Energy (SPE), strength parameters obtained under vacuum for one week were lower compared to samples saturated for 4 weeks by using the method of saturation by gravity. In the samples compacted with Modified Proctor Energy (MPE), vacuum method did not give a successful result.

Keywords

saturation · vacuum · falling head · rigid wall permeameter · undrained shear strength · clay · soil · compaction energy · Proctor

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1 Introduction

Strength of a saturated cohesive soil is lower than the strength of the same unsaturated soil depending on the loading conditions. Thus, even though the soil is not saturated in the current situation, by considering that it may become saturated in the future, it is commonly preferred in geotechnical design to obtain the strength parameters after they are saturated under laboratory conditions.

There are two approaches for the saturation of the soils under laboratory conditions. The most commonly used one among them is the method in which the test sample is saturated before the shearing step in a triaxial testing apparatus. In this method, the success of the saturation process before the shearing step is determined by controlling the saturation parameter (B parameter of Skempton is used widely). The disadvantage of this method is that it is not possible to perform another strength experiment on the triaxial testing apparatus in the event that the saturation process takes long.

In the other approach, the sample that is prepared in a rigid-wall cylindrical mold is saturated under falling head hydraulic gradient before it is connected to the tri-axial testing apparatus for the shearing step. The most important advantage of sample saturation by using this method is that the saturation process is independent from the triaxial testing apparatus. Thus, numerous test samples can be saturated by this method and triaxial testing apparatus can only be used in the shearing step. Since performing the saturation on the undisturbed samples by using this method will affect the stress situation, it is not suitable. On the other hand, this is not question for the disturbed soils. Likewise, initial parameters in disturbed samples (water content, dry unit weight, and compaction level etc.) can always be kept under control.

Generally, the maximum hydraulic load (3 - 4 m) to be applied at the falling head permeameter is limited with the height of the laboratory area. Whereas, in a vacuum environment that is another saturation method, theoretically approximately 10 m water column load can be applied. This value corresponds to - 101.3 kPa which is the maximum vacuum value that can be reached under normal conditions (sea level and 25°C).

The purpose of this study is to examine the efficiency of the saturation by falling head and vacuum saturation methods on the strength parameters (c_u, ϕ_u) of the samples. In accordance with this purpose, first of all the optimum water content and maximum dry unit weight values of a soil at class CL in USCS were obtained under Standard Proctor Energy (SPE) and Modified Proctor Energy (MPE).

Under the same conditions (at optimum water content and maximum dry unit weight) the identical samples prepared within a rigid wall (cylindrical mold) were subject to the saturation process separately by using saturation by falling head method and vacuum saturation method. Saturation durations were varied from 1 week to 4 weeks. After the saturation process, the samples were subject to shear strength tests without drainage. While in the falling head method, maximum 4 m initial hydraulic load was used; minimum - 70 kPa vacuum was applied in the vacuum environment. It was not allowed to have the vacuum, applied to the environment, to be higher than - 65 kPa. Theoretically, it was not practically possible to apply the minimum vacuum value (- 101.3 kPa) to vacuum saturation apparatus for a long time (1 week and more).

In the study, while the strength parameters (cohesion strength, internal friction angle) were used as dependent variables, the independent variables were specified as saturation method (falling head, vacuum), saturation period (between 1 week and 4 weeks) and the compaction energy level of the samples (SPE, MPE).

2 Literature summary

As a result of the extensive literature research, no study primarily examining the effect of the saturation method on strength of the compacted soils was found. Even if there is such study, at least it is not within the knowledge of the authors of this study. According to the findings of some studies conducted on the strength of compacted clays; time, compaction method, and saturation process are among the important factors affecting strength. Some of these results are briefly mentioned below.

Strength and deformation behavior of the clays depend on time and the time effect is efficient on the shear behavior without drainage [14]. When time increases, strength without drainage increases and the sample is more fragile and also has small deformations [10]. This is because the soil structure varies gradually depending on time.

During compaction, in addition to the forces developed between the particles, the stress occurring as a result of the compaction energy applied externally controls the formation of the soil structure. In the compaction procedure, after the compaction energy applied externally is removed, new internal energy conditions on the soil are in question. Depending on time, the structure flocculates gradually due to the distribution of the internal energy, and soil strength increases [13].

Different soil structures are obtained as a result of different (static compaction, dynamic compaction) compaction methods. Thus, compaction method is an effective upon the shear strength of the soil [13].

Ciftci (1991) investigated the effect of saturation on compacted clays over the shear strength without drainage [11]. According to the study, peak shear strength significantly decreased with the increase in the water content depending on saturation.

In another study, Rowshanzamir and Askari (2010) investigated the effect of saturation on the free pressure strength among compacted clay samples [12]. The study mainly examined the effect of anisotropy on the free pressure strength among compacted samples. They conducted unconfined compression test for the samples taken horizontally and vertically according to the sampling direction of the cylindrical sample. They found that the parameter mostly affects the unconfined compressive strength was the water content. When the unconfined compressive strength before and after saturation were compared, they stated that the decrease in the unconfined compressive strength due to saturation was lower in the samples with higher initial water content and higher in the samples with lower initial water content.

3 Material and method

The particle size distribution curve, consistency limits, and specific gravity of the soil used in the study were obtained according to the ASTM D 422, ASTM D 4318, and ASTM D 854 standards, respectively (Yilmaz, 2009) [2–4]. Fig. 1 illustrates the grain size distribution curve of the soil.

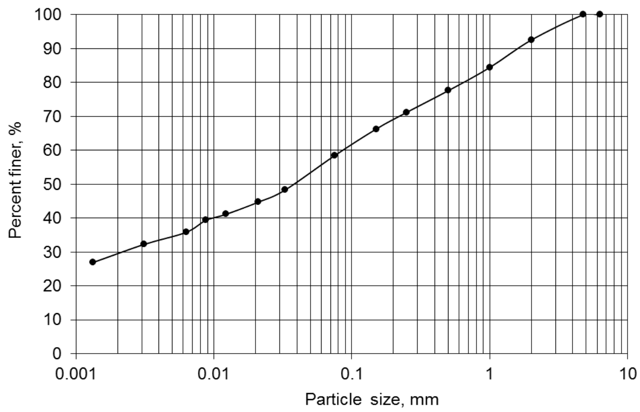

Fig. 1. Particle size distribution curve of the soil used in the study summarizes the consistency limits, specific gravity and soil class according to the Unified Soil Classification System (USCS)

Tab. 1. Some of the physical properties of the soil used in the study

Physical property	Value
Liquid Limit, (%)	47
Plastic Limit, (%)	21
Specific gravity	2.644
soil classification system: Unified Soil Classification System (USCS)	CL

3.1 Compaction Tests

3.1.1 Standard Proctor compaction test

In order to determine the maximum dry unit weight and optimum water content of the soil according to ASTM D 698 standard, the compaction test was performed as summarized below. In a mold with a diameter of 102 mm and a height of 117 mm; the clay was filled up in three equal layers and 25 strokes were applied to each layer with a 2.5 kg hammer by performing falls from a height of 305 mm. As a result of Standard Proctor compaction test, maximum dry unit volume weight was determined as 16.50 kN/m^3 and optimum water content as 19.0% (Fig. 2).

3.1.2 Modified Proctor compaction test

In order to determine the maximum dry unit weight and optimum water content of the clay according to ASTM D 1557 standard, the compaction test was performed. In a mold with a diameter of 102 mm and a height of 117 mm; the clay was filled up in five equal layers and 25 strokes were applied to each layer with a 4.5 kg hammer by performing falls from a height of 457 mm. As a result of Modified Proctor compaction test, maximum dry unit volume weight was determined as 18.40 kN/m^3 and optimum water content as 13.5% (Fig. 2).

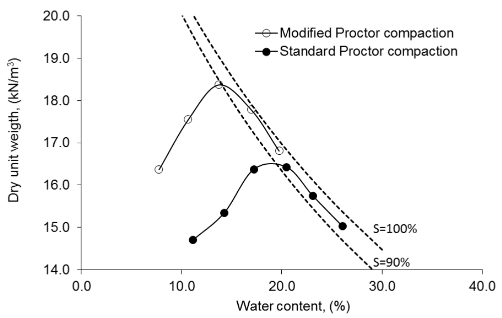

Fig. 2. Standard and Modified Proctor compaction curves of the soil

3.2 Preparation of cylindrical samples for the strength Tests

First of all, after soil was dried in open air, it was sieved from an ASTM No. 4 (4.75 mm) sieve. In order to have the dry density of the samples homogeneous throughout the sample and to minimize the undesired local voids in the sample, the samples were compacted in three layers in the compaction process. The compaction apparatus used (for both SPE and MPE samples) was designed to have the height of every layer as 35 mm and length of the sample as 105 mm and diameter of the sample as 50.0 mm in total (Yilmaz and Ozaydin, 2013). The bottom diameter of the compaction hammers was specified as 49.50 mm. While every layer was being compacted, the layer height and accordingly the layer volume were kept under control from the marked locations on the compaction hammer. Fig. 3 illustrates the compaction apparatus and compaction hammers used.

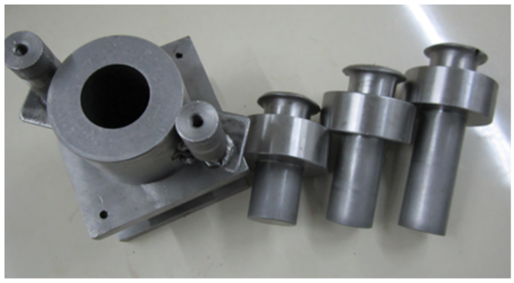

Fig. 3. Triaxial test sample preparation apparatus (Bahari Kheirjouy, 2014)

3.3 Saturation method of the Samples

Two different methods (method of saturation via falling head and saturation process via vacuum) were used as the saturation process of the samples. After the samples were compacted, they were exposed to water saturation method by using one of the two methods until the test day.

In the process of saturation by falling head, the samples compacted in PVC molds were exposed to the saturation process by using an apparatus similar to the falling head hydraulic conductivity (permeability) apparatus (Fig. 4).

Fig. 4. Falling head saturation method setup (Bahari Kheirjouy, 2014)

In the process of saturation by falling head; the samples were separately exposed to saturation process under 4 m hydraulic load for 1 week, 2 weeks, 3 weeks and 4 weeks and then they were subject to the UU tests.

The vacuum saturation equipment is specifically designed and manufactured considering some basic features of the equipment defined in ASTM C 593 [1]. The vacuum saturation equipment (large enough to saturate 4 samples at once) is composed of a ~350 mm high by ~350 mm inside diameter PolyMethylMethAcrylate (PMMA) cylindrical chamber and stainless steel bottom pedestal and lid plates. Both the bottom pedestal and the lid are grooved for circular O-ring seal to ensure tight contact with the chamber. The lid is fastened to the chamber by four equally spaced threaded rods which pass along the outside wall of the cylindrical section and thread into the base plate. Two vacuum line connection (one for vacuum source connection and one for vacuum/air release connection) is located in the lid and a water line connection with control valve is located at the base pedestal. The vacuum line is connected to a commercial vacuum pump and the water line is connected to a reservoir of deaired water. The vacuum is controlled by a pressure valve at the lid. The water level in the vacuum chamber is adjusted so that the bottom inlet of the PVC molds which allow complete access of water to the specimens during saturation were kept fully submerged during saturation process. The suction in the vacuum chamber applies upward movement of water flow through the samples (saturation) under total head difference between the bottom inlet and top outlet on the PVC molds.

In the saturation process by vacuum; the samples compacted in PVC mold were placed in the vacuum setup (Fig. 5). The samples were kept for 1 week in the vacuum setup under approximately - 70 kPa (~7 m water column load) of constant vacuum pressure that was applied till the strength test day. After the saturation process by vacuum, the samples were subject to UU tests.

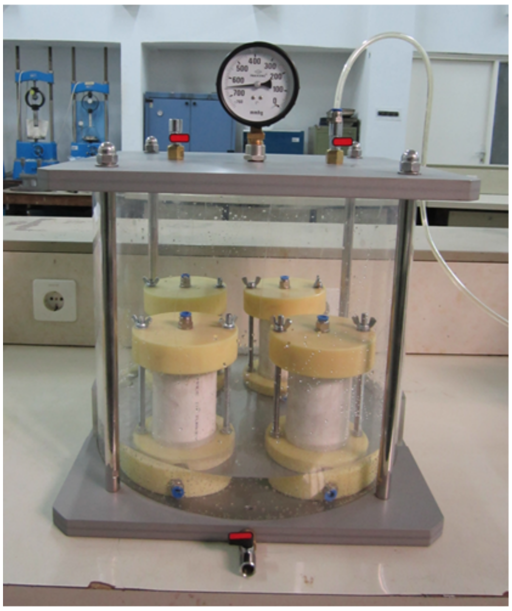

Fig. 5. Vacuum saturation method setup (Bahari Kheirjouy, 2014)

3.4 Performing undrained shear strength tests

UU type triaxial tests of the samples that were prepared by using the compaction apparatus were performed according to the ASTM D 2850 standard as deformation controlled under 0.5 mm/min loading rate [6]. The triaxial tests were performed under 50, 100, 200, and 300 kPa cell pressures.

4 Results and discussion

4.1 Reference undrained shear strength tests

First of all, cohesion strength (or intercept) and internal friction angles of the samples that were not exposed to any saturation process were obtained in order to use as a reference value in the examination of the effect of saturation process on strength parameters. One day following compaction of the samples, they were subject to strength tests. As specified before, the samples were separately compacted at optimum water content and maximum dry unit volume weight obtained by using SPE and MPE. Fig. 6 illustrates Mohr circles and Mohr-Coulomb failure envelopes of the samples at failure.

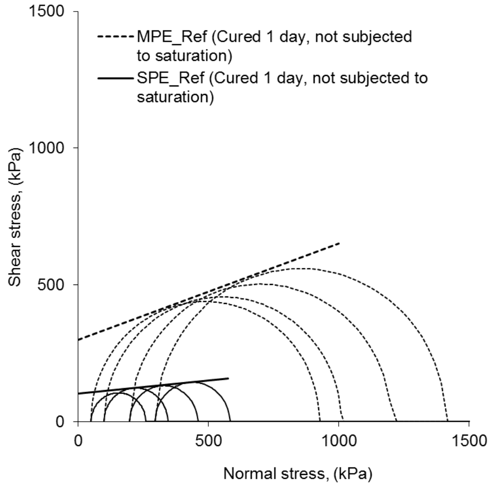

Fig. 6. Mohr circles and Mohr-Coulomb and failure envelopes of the reference samples (Cured one day and not subjected to any saturation process).

As is seen in Fig. 6, cohesion strength and internal friction angle for the samples prepared by using SPE energy were ~102 kPa and ~5.6° respectively. Similarly, cohesion strength and internal friction angles for the samples prepared by using MPE energy were obtained as ~300 kPa and ~19.3°, respectively. Because the failure envelopes from which the cohesion strengths and internal friction angles were obtained via the best tangential line fit method, they were not completely objective. By using the same Mohr circles, different researchers may obtain different cohesion strengths and internal friction angles. Thus, the values were given together with an approximate mark. When the strength parameters were compared; cohesion strength showed an increase of approximately 3.0 times in case the compaction energy increases from the standard energy level (600 kN-m/m^3) to modified energy level (2700 kN-m/m^3) (4.5 times energy increase). Similarly, the increase in the internal friction angle was obtained as 3.5 times.

4.2 Effect of holding in the PVC mold on undrained shear strength

As specified previously [13], after the compaction energy is removed (after the sample was compacted in the PVC mold) new internal energy conditions are in question on the soil. Determination of the effect of holding in the PVC mold (independent from the saturation process) on strength is important. Within this frame, some of the identical samples prepared were kept in the PVC mold and some of them after removing from the PVC mold were kept under the cure environment for 4 weeks (under the same conditions). The samples were not subject to any saturation process within this period. The samples were subject to strength tests at the end of 4 weeks. Mohr circles and Mohr-

Coulomb failure envelopes of the samples at failure are present in Figures 7 and 8 according to their compaction energy levels.

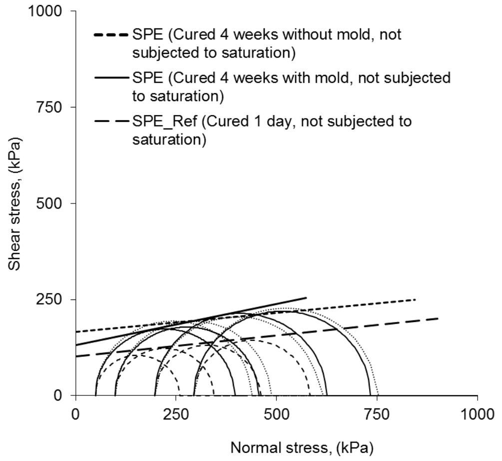

Fig. 7. Mohr circles and Mohr-Coulomb failure envelopes of samples compacted at SPE level (effect of keeping in mold)

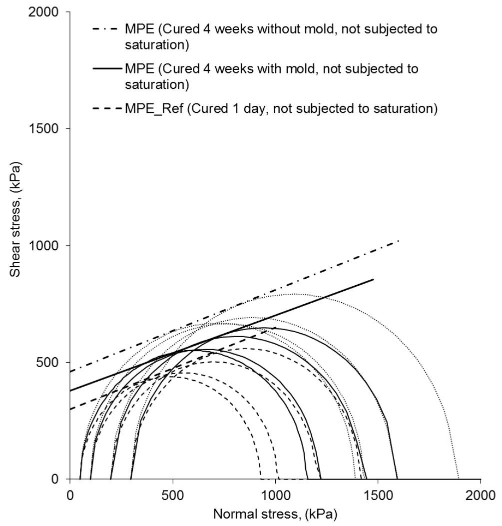

Fig. 8. Mohr circles and Mohr-Coulomb failure envelopes of samples compacted at MPE level (effect of keeping in mold)

According to Fig. 7, while the slopes of the failure envelopes of the samples that were not kept in the PVC mold and that were kept in the PVC mold varied between 6° and 10°; whereas, the cohesion strength ranged between 130 kPa and 170 kPa. When compared to the 1-day SPE sample (internal friction angle of 6° and cohesion strength of 102 kPa), cohesion strength of the samples which were kept in the cure for 4 weeks showed an increase at an average of 50%.

On the other hand, the internal friction angles of the samples compacted at MPE energy level (Fig. 8) which were kept in the PVC mold and not kept in the PVC mold were obtained completely at the same level with the 1-day MPE samples (failure envelopes were almost parallel). Cohesion strength showed an increase of 50% in the samples which were not kept in the PVC mold and an increase of 30% in the samples which were kept in the PVC mold. It was thought that the reason of such behavior change occurred due to the water content. Because there was less water loss in the samples that were kept in the mold under the cure environment, cohesion strength was obtained at lower level. When Figures 7 and 8 were evaluated together, it was understood that the samples compacted with MPE were more sensitive against keeping in the mold compared to the samples compacted with SPE.

4.3 Effect of the saturation duration and method on the undrained shear strength

The effects of the method of saturation by falling head method and the method of saturation by vacuum on the undrained shear strength were separately compared at the SPE level and MPE level (Figures 9 and 10). Mohr circles and failure envelopes at failure in Figures 9 and 10 were shown together. On the figures, also the failure envelopes obtained from the reference undrained shear strength tests were shown.

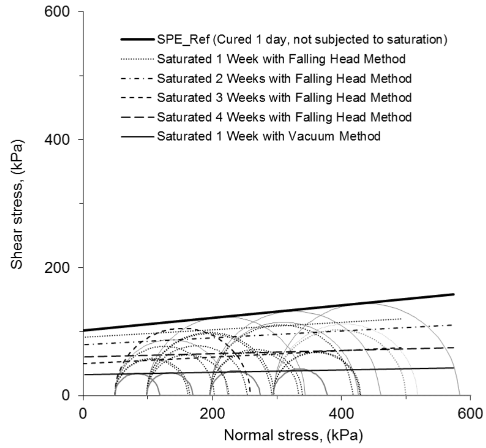

Fig. 9. Mohr circles and Mohr-Coulomb failure envelopes of samples compacted at SPE level (Influence saturation process)

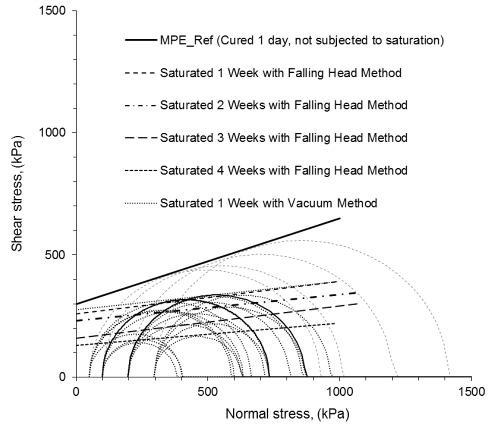

Fig. 10. Mohr circles and Mohr-Coulomb failure envelopes of samples compacted at MPE level (Influence saturation process)

In the samples compacted with SPE (Fig. 9), it is observed that internal friction angle and cohesion strength gradually decreased with the increasing saturation period. While the internal friction angles of the samples which were saturated by falling head method from 1 week to 4 weeks are obtained as 3.4°, 3.0°, 2,9° and 1,5° respectively, their cohesion strengths were obtained as 91 kPa, 80 kPa, 60 kPa, and 50 kPa. For the samples saturated by vacuum, internal friction angle was 1° and cohesion strength was 33 kPa.

According to Fig. 9, the effect of saturation applied for 3 weeks on strength parameters decreased in the method of saturation by falling head. Cohesion strength (33 kPa) obtained in the samples that were saturated by vacuum for 1 week was obtained as lower when compared to the samples that were saturated by falling head for 4 weeks. This was associated with the fact that free air in the water in the samples saturated by falling head prevented completely saturation of the samples and thus caused higher cohesion strength. Thus, in the samples saturated by using the vacuum method; vacuum removes the air in the water and provides opportunity for the movement of de-aired water and thus provides a more efficient saturation.

Internal friction angles of the samples that were compacted with MPE and saturated by gravity for 1 week decreased from 19.3° to 6.5° and their cohesion strength decreased from 300 kPa to 276 kPa (Fig. 10). It is observed that internal friction angle did not significantly change with increasing saturation duration for more than 1 week but cohesion strength decreased gradually (from 276 kPa to 130 kPa). Failure envelope of the samples that were saturated by vacuum for 1 week and the failure envelope of the samples that were saturated by gravity for 1 week were obtained as almost the same. Thus, vacuum method was not so efficient in the samples compacted with MPE. This was associated with the fact that negative pore water pressure was higher in the samples compacted with MPE compared to samples compacted with SPE.

4.4 Effect of the saturation period on the water content

In both saturation methods, an increase is observed in the water content of the sample that was saturated for approximately 10% of the initial water content in the saturation process up to 1 week. In other words, the water content of the samples compacted at SPE level with the initial water content of 19% was 22.5% in average obtained over the samples that subjected to shear tests at the end of 1 week. Similarly, the water content of the samples compacted at MPE level with the initial water content of 13.5% was obtained as 15.1% in average obtained over the samples that tested at the end of 1 week. When water contents of the samples, which were saturated for a longer time (4 weeks), at the end of test were examined, it was observed that their initial water contents increased at approximately 20% (at both saturation methods).

Change of the water content on the basis of the sample was examined from the samples taken from the lower, middle, and upper parts of the sample. In all the samples, the water content was observed to be the highest in the lower part of the sample (water entry part to the sample) and the lowest in the upper part of the sample by decreasing gradually. For example, at the end of triaxial test, water content of a sample saturated for 3 weeks by using falling head method and compacted at SPE energy level was obtained as 25.0% in the lower area, 23.6% in the middle area and 22.4% in the upper area of the sample. Similar trend was also observed in all the saturation methods and all the samples in all the saturation durations. Thus, it was revealed that it was not possible to saturate the sample homogeneously by using these saturation techniques.

5 Conclusions

In this study, the effectiveness of two different saturation methods on strength parameters were compared over a CL type (USCS class) clayey soil. Following results were obtained in the experimental study that was conducted on the samples prepared by using two different compaction energies (i.e. SPE and MPE).

1 By increasing the compaction energy from SPE level to MPE energy level, (an increase of 4.5 times in the energy level) cohesion strength showed an increase of approximately 3.0 times and internal friction angle showed an increase of approximately 3.5 times.

2 In the samples compacted by SPE, the cohesion strength obtained under - 70 kPa vacuum for 1 week were found to be lower compared to the samples saturated for 4 weeks by using the method of saturation by falling head under 4 m hydraulic load. When the relationship of the decrease in internal friction angle and cohesion strength with saturation was considered, the method of saturation by vacuum was more efficient when compared to the method of saturation by falling head.

3 In the samples compacted by MPE, the internal friction angle of the samples saturated under vacuum and falling head for 1 week were almost obtained at the same level.

4 In the samples compacted by MPE; because there was higher negative pore water pressure compared to the samples compacted by SPE; the vacuum method lost its efficiency in the samples compacted by MPE.

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