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Article

Influence of particle size on soil consolidation processes

Influencia del tamaño de partículas en los procesos de consolidación de los suelos

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Abstract

Settlements in infrastructure works such as roads, bridges and highways are often underestimated due to a lack of understanding of the phenomena associated with volumetric deformations of soils. This can lead to significant damage to the structures built on them and in some cases it will be necessary to demolish them or render them useless. This study shows the difference in long-term deformations that occur between two types of soil depending on their particle sizes. The study shows the results of two soil samples subject to consolidation, with identical initial moisture content, but with a different particle size distribution. It also shows how the consolidation process occurs and the direct influence of particle size on the long-term volumetric reduction process of soils.

Objectives	Methodology	Contribution
• Subject soil samples to secondary consolidation processes. • Produce samples of different particle sizes to undergo consolidation processes. • Qualitatively and quantitatively analyze secondary consolidation in samples with different particle sizes.	Soil samples were obtained from a T2 industrial kaolin sufficiently fine to exhibit volumetric deformations by primary and secondary consolidation. This soil was mixed with inert material to make samples with a different granulometry and to analyze the differences that occur in volumetric deformations with different granulometries.	The experimental results derived from the analysis of soil mixtures show the difference in response, both in consolidation times and in their magnitude. In this sense, it is observed that a different soil structure generates a consequent structure of pore sizes, and it is considered possible to study and quantify this process from the distribution of pore sizes.

Soil consolidation, saturated soils, mechanical behaviour

Resumen

Los asentamientos en obras de infraestructura como vialidades, puentes y carreteras frecuentemente suelen subestimarse debido a la falta de comprensión de los fenómenos asociados a las deformaciones volumétricas de los suelos. Esto puede conducir a daños importantes en las estructuras desplantadas sobre ellos y en algunos casos será necesario demolerlas o inutilizarlas. Este estudio muestra la diferencia en las deformaciones de largo plazo que ocurren entre dos tipos de suelo en función de sus tamaños de partículas. En el estudio, se muestran los resultados de dos muestras de suelo sujetas a consolidación, con humedades iniciales idénticas, pero con una distribución granulométrica distinta. También se muestra la manera en que ocurre el proceso de consolidación y la influencia directa del tamaño de partícula sobre el proceso de reducción volumétrica de largo plazo de los suelos.

Objetivos	Metodología	Contribución
• Someter muestras de suelo a procesos de consolidación secundaria. • Producir muestras de diferentes granulometrías para someterlas a procesos de consolidación. • Analizar cualitativamente y cuantitativamente la consolidación secundaria en muestras con diferentes granulometrías.	Se obtuvieron muestras de suelo de un caolín industrial T2 suficientemente fino para exhibir deformaciones volumétricas por consolidación primaria y secundaria. Este suelo se mezcló con material inerte tipo inerte para fabricar muestras con una granulometria distinta y analizar las diferencias que ocurren en las deformaciones volumétricas con diferentes granulometrías.	Los resultados experimentales derivados del análisis de las mezclas de suelo evidencian la diferencia en respuesta, tanto en los tiempos de consolidación, como en la magnitud de estos. En este sentido, se observa que una estructura diferente de suelos, genera una estructura consecuente de tamaños de poro y se considera posible estudiar y cuantificar este proceso a partir de la distribución de tamaños de poro.

Consolidación, suelos saturados, comportamiento mecánico

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Introduction

Soils as construction material and as support elements for the infrastructure of nations represent the first barrier for the civil engineer before creating a successful structure that serves the purposes intended for it (Lambe & Whitman, 1969; Juárez-Badillo, 1975).

Settlements produced in structures are often exceeded in the planned calculations. As an example of this, there is the attempt to build the New Mexico City Airport on highly compressible soils which shows a settlement of 15 centimeters per year due to the extraction of water in nearby areas. The Kansai International Airport in Japan placed on a seabed (Furdoi, 2010) is 4 km long and 1 kilometer wide. It was designed to support long-term settlements, however two years later it had sunk 8 meters more than expected. Another clear example is the Tower of Pisa which took approximately 200 years to complete and currently suffers from a 5.3-degree inclination (Barnes, 2010, Mimura & Jeon, 2011).

The consolidation effects caused by settlements are estimated for infrastructure projects exclusively focusing on primary consolidation, which can be much smaller than long-term deferred consolidation (Lewis & Schrefler, 1987). On the other hand, the type of soil has a fundamental importance in the consolidation process both in the time in which these settlements occur, as well as in their magnitude (Lloret & Alonso, 1980; Cai, Chen, Cao, & Ren, 2018; Pandey et al., 2024; Zaini et al., 2024).

Terzaghi established the methodology to study the consolidation phenomenon. In the consolidation phenomenon, since the soil is saturated, the volumetric deformations of the soil depend on the quantity of water that flows through the soil pores. In addition, the water flow depends on the dissipation of the pore pressure that is generated when an increase in load is applied to the soil. Thus, it is possible to make a coupling between the deformation equations and the water flow equation.

Soil consolidation is a phenomenon that is analyzed from the point of view of the volumetric deformation produced by loads and external agents in the soil.

These volumetric deformations are commonly quantified based on the volume of water expelled in a consolidation test (Rojas & Chávez, 2013). The volume of water expelled, as well as the deformations, are used to extrapolate the laboratory results towards the calculation of settlements in structures and roads using the void ratio as a parameter for this. The information required to carry out and conduct this analysis are a) the initial conditions of the site, that is, the thickness of the compressible layer (Xie et al., 2024), b) the compressibility properties, that is, the slopes of the normally consolidated and preconsolidated sections, c) the load levels to which the soil will be subjected. The latter are obtained from an analysis of the pressures to which the soil layer will be subjected.

To obtain these parameters, it is necessary to know the geometry and the way in which the superstructure will subject the compressible soil layer to stress. That is, an embankment or a foundation slab transmit stresses in a different way to the compressible soil layer because their geometries are different (Berre, 1982; Bowles, 1979; Braja, 2008).

On the other hand, once they are known, it is desirable that the loads remain for the necessary time. The necessary time will be sufficient to reproduce the characteristics that will occur in the field. For this, the theory of soil mechanics uses the concept of consolidation curve, which is analyzed, and the consolidation times are extrapolated to field conditions to identify the times that will be required for the soil to settle or deform due to consolidation under the imposed loads.

Two types of consolidation are identified by soil mechanics theory. The first infers that soil is deformed exclusively by water migration from its particles, without plastic flow or additional deformations (Coduto, 1994). Conventional consolidation equipment can usually transmit these stresses and produce these deformations in relatively short times. That is, a soil sample, representative of a compressible soil stratum, can achieve its final stage of primary consolidation in 24 hours since soil samples are small compared to their represented strata.

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Using a graphical method, these results can be extrapolated, and various soil parameters can be easily determined, such as the hydraulic conductivity of the material, which is a property that varies as the soil consolidates because it is an indicator of the dimensions of the pores in the material sample.

However, the most important result is to quantify the settlements produced by the imposed loads (Wood, 1990).

For this, it will be totally relevant that the pressure that is being transmitted to the soil sample is the same as that suffered by the soil deposit in the field.

In this sense, it is natural that soil never stops suffering volumetric deformations since the migration of water outside its borders slows down but never stops (Chen et al., 2024). In practical cases, this is the reason why it is assumed that primary consolidation is the one that will be used since, on the one hand, it is assumed that it has the largest dimensions, and on the other hand, the waiting times must be practical to develop a geotechnical design that serves the necessary purposes in the field (Thanayamwatte et al., 2024).

On the other hand, if sufficient time is allowed, it will be seen that this slowing down of the deformations does not stop and evolves in its dimensions. This additional process is called "secondary consolidation" and is typical of highly compressible clayey and silty soils.

All these problems are related to the phenomenon of long-term soil consolidation and, although this phenomenon has been studied for a long time, there is no single criterion on the causes that generate it. Various explanations have been given and a large amount of analysis has been carried out to obtain an equation that can explain this phenomenon. Among the main explanations for this phenomenon are: the effect of water viscosity and the various pore sizes (Cotecchia & Chandler, 2000; Futai, Almeida, & Lacerda, 2004).

There are different parameters that can influence the conditions and processes of consolidation, such as the initial humidity of the site, its density, the viscosity of the liquid contained in its pores, and the mineralogical composition.

These phenomena are well described by sophisticated numerical analysis, for example, using the finite element method, or more advanced methods. All of them, however, see the success of their numerical predictions in the reliability with which the parameters are obtained.

Constitutive models for soils have undergone modifications as knowledge of soils and their elemental characteristics has advanced; however, the authors consider that success is based on the adequate recovery of the parameters that feed these constitutive equations (Arroyo & Rojas, 2019).

This research proposes to experimentally exhibit the differences that exist in the consolidation processes of soils in soil mixtures that have comparable initial properties, however, they have a different particle size distribution.

The first section describes the characteristics of the soils and their manufacturing processes. Then, the experimental study process and the equipment used are described.

Manufacturing of the samples

Two samples were manufactured with different particle sizes, but with identical initial humidity using T2 type kaolin clay as the main material. T2 type kaolin is a finely ground material. According to the soil properties, this material is a silicate, it is found within the group of clays and its main component is kaolinite. Chemically, kaolin is known as hydrated aluminosilicate, according to a typical analysis it is composed of 48.56% Silicon Oxide (SiO_2), 37.03% Aluminum Oxide (Al_2O_3), 4.22% Iron Oxide ($Fe2O_3$) and 1.09% Sodium (Na_2O).

Regarding the typical physical properties of kaolin, it is characterized by having a low percentage of non-mesh rejection. 325 (less than 7 percent), has a humidity of less than 3.86%, a pH of 7, its specific density is 2.4 gr.\cc and apparent density 1.09 gr.\cc, the percentage of injection losses at 950° C is 11.80 and, visually, it has a beige color.

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The sand used for the mixture of test 1 is composed of 96.90% Silicon Oxide (SiO^2) and has an actual density of 2.65 g/cm^2, based on its behavior under granulometric analysis we know that 3.15% was retained under mesh no. 20, 45.11% by mesh no. 30 and 41.33% by mesh no. 40.

The mixture for test 1 was prepared with 70% kaolin and 30% sand, adding a total humidity of 40%. That is, it was prepared using 70 g of kaolin mixed with 30 g of sand and moistened with 40 g of water, which gives a weight of 140 g for the mixture. Once the material was prepared and properly homogenized and at rest, the sample was manufactured. The filter paper and the consolidation ring were placed on the consolidometer tray; with the help of a spatula, the mixture was added inside the ring in small quantities without compacting until reaching a height of 2.03 cm and a diameter of 6.2 cm, which gave a volume of 61.29 cm^3. The total wet weight of the sample was 117.2 g and a specific weight of 1.9 g/cm3.

Different proportions of the material were considered for the preparation of the mixture used in test 2. 100% kaolin with a humidity of 40% was used. Following the same procedure for homogenization and manufacturing and considering the same dimensions, this sample had a total wet weight of 113.6 g and a specific weight of 1.85 g/cm^3.

The mixture used for test 1 that contained sand visually had a more liquid appearance, unlike the mixture prepared for test 2 that had a more plastic consistency and was easy to mold.

Consolidation equipment used

Experimental tests indicate that secondary consolidation only occurs in fine soils. When the results of a consolidation test are plotted on the axes of log time versus volumetric strain, a curve is obtained showing a predominant slope where large volumetric changes are observed. As time increases, this slope rapidly decreases to give way to a smaller slope that shows long-term volumetric changes (secondary consolidation). Volumetric changes related to the predominant slope have been termed "primary consolidation," while long-term volumetric strains have been termed secondary consolidation.

The consolidometers used in each of the tests are identical, both are mainly composed of a metal tray, a lever arm and a micrometer with which the deformations are measured (Figure 1).

Box 1

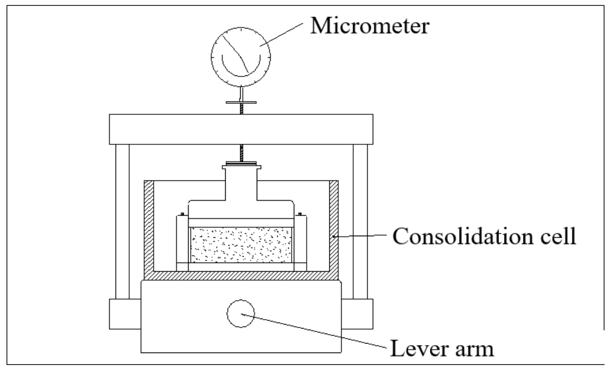

Figure 1
Schematic of the consolidometer used in the study
Source: Own elaboration

As shown in Figure 2, the metal tray has a porous stone embedded inside with a fixed ring, as well as a ring where the sample is placed, a second porous stone that is placed on top, a clamping ring and a loading disk with a uniform base that goes on the porous stone that has the function of applying the load in a uniform manner and at the same time measuring the deformation with the help of a micrometer.

Box 2

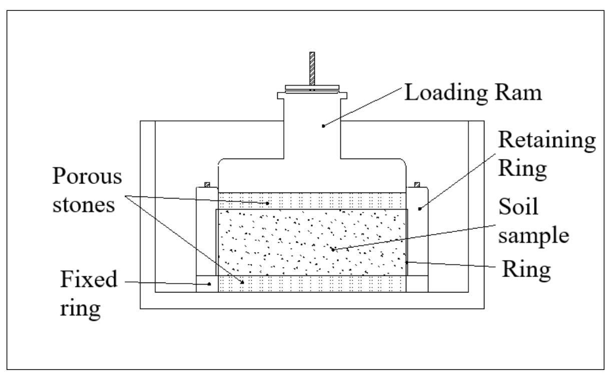

Figure 2
Detail of the soil sample mounting in the consolidometer
Source: Own elaboration

The micrometer can measure up to 12 mm of deformation.

The lever arm has a load plate where, by placing the weights, the corresponding load with the required scale is applied to the sample with the loading disk.

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Sample placement process in the consolidometer

Since the consolidation tray has a fixed porous stone, only the filter paper with the sample and the ring were placed. Another filter paper, a second porous stone and the loading disk were placed on the sample. The retaining ring was inserted and secured with screws. This retaining ring prevents water from draining the sample.

Before placing the tray, we must check that the lever arm of the consolidometer moves easily and that the scale is correct (1:10).

For both tests, once the tray was ready, it was assembled on the fixed base of the consolidometer. The micrometer was placed with the necessary care so as not to move or alter the sample and it was verified that the reading had no modifications to corroborate that it was working correctly.

Next, we continued with the sample saturation stage. Water was added to the tray little by little using a trowel until it covered the lower part of the loading disk and the recording of the readings for each micrometer began every 5 seconds, increasing the time range of the readings as the saturation time passed, that is, starting from 1 min, the readings were recorded every 60 seconds until reaching 5 min. The readings were graphed until the consolidation stage was concluded when the first load was applied.

Results

From the moment the first load was applied, the recording of the readings began by graphing the logarithmic time and the deformation in millimeters in a consolidation curve.

The 1 kg load was added to the consolidometer of test 1, which contained 70% kaolin and 30% sand, that is, a stress of 0.3 ton/m2 was applied, taking into account that the area of the sample is 30.19 cm^2.

In Figure 3, we can see that after 45 seconds the end of the consolidation stage was reached, with the sample deforming approximately 0.04 millimeters.

So far, the sample has deformed 0.58 mm and continues with secondary consolidation.

Box 3

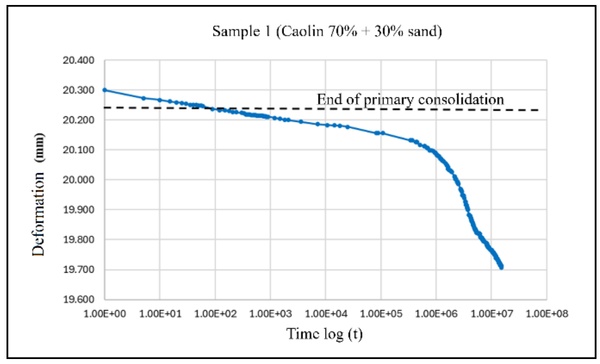

Figure 3
Consolidation curve of test 1 with 70% kaolin and 30% sand
Source: Own elaboration

Box 4

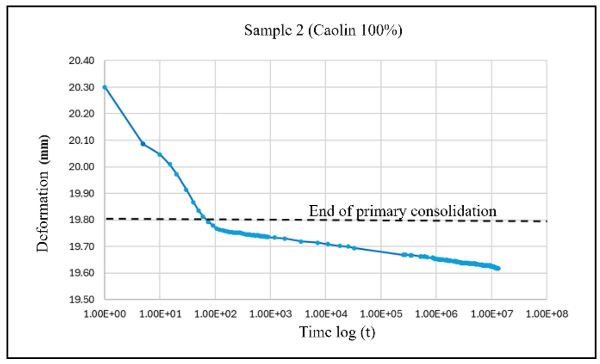

Figure 4
Consolidation curve of test 2 with 100% kaolin
Source: Own elaboration

In test 2, a stress of 5 ton/m2 was added, that is, a load of 1.5 kg was applied to the lever arm of the consolidometer.

Based on Figure 4, we can see that the primary consolidation stage ended after 60 seconds and had a deformation of 0.5 mm. In addition, we can see that it has deformed about 0.68 mm so far.

Conclusions

The experimental results derived from the analysis of the soil mixtures show the difference in response, both in the consolidation times and in their magnitude. This is mainly due to the microstructure generated within the mixtures (Arroyo, Rojas, Pérez-Rea, Horta, & Arroyo, 2015), which must also be due to the manufacturing of the same in terms of their initial humidity and the applied pressures (Della Vecchia, Dieudonné, Jommi, & Charlier, 2014).

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In this sense, a different soil structure would generate a consequent structure of pore sizes and it is considered possible to study and quantify this process from the distribution of pore sizes (Rojas, Pérez-Rea, Gallegos, & Leal, 2012).

The influence of these last two parameters remains to be reviewed to recognize how they influence the compaction processes and establish operating conditions for the compacted materials as a function of their construction processes and the time they last (Tsutsumi & Tanaka, 2012).

Declarations

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author's contribution

Rojas, Eduardo: Contributed to the project idea, research method, technique and manuscript revision.
Reynoso, Eva Guadalupe: Contributed performing the consolidation tests.
Arroyo, Hiram: Contributed to data analysis and interpretation, manuscript writing and revision.

Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

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Abbreviations

No abbreviations are contained within the paper.

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