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An Experimental Study on the Unsaturated Soil Parameters Changes due to Various Degree of Saturation

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Abstract Landslide is a natural disaster often occurring in Indonesia, associated with the rainy season. The slope failure mechanism is the main challenge in the slope stability analysis due to rainfall. The changing of the soil engineering properties under the effect of water infiltration during the rain should be fixed. In this study, the experimental studies were conducted to evaluate the unsaturated soil parameters changes, i.e., suction, cohesion, and internal friction angle, in various degrees of saturation. The filter paper tests were conducted to evaluate the matric suction of soil and develop the soil-water characteristic curve (SWCC) using the Soil Vision software. Fredlund and Xing, Van Genucthen, and Brooks and Corey fit the SWCC: The fitting equation developed by Fredlund and Xing resulted in the highest coefficient of determinant with R^2 of 0.91 and 0.97 for well-graded silty sand and silty sand curves, respectively. Thus, it was used to determine the correlation between saturation, cohesion, and matric suction. Shear strength parameters of soil samples were examined using a direct shear test method. The results show that the increase of the saturation degree reduces the soil suction and shear strength parameters. The result of this study is crucial to develop an understanding of the mechanism of slope failure.

Keywords Cohesion, Unsaturated Soil, Shear Strength, Suction, Slope Stability

1. Introduction

Landslide is a geological phenomenon and one of the most scattered disasters on various earth surfaces. The presence of large-scale soil movements indicates this phenomenon, both in rock falls, slope failures, or shallow discharge flows, which can occur in inland, coast, and sea environments [1]. Landslide is a natural disaster often occurring in Indonesia, associated with the rainy season [2]. Water infiltration from rainfall increases the soil's weight and degree of saturation [3]. This condition corresponds to reducing the suction of the soil. Decreasing the suction of the soil can make the soil's normal stress drop and loosen the soil's shear strength. Finally, it promotes the imbalance of the slope [4]. The landslide induced by rainfall has been studied extensively [2, 3, 5–15]. Understanding of slope failure mechanism is the main challenge in the slope stability analysis study. In this study, undisturbed samples, which are well-graded silty sand (SW-SM) and silty sand (SM) from the site, were used as the soil samples. The experimental series was conducted to evaluate the evolution of unsaturated soil parameters, i.e., suction, cohesion, and internal friction angle, in various saturation degrees. First, the filter paper tests evaluated the soil's matric suction and developed the soil-water characteristic curve (SWCC). Next, shear strength parameters of soil samples were examined using a direct shear test method. Finally, all data were analyzed, and the relative correlation between the soil saturation degree and unsaturated soil parameters was determined.

2. Materials and Methods

2.1. Material

Undisturbed samples from Puncak Bogor, Indonesia were collected as the soil specimen of the experimental work. In addition, two-layer samples were collected from the site at 0 – 1 m depth. Filter paper Whatman 42 with 5cm in diameter is used to conduct the matric suction measurement using the filter paper method. PVC cylinder with 5cm in diameter and height is also used as the mold sample during the measurement of filter paper method.

2.2. Soil Water Characteristic Curve (SCWW)

The soil-water characteristic curve (SWCC) expresses the relationship between matric suction and gravimetric water content, volumetric water content or saturation [16]. The SWCC is a fundamental soil characteristic necessary to determine the parameters of many soil processes, such as infiltration, drainage, solute movement, and water availability for plants. It is also an essential tool in studying the strength and deformation of unsaturated soil [17, 18].

This study used a Whatman 42 filter paper based on ASTM D5298 [19] to measure the matric suction in various soil saturations. The schematic of the filter paper test is depicted in Figure 1. Firstly, two blocks of the soil samples were prepared inside the core cutter cylinder as the container. Next, three layers of filter paper were put between the soil samples. The samples were kept in a vacuum condition for seven days to approach the equilibrium condition. Finally, the initial and final mass of the soil samples and filter paper was measured to identify the water content of each sample and the degree of saturation. A calibration curve based on ASTM D5298 in Figure 2 was used to obtain the soil's matric suction based on the water content of the filter paper.

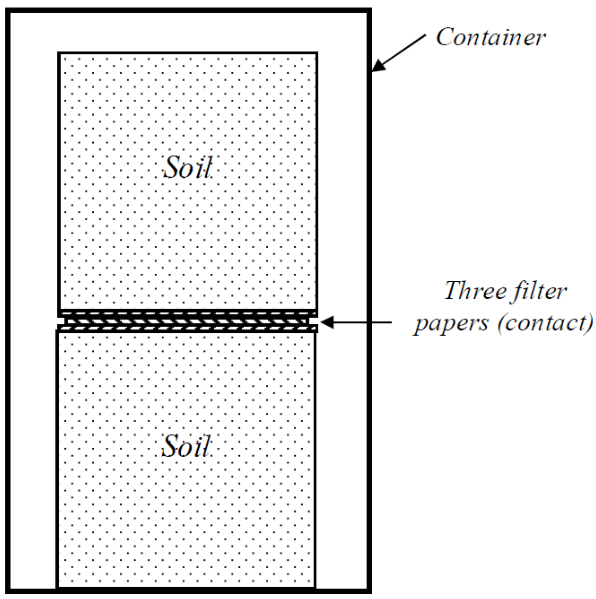

Figure 1. Schematic of the filter paper method [13]

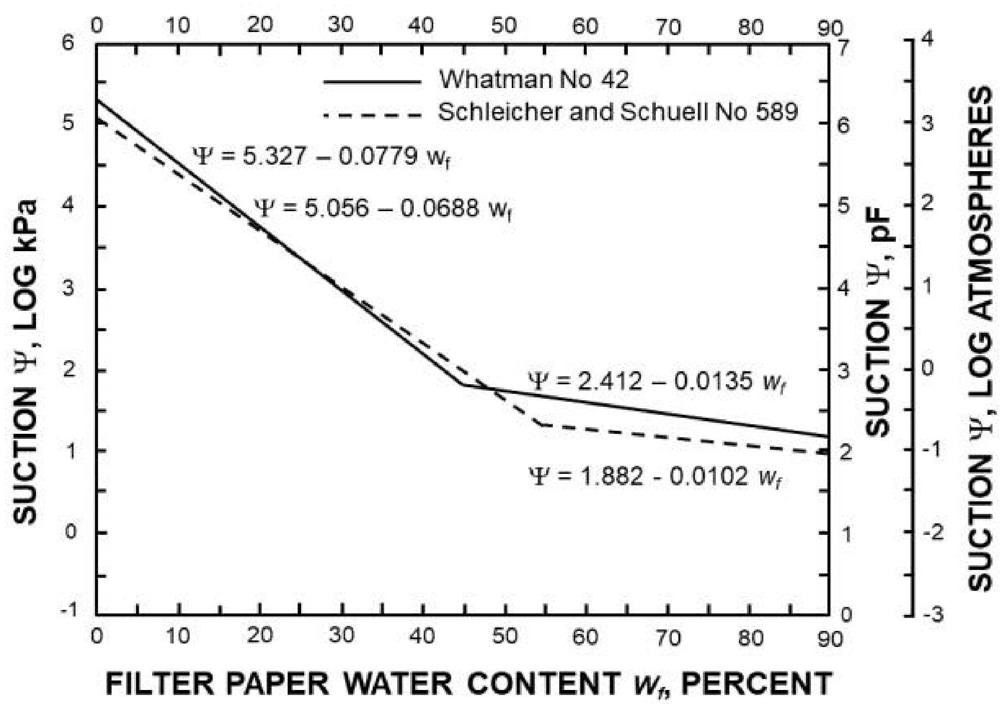

Figure 2. Calibration curve for the matric suction [19]

2.3. Direct Shear Test

The direct shear test was used to measure the shear strength parameters of soil, i.e., cohesion and internal friction angle [20]. This study performed the direct shear test for the soil samples in various degrees of saturation. The direct shear was conducted according to the ASTM standard of ASTM D3080 for the direct shear test [21]. The test was performed on the three specimens for each soil sample. The specimen was placed in a shear box with two stacked rings to hold the sample. The contact between the two rings was approximately the mid-height of the sample. The normal stress of 0.5, 1.0, and 1.5 kgf were applied vertically to the specimen, and the upper ring was pulled laterally until the sample failed or through the maximum strain of 10% of diameter samples. The applied load and the induced strain were recorded at frequent intervals to determine a stress-strain curve for each normal stress. The results entire specimen were plotted on the graph with the peak (or residual) stress on the y-axis and the confining stress on the x-axis. The y-intercept of the curve which fits the test results is the cohesion, and the slope of the line or curve is the friction angle [21].

Experimental condition for the matric suction and shear strength test was conducted from wet to dry conditions (drying process) to evaluate the effect of degree of saturation on soil parameters changes. Undistributed samples were used for the matric suction test, and the remolded samples were used for the shear strength test. Each sample was modified using an oven to obtain different water content. The degree of saturation can be measured by knowing the specific gravity, volume, and soil's water content. A formula to measure the degree of saturation refers to equation (1). Each experiment series were conducted in five various degrees of saturation. Sr is the degree of saturation (%), Wb is the bulk weight (g), Ww is the wet weight (g), Wd is the dry weight (g), Gs is specific gravity (-), and V is the volume of the specimen (cm^3)

$$S_r = (Wb\text{-}Ww)*(V\text{-}Wd/Gs)^{-1} \quad (1)$$

3. Result and Discussion

3.1. Soil Properties

The laboratory test results for soil's physical and mechanical properties are presented in Table 1. Two types of soil were classified based on the USCS (Unified Soil Classification System) method using grain size distribution data and the Atterberg limit test. SW-SM classified the top layer soil as well-graded silty sand and symbolled. The upper layer of soil was classified as silty sand and symbolled by SM. The soil's grain size distributions are depicted in Figure 3.

Table 1. Physical and mechanical properties of soil samples in this study

Parameter	SW-SM	SM
Specific gravity, Gs [-]	2.593	2.508
Initial water content, *w* [%]	62.5	52.0
Initial saturation, Sr [%]	86.2	92.7
Porosity, n [-]	0.70	0.63
Dry density, γd [g/cm^3]	0.83	1.02
Permeability, k [cm/s]	0.35	0.0036
Liquid limit, L_L [%]	56.7	66.6
Plastic limit, P_L [%]	32.3	34.2
Plasticity index, P_I [%]	24.4	32.4

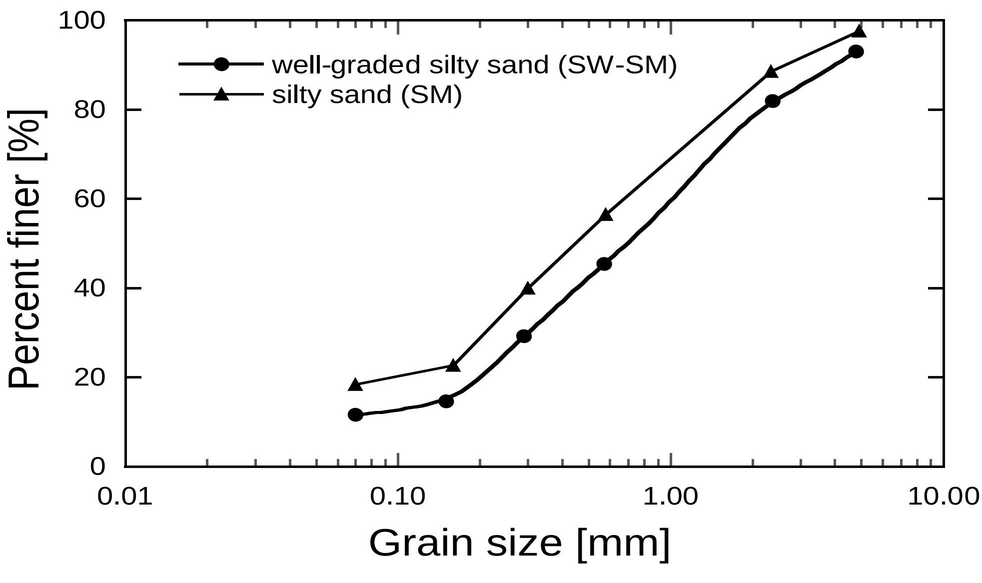

Figure 3. Grain size distribution curve for soil samples in this study

3.2. Matric Suction

The samples were modified to obtain a different saturation condition and develop the SWCC graph. Five cases were examined for each soil type to obtain the water content in the filter paper method. Soil suction was calculated using the calibration curve in Figure 2. The result of the filter paper method is depicted in Table 2 and Figure 4. Based on Figure 4, both SW-SM and SM soil have a similar trend. However, increasing the soil saturation degree reduces the matric suction value. The matric suction value of the soil changed rapidly from about 10 to 105 kPa when the soil saturation degree was modified. In such a comparison, the suction value of silty sand (SM) soil changed at the shorter interval of saturation degree rather than the suction of well-graded silty sand (SW-SM). The result indicates that within a similar soil type, the grain distribution of soil brings the difference in soil suction parameters. Gallage et al. [22] reported that grain size distribution significantly affects the SWCC trend.

Soil Vision software was used to develop the soil-water characteristic curve (SWCC) based on the matric suction experimental data. The fitting curves of well-graded silty sand and silty sand are depicted in Figure 5. This analysis used three fitting equations to fit the SWCC: Fredlund and Xing, Van Genucthen, and Brooks and Corey. The highest determinant coefficient (R^2) for each fitting equation was used to determine the SWCC curve. Fredlund and Xing's formula is the fitting equation with the highest R^2 for each soil. The R^2 of well-graded silty sand and silty sand curves are 0.91 and 0.97, respectively. Hence, the curve fitted by Fredlund and Xing formulas was then used to develop the correlation of saturation and matric suction to shear strength parameters.

Table 2. The result of the soil matric suction test

Cases	Well-graded silty sand		Silty Sand	
	Sr [%]	Matric Suction [kPa]	Sr [%]	Matric Suction [kPa]
1	75.2	4.8	86.1	17.3
2	62.8	14.1	66.2	796.4
3	51.0	1786.8	59.2	2814.6
4	38.7	5181.4	26.3	96764.5
5	25.0	38297.5	24.7	106361.6

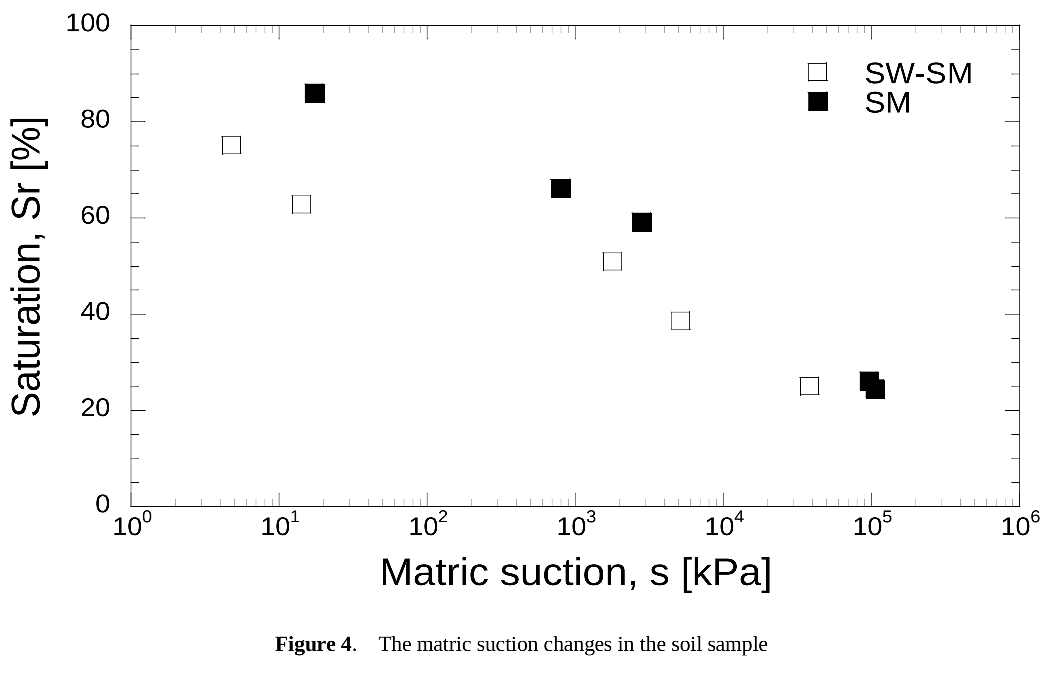

Figure 4. The matric suction changes in the soil sample

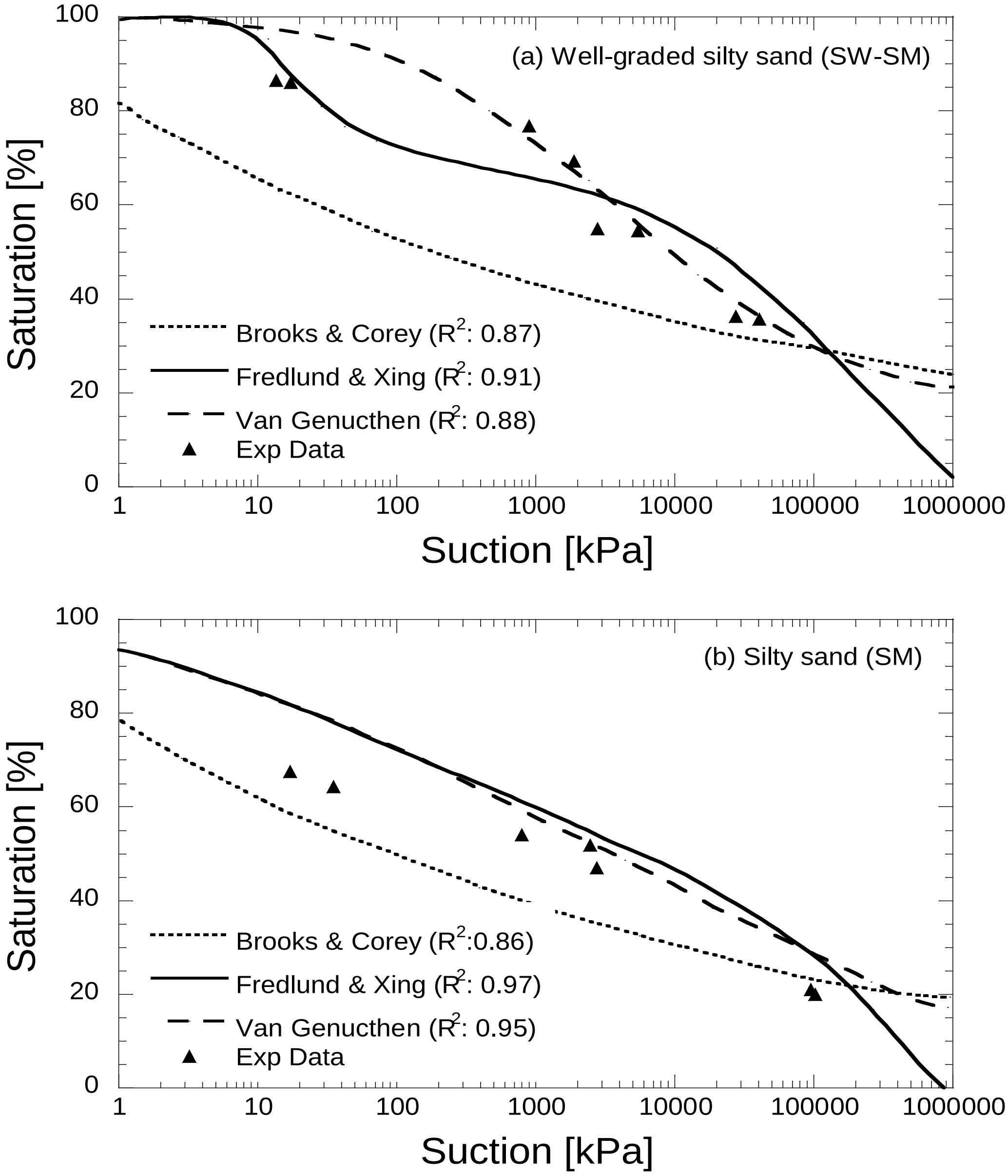

Figure 5. SWCC fitting curve; (a) Well-graded silty sand; (b) Silty sand

3.3. Shear Strength Parameters

Soil Water Characteristic Curve (SWCC), which expresses the relationship between matric suction and gravimetric water content, volumetric water content, or saturation, is the primary tool to predict the shear strength parameter in the unsaturated soil. Besides the cohesion and internal friction angle, the matric suction value also affects the shear stress of unsaturated soil. Shear stress is an essential parameter in geotechnical engineering. The direct shear test was conducted at various degrees of saturation. Five conditions of saturation were examined through the test for each soil type. Table 3 presents the result of the shear strength test for well-graded silty sand (SW-SM) and silty sand (SM). The initial dry density of each soil type was used to control when the samples were remolded, 0.81- 0.83 gr/cm^3 and 1.00 – 1.09 gr/cm^3 for the well-graded silty sand (SW-SM) and silty sand, respectively. The difference in the saturation condition of soil brings changes in soil shear strength parameters. The significant cohesion reduction of 0.29 to 0.09 kPa or 70% is measured by the increasing saturation of 9.4 to 90.2%. In addition, the changes in saturation showed an insignificant impact on the internal friction angle of both soil samples. The correlation between saturation and cohesion for each soil is shown in Figure 6. The figures present the correlation between saturation and cohesion. The increase in the soil saturation degree reduces the matric suction and shear strength parameters. The cohesion of the soil increases as matric suction was also increased. The initial saturation changes from fully saturated indicated bring about a significant effect on the cohesion. The result shows a similar trend to the research conducted on sandy clay soil [23].

Table 3. Summary result for the shear strength test of soil

Cases	Dry density (γd), [gr/cm^3]		Saturation (Sr), [%]		Cohesion (c), [kPa]		Friction angle (φ), [°]	
	Well-graded Silty sand (SW-SM)	Silty sand (SM)	Well-graded Silty sand (SW-SM)	Silty sand (SM)	Well-graded Silty sand (SW-SM)	Silty sand (SM)	Well-graded Silty sand (SW-SM)	Silty sand (SM)
1	0.83	1.05	9.4	22.7	0.29	0.71	11.3	11.3
2	0.83	1.09	32.7	49.3	0.26	0.58	9.7	16.7
3	0.83	1.07	45.9	58.2	0.24	0.53	10.2	16.5
4	0.82	1.06	88.8	71.9	0.19	0.46	10.2	12.1
5	0.81	1.00	90.2	92.7	0.09	0.42	6.3	9.94

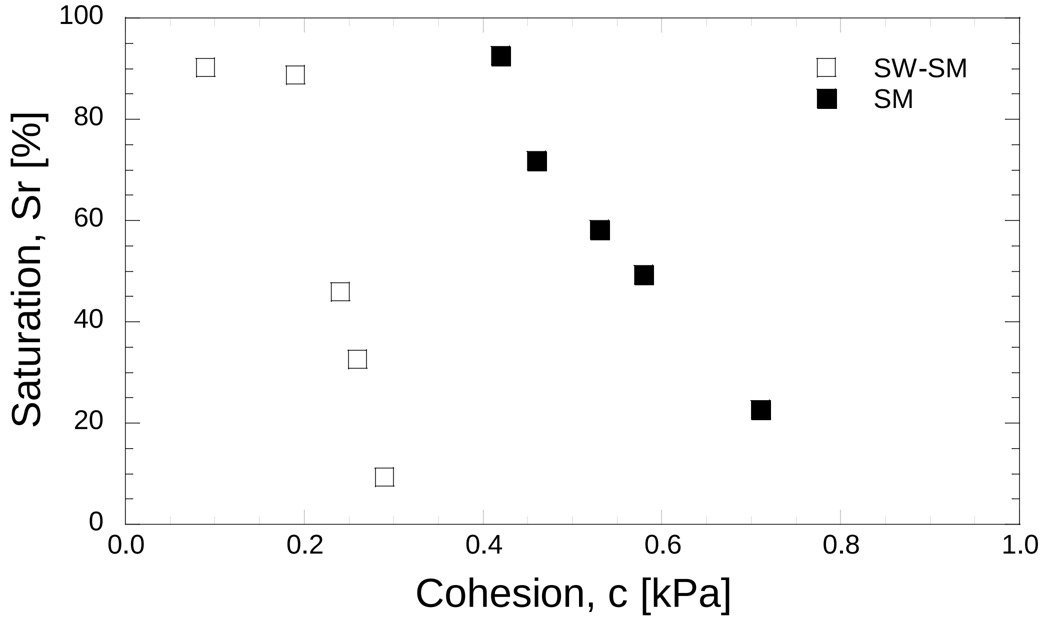

Figure 6. Cohesion value in various degrees of saturation

4. Conclusions

The effect of infiltration induced by rainfall on the unsaturated soil parameters was evaluated. A series of laboratory tests were conducted to determine the significant impact of soil parameter changes influenced by the soil saturation degree. Soil Vision software approximated the entire soil-water characteristic curve (SWCC) using a proper curve fitting equation representing measurable data points. The Fredlund and Xing equation was utilized to determine the SWCC. The entire data was analyzed to find the correlation of measured soil parameters. This study shows that soil saturation degrees have a high correlation to matric suction and the cohesion of the soil. The increase in the degree of saturation reduces matric suction and cohesion; however, it does not significantly impact the internal friction angle. The result of this study is crucial to developing an understanding of the mechanism of slope failure. This phenomenon was used to mitigate landslides due to infiltration during rainfall.

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