UNSATURATED BEHAVIOR OF STABILIZED CLAY: ASSESSMENT OF LOW-CARBON BINDERS IN A FIELD STUDY

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KEYWORDS

Dry deep mixing, low carbon binders, SWCC, soft clay, partial saturation

ABSTRACT

The stabilization of soil with cementitious materials often induces desaturation. This study investigates the stabilization of soft clay after a one-year curing period under real field conditions. Three binders—Terra Poz, Terra Green, and Terra GTC—are tested to assess their potential as low-carbon substitutes for ordinary Portland cement (CEM I) in soft clay stabilization at Malminkenttä, an old airfield in Northeast Helsinki. Stabilization involves dry deep mixing of the low-carbon binders with saturated soft clay in separate columns.

Measurements of total suction are conducted using a chilled mirror device, establishing the soil-water characteristic curves (SWCC) under both drying and wetting paths. The impact of stabilization with different binders on air entry value, saturation behavior, and residual water content of the samples is analyzed.

Observations indicate that hydration and reactions between the clay and binders lead to a reduction in water content of the stabilized soil, resulting in persistent unsaturated behavior even after one year in a saturated soil environment.

1. INTRODUCTION

The dry deep mixing method (DDM) has been extensively used in Finland in the last four decades to improve the properties of very soft clays, which are found across the country. In this method, lime and cement have been used as the binder materials which can easily react with the high-water content of Finnish clays. However, due to the large carbon footprint that these materials have, continuing to use them would hinder any efforts towards a carbon neutral society. The city of Helsinki for instance, has decided to stop completely the usage

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of only lime and cement in column stabilization and it is now carrying out an extensive field and laboratory testing program along with environmental monitoring of field-mixed columns stabilized with low-carbon binders. This testing is being performed in *Malminkenttä*, an old airfield in Northeast Helsinki with clay deposits that consist of sensitive, high plasticity 5 to 20 m deep clay layers. The water content of some of the layer is up to 160%. The area has been designated as the location for a future residential plan development that requires an extensive soil improvement. If deep mixing is to be used, the total length of the required stabilized columns in Malminkenttä to improve the whole area is estimated to be 100 million meters. This would represent an enormous amount of carbon emissions if the stabilization was done with the traditional lime/cement binder.

Many of the binders used in Malminkenttä have shown to be an adequate performance for soft soil stabilization [1]. In this study, the soil-water characteristic curves (SWCC) of stabilized field-mixed with three different low-carbon binders used in Malminkenttä is obtained and compared against one another. The samples were extracted from field columns recovered after 1 year of curing in Malminkenttä and belong to the most upper part of the column, between 1 m to 2 m depth. Specimens from the columns showed a persistent unsaturated behavior even after one year within the saturated soil environment. This behavior has implications in the way columns are analyzed and simulated as explained in Bozkurt et al. [2], where numerical simulations of undrained extension triaxial tests resulted more accurate when the stabilized soil was simulated as partly saturated. Thus, a preliminary study of the partly saturated conditions of these columns is performed as a starting point to understand the effects of partial saturation on strength and conductivity of field columns.

2. MATERIALS AND METHODS

2.1 Clay deposits

The specimens tested in this study belong to columns that were initially constructed with Malminkenttä soft clay, a fully saturated and normally consolidated postglacial clay with high plasticity and low shear strength. The water content at the depth the samples in this study belong to (1-2m) is between 90 to 120%, with a shear strength between 7 to 15 kPa and a sensitivity value of around 30. The groundwater level has been measured from five groundwater pipes at the location of the original columns. According to measurements of the pipes, the pressure level is about 0-1 m above the ground (+15 - +16 MASL). Thus, the columns are surrounded by fully saturated soil.

2.2 Field-mixed specimens

In Malminkenttä, deep mixing with dry binder was used to build columns in different test areas. In this study, the stabilized material was extracted from stabilized columns that were recovered with the help of a steel pipe to a depth of approx. 3 m and lifted with an excavator's bucket. Then, steel tubes of 51 mm were used to extract cylindrical specimens by pressing the tubes against the central part of the lifted columns along the longitudinal axis of the columns in the section that belongs to 1 to 2 meters depth. Before starting the measurements, the specimens were extruded from the tubes and their initial water content was measured to determine their initial degree of saturation. Then, the specimens were placed in a triaxial cell and subjected to high back pressure of around 400 kPa for several days with periodic measurement of B-values. Once a B-value higher than 0.95 was measured, the specimens were deemed as saturated and removed from the triaxial cell to start the suction measurements.

The specimens used for the determination of the SWCCs consist of three different binders: (1) a gypsum-based binder (Nordkalk Terra GTC) and two lime kiln dust (LKD)-based binder (Nordkalk Terra Green and Nordkalk TerraPoz). The emissions from the production of these binders are significantly lower than emissions from purely lime/cement-based binders. The components of these binders and their ratios are presented in Table 1, along with the carbon emission from their production.

Table 1. Binders used in the study.

Binder	Components	Percentage (%)	Emissions (kgCO2e/t)
Terra GTC	gypsum	33	186
	slaked lime	33	
	CEMIII/A	33	
Terra POZ	CaO	33	563
	LKD	33	
	CEMIII/A	33	
Terra Green	LKD	50	237
	CEMIII/A	50	

2.3 Suction measurements and analysis

For the suction measurements in this study dewpoint potentiometer (WP4) was used. This method is an indirect measurement which determines water potential by balancing the liquid-phase water of the sample with the vapor-phase water in the enclosed space above the sample. The correlation between the total suction of the sample and the vapor pressure of the air in the sealed block chamber is described by Kelvin's function in Equation 1 [3].

$$\Psi=\frac{RT}{M} x ln \frac{P}{P_0} \quad (1)$$

where R is the universal gas constant, M is molecular mass of water, T is the temperature of the sample, P is the vapor pressure of air and P0 is the saturation vapor pressure at the sample temperature.

The saturated samples were placed in small metal cups to measure their mass and suction at 100% degree of saturation. The samples were then left to air-dry, with regular suction measurements taken during the drying process. This cycle was repeated until the suction measurements stabilized, indicating the samples were fully dried. A desiccator with drying silica gel packets was used to ensure the samples reached the driest condition possible. After drying, the stabilized samples were placed in humidity-controlled rooms with varying relative humidity levels of 45, 65 and 100% for at least 24 hours each, to reach equilibrium. Full saturation, with suctions close to zero, was achieved by spraying water on the samples. The samples were then dried in an oven, and the gravimetric water content and degree of saturation at different stages of the drying and wetting paths were calculated. The experimental data was fitted by using the model proposed by Van Genuchten [4] to evaluate the Soil-Water Characteristic Curves (SWCCs). The model equation is given as Equation 2:

$$S_r = \left[\frac{1}{1+(\alpha h)^n}\right]^m \qquad , (m\text{=}1\text{-}1/n) \qquad (2)$$

where S_r represents the degree of saturation, h denotes suction and is a positive value, and α, n and m are three parameters that are determined through fitting the model to experimental data.

3. RESULTS AND DISCUSSIONS

The Soil-Water Characteristic Curve (SWCC) defines the relationship between suction and either water content or degree of saturation in soil as it transitions between the saturated and unsaturated phases. The SWCC is widely used to predict the permeability, shear strength, and deformation of unsaturated soils [5,6,7]. In this work the total suction measurements of stabilized soft clay samples after one year of field curing are plotted against their degree of saturation. The laboratory data and the fitted curves are depicted in Figure 1. The shape and characteristics of SWCCs are distinctly influenced by the type of the binder used in stabilization. Notably, the degree of saturation corresponding to suction in the wetting path is lower than that in the drying path, though this effect is minimal at the suction corresponding to full saturation (Sr_s) in the case of the Terra Green binder. This hysteresis behavior, observed in both drying and wetting paths, has been documented in previous studies for the cement-stabilized clay samples in Liu et al. [7] and for fly ash-stabilized silt and clay samples in Wen et al. [8] study on.

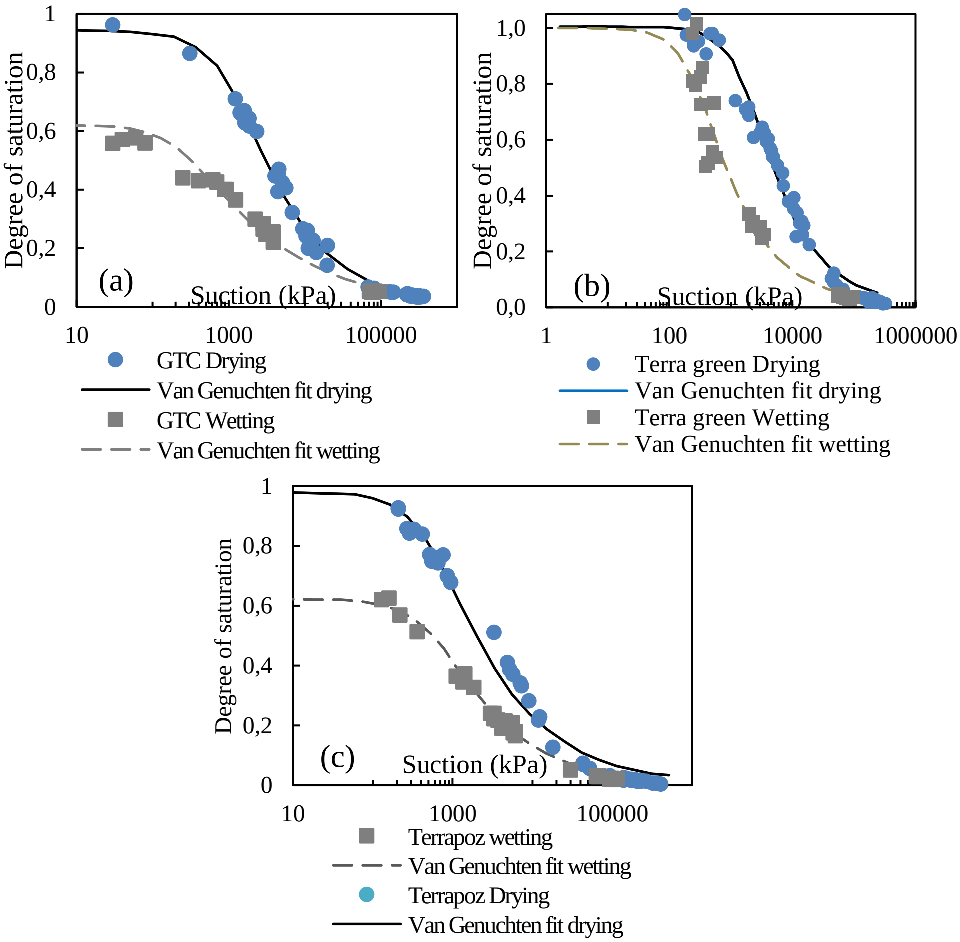

Figure 1 Drying and wetting SWCCs of stabilized soft clay after one year (a)with Terra GTC binder, (b) with Terra Green binder, and (c) with Terra Poz binder.

In samples containing Terra GTC and Terra Poz binders the hysteresis behavior is more pronounced in capillary saturation and transition zones. However, in samples containing Terra Green, the lag is visible only in the transition zone. The difference between the drying and wetting paths is not as apparent in the residual zone, regardless the type of samples. The observed behavior can be related to factors such as the ink-bottle effect, where the heterogeneous pore structure, radius of pore channels, and whether the pores are draining or wetting, affect the water retention capacity of the soil. Additionally, the angle of contact between the soil grains and/or cemented products, possible trapped air, and the shrinkage or swelling of soil during drying and wetting phases contribute to the shape of hysteresis [7, 9]. Chen et al. [10] explains that as the initial void ratio decreases, the ink-bottle effect weakens, leading to a reduction in soil hysteresis potential and a contraction of the SWCC hysteresis loop. Similarly, when the pore size decreases under a fixed void ratio, the ink-bottle effect fades, resulting in a shorter distance between the drying and wetting curves as the suction increases.

In Table 2, the properties of the soil water characteristic curves based on the Van Genuchten equation are presented. From the values of the coefficient of determination (R^2) it can be presumed that this model can be fitted relatively well to the experimental data of stabilized samples in both drying and wetting phases. The air entry value (AEV), indicating the point where the soil desaturation begins, is highest in sample containing Terra Green during the drying phase, followed by Terra GTC and Terra Poz.

On the other hand, the degree of saturation in the residual suction area, residual saturation (Sr_r), displays values approaching zero regardless of the type of the binder. It's noteworthy to mention that achieving the dry conditions is highly unlikely not only due to the climate of the region, but due to the fact that the stabilized columns are situated below the groundwater level.

The process of stabilization aims to establish interparticle bonding, which fills up the pores through hydration and pozzolanic reaction products, consequently reducing pore size and increasing the AEV parameter. The elevated AEV values observed in Terra Green and Terra GTC samples suggest better stabilization with these binders, consistent with the strength analysis findings reported in the research conducted by Ramírez and Korkiala-Tanttu [1].

The initial in-situ water contents of the samples after one year of curing in Malminkenttä were 77.3%, 89%, and 68.7% for Terra Green, Terra GTC, and Terra Poz bearing samples, corresponding to a degree of saturation of 91.7%, 90%, and 90.5%, respectively. With the application of back pressure in a triaxial cell (400 kPa, for several days) to achieve full saturation and by examining the SWCC curves, it is evident that the conditions of all the samples fall within the transition zone, beyond the AEV point. This likely indicates that the hydration process of the added binders, which led to the desaturation of the soil, is not yet fully completed in the tested area, and the hydraulic properties, permeability, settlement, and strength characteristics of the soil are still developing toward their saturated final state.

Table 2. The parameters of SWCC fit by Van Genuchten [4] equation.

	Drying path					
	Sr_s	Sr_r	α	n	AEV (kPa)	R^2
Terra GTC	0.94	1.0e-10	0.0008	1.59	500	0.996
Terra Green	1.12	3.7e-21	0.0004	1.69	650	0.984
Terra Poz	0.92	1.0e-18	0.0016	1.52	230	0.987
	Wetting path					
	Sr_s	Sr_r	α	n	AEV (kPa)	R^2
Terra GTC	0.56	6.2e-16	0.0020	1.44	117	0.988
Terra Green	1.01	0.003	0.0034	1.59	105	0.985
Terra Poz	0.62	1.0e-16	0.0018	1.56	290	0.988

4. CONCLUSIONS

The behavior of binder-stabilized clay was analyzed through the study of the soil-water characteristic curve (SWCC) of the extruded samples from the field. SWCCs were established for stabilized soil under both drying and wetting paths, enabling the assessment of the impact of the different binders used on unsaturated properties of the samples.

The findings facilitate establishing a correlation between the strength properties and hydraulic conductivity of the stabilized soil under unsaturated conditions post-stabilization process. Furthermore, a prediction could be made regarding the time required to achieve the minimum strength properties at full saturation using the soil water retention capacity and unsaturated hydraulic conductivity.

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