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Cracks in Soils Related to Desiccation and Treatment

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Abstract: Soils tend to shrink when they lose moisture. In particular, fine-grained soils are susceptible to shrinkage and the resulting volume change.Shrinkage can cause cracking of soils that can adversely influence the engineering properties and behavior of the soils.The adverse effects include decreased strength of the cracked soils and increased flow through the soils. The objective of this research is to review previous studies, explain the problems encountered, and then suggest a way forward for future studies. The study shows that when there is an increase in soil density, there is a decrease in the volume of the voids in the soil, and this comes with an attendant reduction in volume shrinkage, which in turn causes a decrease in cracks in the soil. This shows that the type of clay (soil) has a direct effect on volume changes. Moreover, the study showed that treatment by cement and lime is not suitable. Treatment with fiber is a good method used to curtail and resist shrinkage in tensile force, but it is not suitable for all types of soil. In addition, microscopic analysis is a powerful method used in determining volume change. Consequently, itis recommended that scanning microscopy and digital image analysis be used for all analyses of soil with or without fiber and nanomaterial.

Key words: Soil Mechanics, Cracking of Soil, Soil Desiccation, Hydraulic Conductivity, Soil Image Analysis

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INTRODUCTION

Recent periods of extended rainfall have been accompanied by a higher incidence of slope failure (landslide). Therefore, if the climate changes according to the recent predictions, i.e.,wetterwinters and more extreme rain events, the rate at which slopes are likely to fail in the future will increase considerably. The mechanism of failure is thought to be governed by permeability, a much under investigated parameter in geotechnical engineering. Permeability is controlled by its macro- and micro scale structure. Furthermore, soils tend to shrink when they lose moisture. In particular, fine-grained soils are susceptible to shrinkage and its resulting volume change. Shrinkage can cause cracking in soils, and this may have an adverse impact on the engineering properties and behavior of the soils. As a result, the integrity of structures and facilities associated with these soils may be threatened. These adverse effects include decreased strength of the cracked soils and increased flow through the soils.

Cracks create paths for the transfer of fluids.Broken soils can increase the infiltration of surface water into the containment system or joy of fluids into the surrounding soil and groundwater (Benson, 1994).

The magnitude of the changes that result from the shrinkage and swelling of fine soil particles is often large enough to cause damage to small buildings, highways, and sidewalks.The yearlycost of damages to buildings, roads, airports, pipelines, and other structures is approximately 9 billion dollars (Jones, 1987).

Type of Cracking:

The causes of cracking could be either a volumetric change in the soil body or a consequence of pressure exerted on the soil body. Gray, (1989) categorized cracks into two major types, in line with the system of their formation:

1. Mechanical cracks:These are cracks that are formed via deposition or because of inappropriate construction.A good example of this is cracks with no good linkage between lifts and poor compaction.
2. Physicochemical cracks: This could be subdivided into three categories: syneresis cracks, cracks caused by freeze-thaw cycles and cracks initiated by thorough drying of the material.

Factors That Affect Cracking:

The following factors influence the shrinkage and cracking activities of soils: clay mineralogy, clay content, compaction conditions, drying process, wetting and drying cycles, soil particle orientation, unit weight, pore fluid, and exchangeable ions.

Formation of cracks is enhanced by the availability of clay (Holtz, 1981). When the plasticity index is high, the probability of shrinkage and swelling increases, while the extent of reduction in size drops to a minimum. However, the danger of shrinkage and cracking can be minimized by fortifying clay soil with coarse-grained materials (Kleppe, 1985). For the fabrication of a liner in arid sites, Daniel and Wu, (1993) suggested the use of clayey sand with a low hydraulic conductivity and low shrinkage values.

Compression activities and water content level have an impact on the drying pattern and hence the

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cracking of soil. Low-density porous and wet soil has the tendency to shrink.This makes the soil more readily prone to cracking, while highly dense and well-drained soil exhibits reduced shrinkage and a reduced risk of cracking. Daniel and Wu (1993) suggested the use of highly dense and well-drained soil for construction works in arid areas to discourage cracking. The results ofhydraulic conductivity tests carried out by Albrecht and Benson (2001) on compacted and saturated soils during wetting and drying cycles showed that shrinkage strain is directly proportional to both the plasticity index and clay content and indirectly proportional to compaction effort and closeness to the optimal water content. In addition, soil samples with high strains often have their hydraulic conductivity as high as three orders of magnitude larger than soils with low strain. In terms of the cracking activities of mixtures of sandy and clayey soils, Kleppe and Olson, (1985) found that shrinkage is directly proportional to the density of the mixture.

Restriction of pressure is also a major factor in cracking phenomenon. The results of tests conducted by Boynton and Daniel, (1985) on two types of clays by preparing slabs with a thickness of 6.4 cm showed that desiccation cracks approximately 1-mmwide ran through the entire thickness of the slabs. The path where the crack went through was cut and adjusted for hydraulic conductivity tests in flexible-wall parameters. The results further showed that pressure restrictions of 4 to 8 kPa were just enough to close cracks, while pressures beyond 8 kPa completely sealed up the cracks and thus greatly lowered the hydraulic conductivity of the soils. In addition to wetting and drying cycles, the drying process significantly affects the cracking of soils. Kleppe and Olson, (1985) observed a substantial increment in cracking for highly dense clay samples that were saturated with water before being dried.

Witt and Zeh, (2005) studied cracks due to desiccation cover lining system phenomena and design strategies. They concluded that the risk of desiccation for covers made exclusively of mineral liners of compacted clay or geosynthetic clay liners could be analyzed and assessed by designing the stratification and thickness of the different soil layers. However, under very dry or semiarid conditions, very thick earth covers are needed to prevent desiccation.

A range of water content near the optimal value with the higher compactive energy measures was demonstrated to be appropriate in meeting three objectives: low hydraulic conductivity, reduced ability to shrink and crack when dried and sufficient to support the shear strength of structural loadings (Daniel and Wu, 1993).

Albrecht and Benson, (2001) studied the effect of desiccation on compacted natural clays. They found the volumetric shrinkage strain occurring in compacted natural clays during desiccation to be a direct function of the volume of water/volume of soil when the soil was saturated. Soils with higher clay content and higher plasticity index generally have a greater volume of water and, thus, are more prone to large volumetric shrinkage strains during drying. In addition, specimens compacted near the optimal water content with a higher compaction effort have less water/unit volume when saturated and lower volumetric shrinkage strains (Fig. 1). Tests performed on specimens that cracked during drying indicated that the hydraulic conductivity increased by as much as 500 times, and the largest increase in hydraulic conductivity occurred for specimens compacted when wetterthan the optimal water content. The largest increases in hydraulic conductivity and shrinkage strains occurred after the first drying cycle. Thus, one drying cycle appears sufficient to severely damage compacted clay barriers if they are not protected. Moreover, healing of damage caused by desiccation is unlikely to occur during extended periods of hydration, unless the effective stress is increased considerably. No significant decrease in hydraulic conductivity was observed in specimens permeated for a period of 350 days.

After plotting the data in table 1, the results show that compactingthe soil atan optimal water contentproduces the lowest volume change and thus the lowest number of cracks (Fig.2). The same results were obtained by Albrecht and Benson (2001).

Varagon Puljan (2010) studied the shrinkage and expansive strain of compacted soil at wet side of optimal water content, optimal water content, and dry side of optimal water content (Table 1).

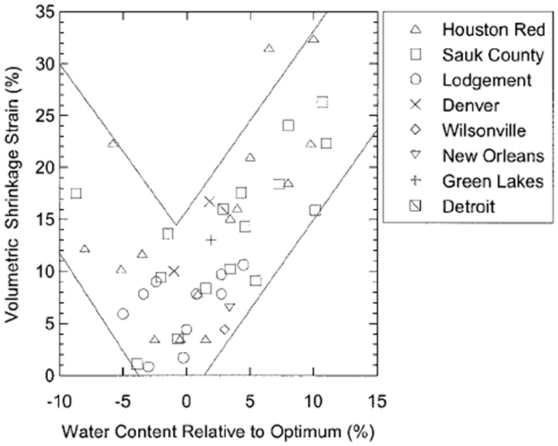

Fig. 1: Volumetric shrinkage strain versus compaction water content relative to the optimum (After Albrecht and Benson, 2001).

Table 1: Shrinkage and expansive strain of two different types of soil (after Varagon Puljan, 2010).

Soil (shrinkage type	Plasticity Index	Compaction condition	Water content	Dry density	Shrinkage strain	Expansive strain	Total volume change strain + expansive strain)
CH	37	Wet OPC (standard)	33	15.1	24.66	7.5	32.16
		OPC (standard)	23	15.9	14.04	15.25	29.29
		Dry OPC (standard)	13	15.1	6.15	26.93	33.08
CL	16	Wet OPC (standard)	20	17	10.97	3.11	14.08
		OPC (standard)	16.5	17.9	5.3	5.04	10.34
		Dry OPC (standard)	13	17	3.33	8.23	11.56

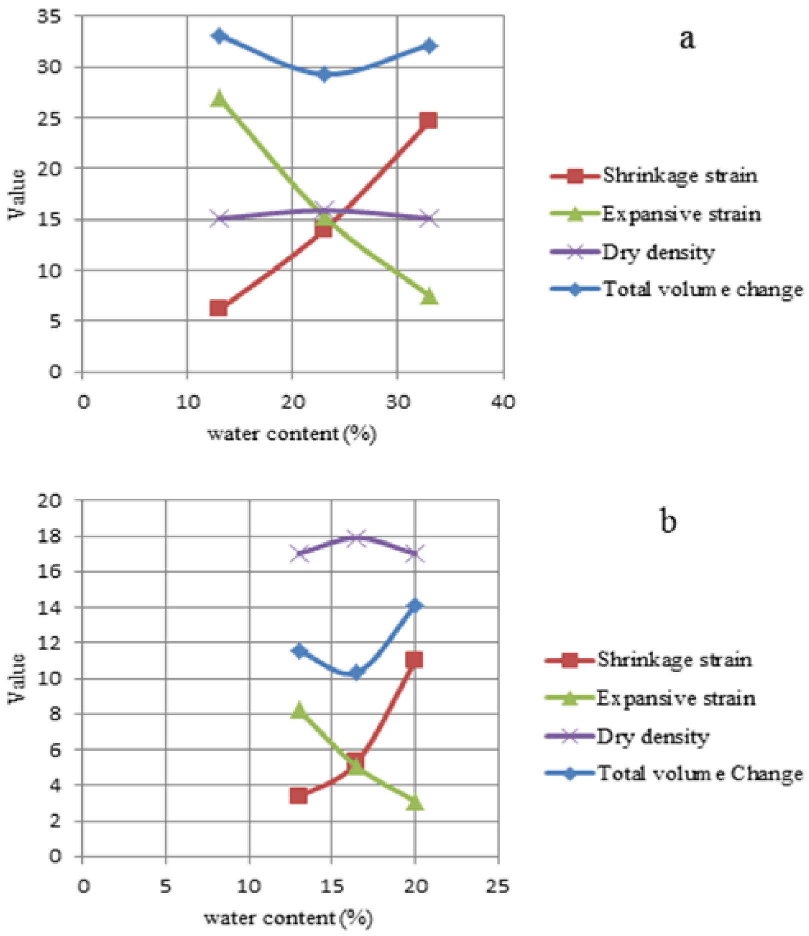

Fig. 2: The relationship between shrinkage strain, expansive strain, dry density, and total volume change versus water contentfor (a) high-plasticity clay soil (CH) and (b) low-plasticity clay soil (CL).

Krisdani, Rahardjo *et al.*, (2008) studied the effect of drying rates on the shrinkage characteristics of residual soil obtained from Bukit Timah Granite (Singapore) and mixtures of residual soil and fine sand. The results of the shrinkage tests showed that drying rates affected the speed of the void ratio and the degree of saturation changes in the soil. However, the shrinkage curves of the soils were not affected by the drying rates. A unique shrinkage curve was obtained for one type of soil under different drying rates.

Furthermore, Nahlawi and Kadikara (2006) carried out laboratory experiments on the desiccation and cracking of thin soil layers and showed that the cracking water content (wc) increased with increased clay layer thickness. The desiccation coefficient (k) represents the desiccation rate, which decreases as the clay layer thickness increases under similar environmental conditions. In addition, the ratio of crack spacing to the depth (s/d) was found to decrease with increasing soil thickness.

Matric suction of soil increases with increasing crack volume, both for evaporation and infiltration conditions (Fredlund, *et al.*, 2010). When there is a substantial volume of cracks in the soil, the matric suction is essentially uniform along the ground surface.

Inci (2008) studied the numerical modeling of desiccation cracking in compacted soils. His results indicated that a higher average water content does not necessarily mean less potential for crack propagation. Water content, resulting stress and module variations are more critical for determining cracking potential and crack propagation.

Rao and Revanasiddappa (2006) reported that cyclic wetting and drying increases the degree of expansiveness and reduces the collapse tendency of residual soil. Based on laboratory results, it is recommended that residual soil fill should be compacted on the wet side of optimal water content at a given dry density because laboratory specimens compacted at this condition exhibited marginal swell and collapse potential (?2%) after cycles of wetting and drying.

In another study on the shrinkage/swelling of compacted, clayey, loose and dense soils, Nowamooz and Masrouri (2009) observed that the compression curves of the expansive, compacted, loose and dense samples in the saturated state obtained by the free swelling method demonstrated that the normally consolidated line (NCL) is not a straight line and that it transforms to a nonlinear exponential form known as the normally consolidated curve (NCC). The dense samples showed cumulative swelling strains, while the loose samples showed an accumulation of volumetric shrinkage under wetting and drying cycles.

Finally, according to results obtained by Omidi (1993), Albrecht and Benson (2001), Osinubi and Eberemu (2010), Osinubi and Nwaiwu (2008), Harianto, Hayashi *et al*., (2008), and Puljan (2010) (Fig.3), the shrinkage strain depended on three main parameters: mold water content, dry density (compaction effort), and soil plasticity index.If the plasticity index of soil increases,the mold water content increasesand the shrinkage strain increases. In addition, the increase in the compaction effort leads to an increase in the dry density and then a decrease in the shrinkage strain.

Mechanisms of Cracking:

A desiccation crack comes from the volume change of the soil.According to Haines (1923), the drying process of saturated soils has two significant stages, referred to here as primary and residual drying (Fig. 4). Initial drying (primary drying) is the first stage of drying that happens when the soil loses the water without entering the air. Because the air does not enter the soil, changes in the size are equal to the volume of water change.

The biggest change in volume occurs during the initial stages of drying. The second phase of drying is residual drying.In this phase, the air enters the soil and replaces the water molecules with air. Abu-Hejleh and Zejleh, (1995) studied the water content void ratio curve (Fig.5) and divided the desiccation in soil into two stages. First,the soil loseswater content,and thus, the void ratio decreases.This results ina volume change until the shrinkage limit (Ws) is reached;then,the soil will no longer experience volume change. For example, if the soil is dried below Ws, it will have the same volume as at Ws, so all the cracks happen in the first stage. Cracks initiate one-dimensional shrinkage when the total lateral tensile stresses on the soil surface become equal to the tensile strength of the soil,whichhappens when surface water flows upward because of evaporation, resulting in consolidation of the soil layer.

A theoretical relationship between water content and volume change is given by Peron, Delenne *et al*., 2009):

$$\varepsilon_v = \frac{G_s}{1+e_o}\Delta w = \ \alpha_t \Delta w$$

Where G_s is the specific gravity of the soil particles, e_o is the theoretical value of the initial void ratio, and is the theoretical coefficient of linear shrinkage.

The stress during shrinkage of a circular sample occurs when the edge of the sample does not allow the shrinkage to distribute uniformly over thesample surface, but if the edge is free to shrink, the stresses become radial with a maximum at the center andless stresses along the radius (Costa, 2009).

According to Peron, Delenne *et al*., 2009), the samples that shrink homogeneously do not produce any cracking or intergranular forces because ofthe geometrical conditions, so any relative motion between grains is fully accommodated and the grains remain in contact. While in nonhomogenous shrinkage, the crack can appear anywhere along the vertical axis, not necessarily in the middle;thus, the maximum tensile stress can be anywhere in the soil. The end of cracking, the final number of cracks and the spacing were directly controlled by the imposed drying kinetics and the shrinkage limit. The link between particle failure and new cracks occurs as long as the grains continue shrinking.

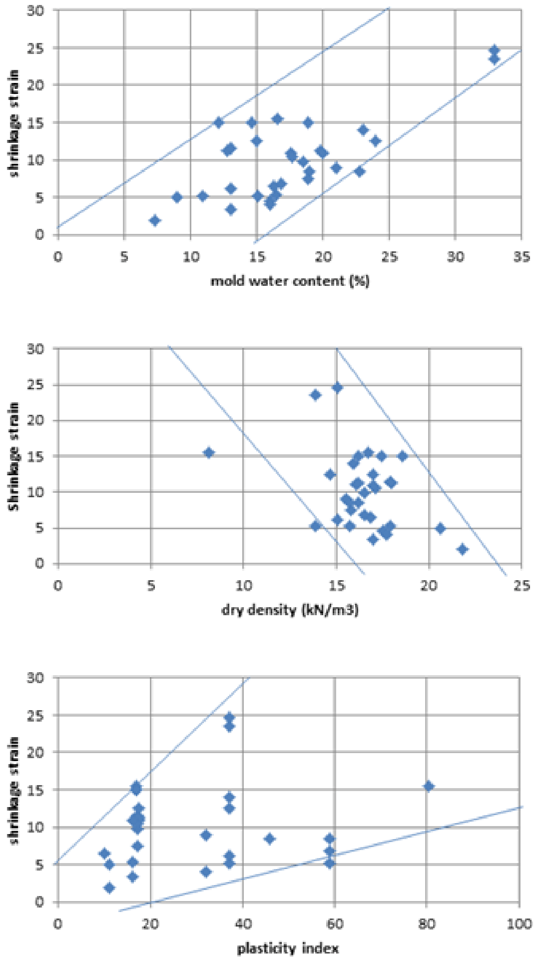

Fig. 3: Effect of mold water content, dry density, and plasticity index on the shrinkage strain for different types of soil (afterOmidi (1993), Albrecht and Benson (2001), Osinubi and Eberemu (2010), Osinubi and Nwaiwu (2008), Harianto, Hayashi *et al*. (2008), and Puljan (2010).

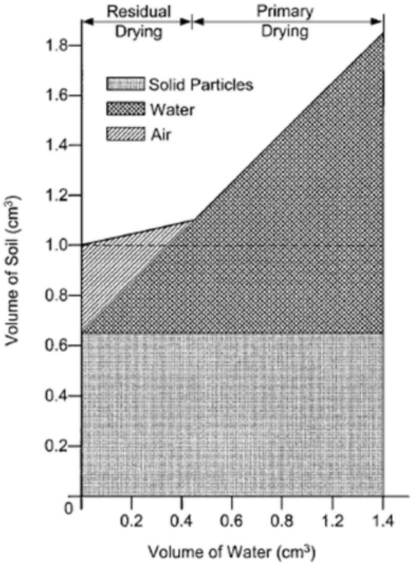

Fig. 4: Stages during drying (after Haines, 1923).

Microscopy and Digital Image Analyses:

A scanning electron microscope study on the water in the soil or on the fine grains in the soil, such as clay,was used to measure the contraction, expansion, and void ratio. Cold-stage electron microscopy (SEM) with a rapid cooling technology makes it possible to investigate the phase of water within the unsaturated soils,which can be extrapolated based on the hydraulic conductivity of unsaturated soil by images taken with SEM. These observations can be produced only by using the principles of the new technology, and this technique can be improve by using a device to control the rate of cooling (Gvirtzman, 1987).

Montesh, (2003) studied swelling-shrinkage measurements of MX80 bentonite using coupled environmental scanning electron microscopy and image analysis, as shown in Fig.6. Another study by Montesh (2003) was performedon bentonite. The results showed that coupling environmental scanning electron microscopy (ESEM) with digital image analysis (DIA) is a powerful method of estimating the swelling-shrinkage potential of expansive clays (Fig. 7).

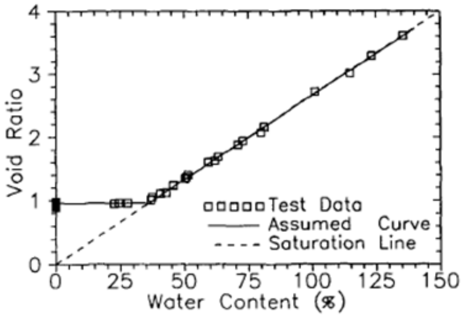

Fig. 5: Shrinkage curve for china clay (after Abu-Hejleh and Znidarcic, 1995).

In another study, Tang, Shi *et al.*, (2008) considered the factors influencing the geometrical structure of surface shrinkage cracks in clayey soils using image analysis. For different soils, the extent of cracking was found to correlate directly to the fines content and the plasticity index. It was observed that cracking takes place in three stages: main crack initiation stage, subcrack initiation stage and terminal stable stage. Main cracks initially start on the soil surface and then form main aggregates. Subsequently, main aggregates split into several subaggregates via subcracks. After all aggregate sizes have stabilized, cracking terminates, and the final crack pattern is formed.

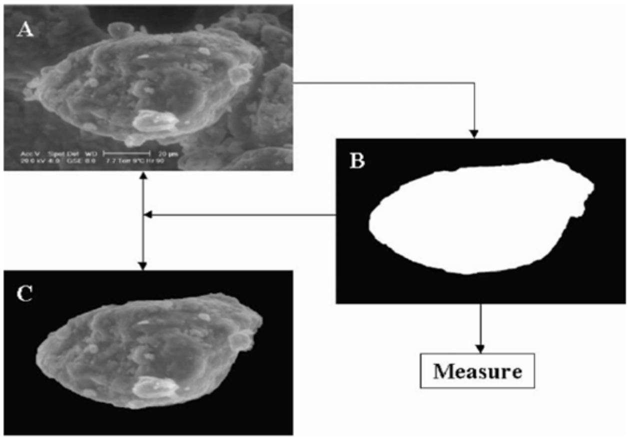

Fig. 6: Digital image analysis methodology. (A) ESEM image(B) Image binarization and isolation of the surface "aggregate" of interest; (C) Image reconstitution and control verification (after Montesh, 2003).

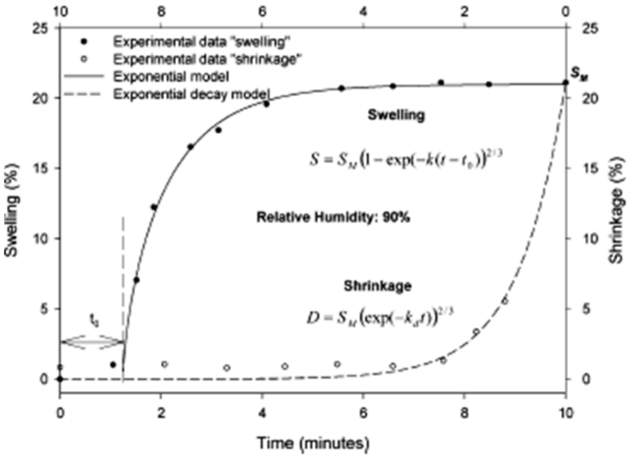

Fig. 7: Swelling-shrinkage cycle of raw bentoniteat 90% relative humidity. Experimental data fitted by exponential models (after Montesh, 2005).

Moreover, Peng, Horn *et al*., (2006) studied the quantification of soil shrinkage in 2D by digital image processing of the soil surface. This study introduced a new method to measure soil cracks nondestructively and continuously by digital image analysis. Using Adobe Photoshop and Windows Scion 4.02 image processing, the proposed procedure accurately identifies changes as small as 1.0 mm2 and shows differences even when areas of soil cracks increase by as little as 1%.

Crack Treatment:

There are different types of treatments for old materials, such as cement and lime, and new materials, such as fiber. From table (2), the treatment by fiber for high-plasticity index silty soil was powerful, while for clay soil, the powerful material for treatment was lime and silica fume.From the study conducted by Guney, Sari *et al*., (2007) on the impact of cyclic wetting-drying on the swelling behavior of lime-stabilized soil, it was observed that lime-stabilized soils are negatively affected by the wetting-drying cycles. In other words, the beneficial effect of lime stabilization in controlling the swelling potential of lime-treated samples is partially lost upon subjecting them to cycles of wetting and drying. The results of the study showed that lime-stabilized, expansive, clayey soil must not be used in the regions where wetting and drying cycles are significant. Another study showed that soils with a plasticity index above 20 are not suited to cement stabilization using manual presses because of problems with excessive drying shrinkage, inadequate durability and low compressive strength (Walker, P.J., 1995).

Table 2: The effect of different treatment materials on the shrinkage strain, swelling strain, and hydraulic conductivity.

Soil properties			Treatment Material	Reduction in shrinkage strain	Reduction in swelling (%)	Change in hydraulic conductivity (%)	Impact of cyclic wetting and drying on treated soil	Reference
Sand	Silt	Clay	0.4% Polypropylene Fiber (RCP17T)	Low	-	-	-	Hariant, Hayashi *et al*., (2008)
			0.6% Polypropylene Fiber (RCP17T)	Low	-	-		
35%	52%	13%	0.8% Polypropylene Fiber (RCP17T)	Medium	-	-		
PI = 80.3		1%	High Polypropylene Fiber (RCP17T)	-	-			
			1.2% Polypropylene Fiber (RCP17T)	Medium	-	-		
Sand	Silt	Clay	4% lime	Medium	-	Large increase	-	Omidi (1993)
			7% lime	High	-	Large increase		
16.2%	31.4%	52.4%	9% lime	High	-	Large increase		
			4% cement	Medium	-	Large increase		
			7% cement	High	-	Medium decrease		
PI = 36.6			12% cement	Medium	-	Large decrease		
			0.25% fiber	Low	-	Small decrease		
			0.5% fiber	Low	-	Small increase		
Sand	Silt	Clay	4% lime	Medium	-	Large increase	-	
			7% lime	Medium	-	Large increase		
5.1%	49.6%	45.3%	9% lime	Medium	-	Large increase		
			4% cement	Low	-	Large decrease		
			7% cement	Medium	-	Large decrease		
PI = 19.7			12% cement	Medium	-	Large decrease		
			0.25% fiber	Low	-	Small increase		
			0.5% fiber	Low	-	Small increase		
Sand	Silt	Clay	4% lime	Medium	-	Large increase	-	Omidi (1993)
			7% lime	Medium	-	Large increase		
			9% lime	Medium	-	Large increase		
63.8%	12.7%	23.5%	4% cement	Low	-	Large decrease		
			7% cement	Low	-	Large decrease		

	12% cement	Medium	-	Large decrease		
PI = 5.2	0.25% fiber	Low	-	Small increase		
	0.5% fiber	Low	-	Small increase		
Sand Silt Clay 4% 15% 81% PI= 350	3% Lime	High			The maximum swelling potential reduction occurred at the first cycle, but the swelling potential of lime-treated samples is partially lost upon subjecting them to cycles of wetting and drying.	Guney, Sari et. al., (2007)
	6% Lime	High				
Sand Silt Clay 9% 18% 73% PI= 315	3% Lime	High				
	6% Lime	Medium				
Sand Silt Clay 7% 18% 75% PI= 208	3% Lime	High				
	6% Lime		Negative effect			
Clayey soil with PI=9.9	5% Blast furnace slag	Low	-	-	The maximum shrinkage strain at the first cycle and the difference between treated and untreated samples is partially lost upon subjecting them to cycles of wetting and drying.	Osinubi and Nwaiwu
	10% Blast furnace slag	Medium	-	-		
	15% Blast furnace slag	Low	-	-		
Clayey soil with PI=37	10% Silica Fume	-	Medium	Medium decrease	-	Kalkan (2009)
	20% Silica Fume	-	High	Medium decrease		
	30% Silica Fume	-	High	Large decrease		

Furthermore, from the study by Rifai and Miller, (2009) on the theoretical assessment of the increased tensile strength of fibrous soil undergoing desiccation, a theoretical model was developed to describe the mechanism of the increased tensile strength due to fiber inclusion in the soil. Fiber inclusion increased the tensile strength of the fiber-soil composite significantly. This increase in tensile strength is expressed as a function of fiber and soil-water contents. Fiber content increases the tensile strength of the soil because of the increase in the number of fibers crossing the crack plane, which in turn increases the soil's resistance to cracking.

Previous studies by Viswanadham, Phanikumar *et al*., (2009) on the swelling behavior of a geofiber-reinforced expansive soil showed that reinforced expansive clay specimens with polypropylene fiber reduced heave, swelling, and swelling pressure (ps).

The results of the study on the influence of freeze-thaw cycles on the unconfined compressive strength of fiber-reinforced clay by Ghazavi and Roustaie (2010) showed that the unconfined strength of all reinforced and unreinforced samples decreased by 20%-25% when the number of freeze-thaw cycles increased. The addition of 3 wt% fibers increased the unconfined compression strength of soil for polypropylene fibers by 160% and 60% before and after applying cycles, respectively. For steel fibers, these increases are approximately 7% and 6% before and after applying cycles, respectively.

Discussion and Conclusion:

Most of the changes in soil structure or the total volume occur during the initial drying phase. Invariably, this means that if the water content of soil decreases, then the volumetric shrinkage also decreases. Likewise, if soil density increases, the volumetric shrinkage decreases, which in turn causes cracks in the soil to decrease as well.

Treatment with cement to reduce the volume changes in soils yields good results (Walker, P.J., 1995), but this type of treatment becomes unsuitablefor soils with a high plasticity index.If lime-treated soil is exposed to cyclic wetting and drying, the result is a loss of cohesion between the grains of soil and cement, which leads to an increased change in soil volume.Thus, the lime treatment is only appropriate for places that are not exposed to wetting and drying cycles (Guney, 2007). Fiber treatment is considered one of the best methods in the prevention of cracks because with an increment in the content, there is a great reduction in the value of the crack intensity factor. This increases the strength of the soil, but fiber treatmentsare not effective for all type of soils, especially clay soils.

Modeling of clayey materials is usually approached by associating phenomenological models with the elastoplastic concepts and those of diffuse damage or rupture mechanics but without a real relationship with hydromechanicalmodeling. Within this framework, the contributions of physicochemistry and microscopy are often treated as guides in explaining the observed phenomena.Recently, several researchers tried to introduce methods resulting from metallurgy (self-consistent approaches) and the mechanics of granular media (homogenization methods, discrete elements, etc.) into the modeling of argillaceous media. This takes into account the physical phenomena occurring at the microscopic scale in clayey media subjected to desiccation (suction effect and temperature), thus improving the modeling of the long-term behavior of these soils. These studies are very important in civil engineering problems, storage of radioactive waste and desiccation due to climatic changes.

Furthermore, it has been established that the use of environmental scanning electron microscopy combined with digital image analysis (DIA) for treated and untreated soil is one of the best analytical tools that can be utilized in this field.

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