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Evaluation of high plasticity clay stabilization methods for resisting the environmental changes

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Abstract. One of the most important factors that should be considered for using any ground improvement technique is the stability of stabilized soil and the durability of the provided solution for getting the required engineering properties. Generally, most of the earth structures that are constructed on clayey soils are exposing movements due to the long periods of drying or wetting cycles. Over time, environmental changes may result in swells or settlements for these structures. In order to mitigate this problem, this research has been performed on mixtures of high plasticity clay with traditional additives such as lime, cement and non-traditional additives such as polypropylene fiber. The purpose of the research is to assess the most appropriate ground improvement technique by using commercially available additives for resisting the developed desiccation cracks during the drying process and resisting the volume changes that may result during wet/dry cycles as an attempt to simulate the changes of environmental conditions. The results show that the fiber-reinforced samples have the lowest volumetric deformation in comparision with cement and lime stabilized samples, and the optimum fiber content is identified as 0.38%. In addition, the desiccation cracks were not visible on the samples' surface for both unreinforced and chemically stabilized samples. Regarding cracks resistance resulting from the desiccation process, it is observed, that the resistance is connected with the fiber content and increases with the increase of the fiber inclusion, and the optimum content is between 1% and 1.5%.

Keywords: desiccation test; dry/wet cycle test; environmental changes; fiber-reinforcement; soil stabilization

1. Introduction

Many earth structures are constructed on clayey soils which have a tendency to shrink and swell when subjected to climatic changes such as long drying periods during summer or drying/wetting cycles due to seasonal changes. During dry periods, clay near the surface of the slope shrinks resulting in desiccation cracks. Deep cracks expose the interior of the soil mass, thus allowing further cracking to occur. When subsequent wetting of the slope occurs due to rainfall, the extensive network of cracks and fissures created during the clay shrinkage allows for rapid per-location of rainwater. Consequently, an extensive network of fissures and cracks is developed. By this, and when the water fills the developed cracks, the clay along with the cracks' paths swells, and the strength decreases. During the time, and due to the exposure to cycles of shrinking and swelling, a failure of the slope may results. Also, the extreme drought and the subsequent rainfall can threaten the stability of dams (Chao-Sheng *et al*. 2011). In engineering applications, clayey soils that are liable to desiccation cracking are widely used in constructing liners, and slurry walls for the containment of solid or liquid wastes. The presence of cracks usually leads to a decrease in the structural and functional utilities of the contaminant barriers listed previously (Miller *et al*. 1998). In other instances, cracking usually implies that groundwater recharge can take place more rapidly than drawdown in exposed terrain, which is a situation that can produce instability in natural slopes and vertical cuttings (Baker 1981), and it can reduce the bearing capacity of foundations (Silvestri *et al*. 1992). Because of the increasing frequency of extreme drought and the persistent use of clay in engineering construction, soil desiccation cracking and volume changes due to climatic changes (drying/wetting cycles) receive increased attention in research and field demonstration projects.

A significant number of researches have been conducted to develop several treatment methods to stabilize clayey soils and to reduce the damaging effects of these soils. All these methods may have the problematic conditions of being inefficient in terms of sustainability and resisting the environmental effects and expensive due to using some expensive materials. Hence, new methods are still being investigated to increase the strength properties and reduce the volume changes of expansive soils (swell behavior) and improve the other engineering properties by using different additives and materials (Akbulut *et al*. 2007, AlZubaidi *et al*. 2013, Al-Mahbashi *et al*. 2015, Al-Bared *et al*. 2019). However, the majority of these methods do not address cracking behavior and volumetric changes due to environmental conditions. So thus, new methods are still needed to reduce volumetric strain related clayey soil movements. In addition to reductions in heave and shrinkage volume changes, the costs of the new stabilizing materials should be given some consideration in the overall

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assessments of new treatment methods.

In recent years, randomly oriented natural and synthetic discrete fiber materials have been added and mixed into problematic soils to improve the strength behavior of soils. A lot of experimental investigations have been performed on the reinforcement of soils with fiber materials (Akbulut *et al*. 2007, Kumar *et al*. 2007, Sivakumar Babu *et al*. 2008, Viswanadham *et al*. 2009). These previous researches present that strength characteristics of fiber-reinforced soils consisting of randomly oriented discrete fibers are a function of fiber content and fiber-surface friction along with the soil and fiber strength properties. Tang *et al*. (2016) showed that fiber inclusions increased the tensile strength. Muhammad Ali *et al*. (2020) showed that fiber inclusions increased the unconfined compressive strength and reduce both swell pressure and swell potential.

Reinforcement of expansive soils with fibers submits an alternative method to chemical stabilization methods and other methods for reducing swelling potential. Hoy *et al*. (2017) has proved by the use of geosynthetics the short-term and long-term improvement of the bearing capacity of shallow foundations and reducing the post-construction settlement of foundations built on embankments. Randomly distributed short fibers including natural, synthetic, and waste fibers have shown reasonably good potential for soil reinforcement applications, such as for the repairs of a slope veneer or in partially failed slopes (Mirzababaei *et al*. 2017). Yilmaz (2015) presented that the efficiency of combination of fly ash and polypropylene fibers increased the unconfined compressive strength of expansive clays. An increase in fiber content caused to reduction in swelling potential of lime stabilized clayey soil was reported by Cai *et al*. (2006). However, the reports on the use of randomly oriented natural and synthetic discrete fiber materials to study the desiccation cracks behavior and to reduce the volume changes that result due to climatic changes in expansive soils have not been settled yet. The same in reference to the stabilized clayey soils by chemical additives where most of the researches have been focused on the stabilization of soils using various additives such as lime, cement, fly ash, industrial waste products, potassium nitrate, calcium chloride, and phosphoric acid (Aiban *et al*. 2006, Kalkan 2006, Guney *et al*. 2007, Segetin *et al*. 2007, Degirmenci *et al*. 2007, Harichane *et al*. 2011, Sunitsakul *et al*. 2012, Yilmaz and Ozaydin 2013). These previous researches were concerned with improving the strength characteristics and behavior, and swell/compressibility behavior, whereas there were very limited researches concerned in cracking resisting and reducing the volumetric changes due to the climatic conditions.

Therefore, this research came to assess the feasibility of using short polypropylene fibers to reduce the development of desiccation cracks in clay and reduce the volumetric changes due to dry/wet cycles. Furthermore, evaluating the most appropriate stabilization methods by assessing the usage of chemical additives (cement, and lime), and fiber additives and their effectiveness on the cracking and volumetric changes.

2. Materials used

2.1 Lime

Lime is one of the oldest and still popular additives used to improve engineering properties of soils. Generally, there are four major limebased additives used in geotechnical construction: hydrated high calcium lime $Ca(OH)_2$ which was used in the cuurent study, calcitic quick lime CaO, monohydrated dolomitic lime $Ca(OH)_2$ MgO, and dolomitic quick lime CaO MgO. Lime treatment causes chemical reaction similar to cement and can be used for both modification and stabilization purposes, chemical reaction between soil and lime results in a reduction in water content. Further, lime addition increases the optimum moisture content but decreases the maximum dry density, significant reduction in plasticity index, and finally, immediate increase in strength. Extensive studies have been carried out on the stabilization of clay soils using lime (Abass 2013, Asgari *et al*. 2013, Bozbey and Garaisayev 2010, Ghobadi *et al*. 2013, Harichane 2011, Harichane *et al*. 2010, Harichane *et al*. 2011, Stoltz *et al*. 2012, Wang *et al*. 2013, Tran 2014, Nguyen 2015, Kiliç *et al*. 2016, Ahmad *et al*. 2020) confirmed the positive effect of lime addition on the reduction of swelling, plasticity index, and the increase of the strength in clayey soils.

2.2 Portland cement

Portland cement is a finely divided material that results from inter-grinding clinker and gypsum. Clinker is a pyro-processed hydraulic material composed of four major oxide phases: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium alumino-ferrite (C_4AF) (in cement chemistry notation, C=Ca, S=SiO_2, A=Al_2O_3, and F=Fe_2O_3). The two calcium silicate phases are the most important with regard to soil stabilization. Generally, cement is widely used in civil engineering applications such as road construction, embankments, foundation slabs and piles. Many studies have confirmed that cement-soil mixture has high stiffness properties for expansive soils (Portelinha *et al*. 2012, Pakbaz and Alipour 2012, Aparna 2014, Ghobadi *et al*. 2014, Tran *et al*. 2014, Ikhlef *et al*. 2015, Sharo *et al*. 2022). Referring to the chemical composition of the added cement and the mineralogical composition of the soil, several chemical reactions can occur between the calcium hydroxide in the cement and the silica and alumina in the clay. These reactions cause a change in the soil structure in the short term by allowing granular re-arrangement by flocculation and afterward, pozzolanic reactions result in the formation of cementitious compounds binding soil particles, resulting in the stiffening of the soil in the long term (Pakbaz and Alipour 2012, Ikhlef *et al*. 2015).

2.3 Polypropylene fiber

Polypropylene fiber (PP) is a versatile thermoplastic material, which is produced by polymerizing monomer units of polypropylene molecules into very long polymer

Table 1 Properties of the used polypropylene fibers

Behavior parameters	Values
Fiber type	Single fiber
Unit weight	0.91 g/cm^3
Average diameter	0.034 mm
Average length	12 mm
Breaking tensile strength	350 MPa
Modulus of elasticity	3500 MPa
Fusion point	165°C
Burning point	590°C
Acid and alkali resistance	Very good
Dispersibility	Excellent

Fig. 1 Used polypropylene fiber

molecules or chains in the presence of a catalyst under carefully, controlled heat and pressure. Propylene is an unsaturated hydrocarbon, containing only carbon and hydrogen atoms. Many forms of commercial polypropylene are available. One form of PP is a semi crystalline solid with good physical, mechanical and thermal properties. Another form of PP, produced in much lower volumes as a byproduct of semi-crystalline PP production and having very poor mechanical and thermal properties. The crystallizable form of PP is termed as "isotactic" PP and the non-crystallizable form is termed as "atactic" (Brown *et al.* 2002).

Polypropylene fibers are also produced as continuous cylindrical monofilaments that can be chopped to specified lengths or as films and tapes that can be fibrillated to form the fibrils of rectangular cross-section.. Table 1 summarizes the properties of the polypropylene fibers used in this study as shown on its identification card (as provided by the manufacturer). Fig. 1 shows the shape and type of the used material.

The main reason for selecting this type of fiber to be considered in this research is the fact that these fibers are more industrial materials commonly used, as well as, because of its low cost (with reference to other traditional additives) and their nature chemical inert where this material cannot be absorbed, and they do not interact with soil moisture. According to Hejazi *et al.* (2012), the general advantages of fiber composite soils are the availability, economical benefits, easy to work and rapid to perform, and the feasibility of its utilization in all weather conditions. However, it is important to refer that obtaining a homogeneous soil-fiber matrix in the field is troublesome as reported by many researchers in comparison with the hand mixing (lab mixing) that allows fibers to merge properly with the soil mass, but this issue can be overcome and mitigated by oscillatory or helical mixing techniques (Hejazi *et al.* 2012).

Table 2 Characteristics of the studied soil

Soil properties	Value
Specific gravity	2.70
Liquid limit	57%
Plastic limit	22.67%
Plasticity index	34.33%
Unified Soil Classification System (USCS)	CH
Optimum moisture content	22.5%
Maximum dry density	1.57 g/cm^3
Sand (4.75-0.075 mm)	24%
Silt (0.075-0.002 mm)	39%
Clay < 2 μm	35%
Shrinkage limit	12.3%
Maximum Swelling Strain	16%

2.4 Clayey soil identification

The soil used for the test program was obtained from the excavation for a residential construction project in Gaziantep, Turkey. The site for soil collection was selected because the clayey soil appeared to be rather uniform. Before tests were conducted, a series of index property tests were performed to determine the general characteristics of the expansive soil. The index property tests included gradation analysis, hydrometer analysis, Atterberg limit tests, and specific gravity test. The results of laboratory testing are summarized in Table 2.

3. Laboratory tests' investigations and preperations

Laboratory experimental program was conducted on clayey soil with high plasticity for studying the feasibility and effectivity of polypropylene fiber on the cracks development and volumetric changes; and comparing this efficiency with cement and lime as clayey soil stabilizers. For that, three fiber contents were considered (0.5%, 1%, and 1.5%), and the cement and lime content were identified based on the extensive researches that were conducted on the same type of soil where they were concerned in improving the compressibility behavior and strength characteristics (Tabatabaei and Aghaei-Araeik 2006, Al-Layla *et al.* 2008, Mohammed *et al.* 2010, Calik and Sadoglu 2014, Reddy *et al.* 2015, Jair *et al.* 2018, Sharo *et al.* 2019, Ahmad *et al.* 2020, INDOT 2020). Most of these researches have been figured out the optimum contents of both cement and lime to be added for getting the best-required properties and these contents can be summarized in the study of INDOT (2020), that stated or suggested the optimum content for lime which is (5% to 7%), and for cement is (4% to 6%). Therefore, for the current study, it was considered the following contents (Lime 6%, Cement 5%) based on previous studies. After that, the tests program was designed as the following:

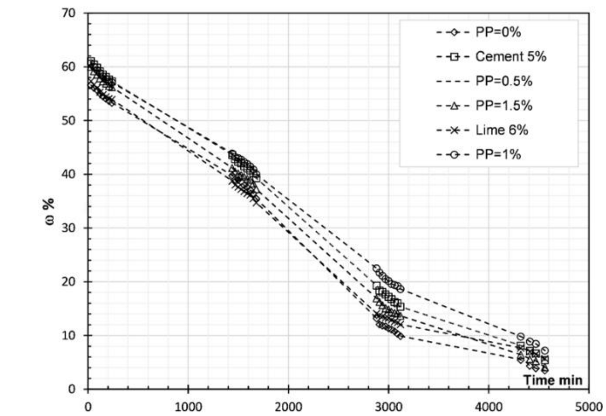

Fig. 2 Water content changes with time (evaporation rate) for treated and untreated samples

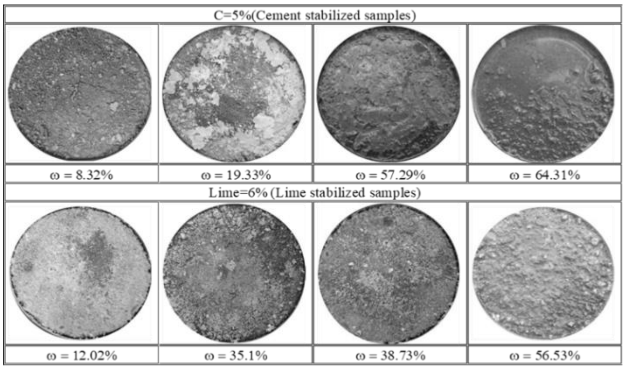

Fig. 3 Surface samples photos during the drying process for cement and lime stabilized samples

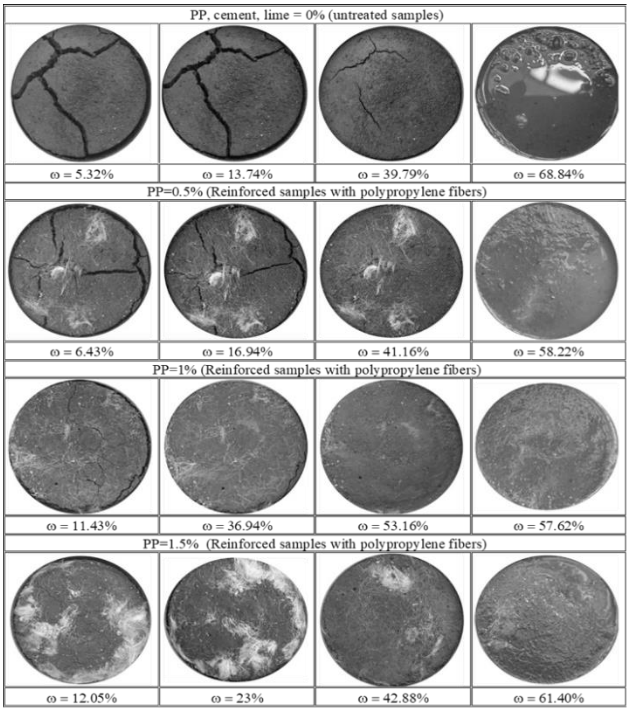

Fig. 4 Surface samples photos during the drying process for reinforced and untreated samples

Firstly, studied soil characteristics and index properties were determined and then compared with that of samples stabilized with polypropylene fibers (fibrillated polypropylene fiber), where three fiber contents were considered (0.5%, 1%, and 1.5%). The fiber content is the studied ratio multiplied by the dry weight of the soil for each sample. Secondly, studied soil was mixed with the identified content with cement and lime separately, and then compared with that of samples stabilized with polypropylene fibers and with untreated soil. The cement and lime content is the studied ratio multiplied by the dry weight of the soil for each sample. Thirdly, desiccation/drying test, dry/wet cycles test were conducted after preparing the related samples.

3.1 Desiccation/drying tests

Firstly, the samples were dried (air-dried by oven at 100° C) and then they were sieved by using a sieve size 2 mm diameter to remove the large particles, and then samples were submerged with distilled water under approximate moisture content of 170%. After that, they were poured into circular cans, shape diameter 70 mm, and placed (for 5-minutes) on a vibrator apparatus to eliminate the air bubbles in the soil. After that, the samples were covered and left for 72 hours to allow soil deposition (precipitation). The thickness of the samples was measured, which was about 8mm, and its moisture after precipitation was about 90%.

Before submerging stage, the mixing of soil and fibers was through fiber manually mixing into the dried soil with distilled water. The water content was above the liquid limit (LL) to form a slurry. The exact amount of water was weighed and slowly added to the mixture of soil and fiber. The resultant slurry was mixed by hand steer for about one hour until a smooth liquid resulted to ensure the uniformity of the fiber distribution in the mixture by visual examination. This procedure also was done for lime and cement stabilized samples after considering the optimum content of 6% and 5% respectively. After that, the four kinds of samples (untreated samples, reinforced samples, cement stabilized samples, and lime stabilized samples) were submerged as mentioned above. For lime and cement stabilized samples, the curing period was ignored as the thickness of these samples was very thin and the deposition period of three days ensured a good uniformity and interaction between the added material and the slurry (soil and water).

For each situation, four samples were prepared for the drying test at room temperature of (25±1°C). After that, samples were placed in the oven at a constant temperature of (50°C). During the drying process, the missed amount of water was measured (with 0.01 gr accuracy) and the corresponding humidity at each time was calculated. The surface of these samples was also monitored/photographed during the same periods by using a digital camera (with a focal length of 35 mm) to monitor the development of the cracks and to determine the engineering specifications of the cracks (length, width). This mechanism is called visual analysis. Therefore, at the end of these tests, two outputs have been found as follows:

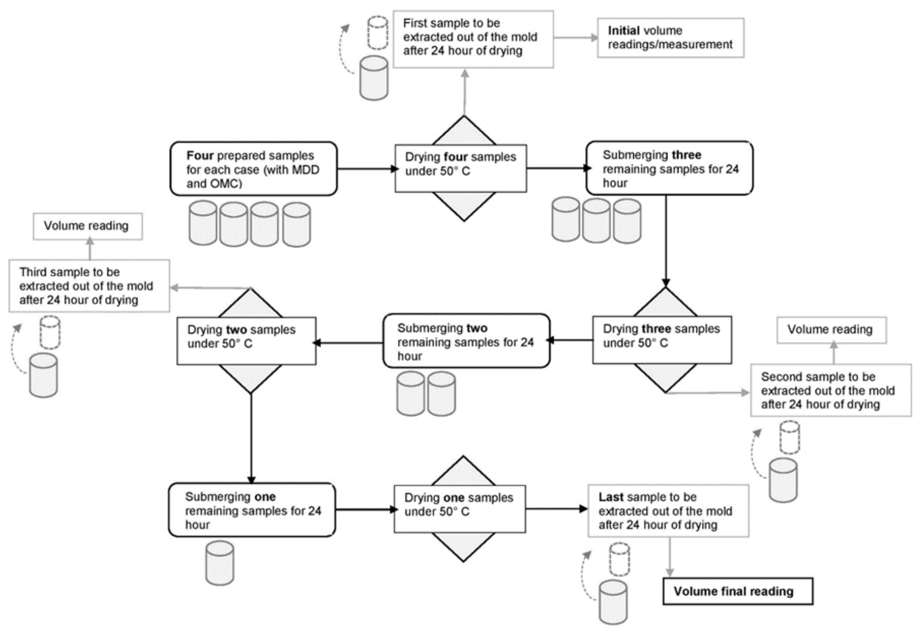

Fig. 5 Schematic chart for volume change (dry/wet cycles) test

1. Representation of water content changes with time (evaporation rate) for each situation by depicting the experimental results (changing the water content with respect to the time) as shown in Fig. 2.

2. Photographic database by photographing the samples surfaces for different time periods for all situations, and this database was analysed by using MATLAB program for determining the crack's properties (length, width, area). Figs. 3-4 show the digital photos of samples at different stages during the drying process.

3.2 Volume change (dry/wet cycles) tests

Four kinds of samples (untreated samples, reinforced samples, cement stabilized samples, and lime stabilized samples) were prepared at the optimum moisture content and maximum dry density determined for untreated soil. To achieve the desired maximum dry density, untreated soil and fibers were poured progressively into the Proctor mold and then subjected to static compaction by a jack. The mixing of soil and fibers was manually mixed into the soil with approximately 10% of moisture content (half of the optimum moisture content (OMC) approximately) until a random distribution of fibers by visual examination was achieved. In this step, 10% of moisture content was considered for the prevention of segregation of fibers from the soil. Second, a certain amount of water was added to the mixture of fibers and soil prepared in the first step to achieve the optimum moisture content. After the completion of the static compaction, all the samples were extracted by using a metal cylinder (10 cm in height and 11.7 cm in diameter). This procedure was repeated to prepare compacted homogeneous samples for both lime-soil mixture and cement-soil mixture as well. After the completion of the static compaction, all the samples were transferred into a curing room of (24∓1°C) in which they were cured for 21 days (this was for both cement and lime stabilized samples).

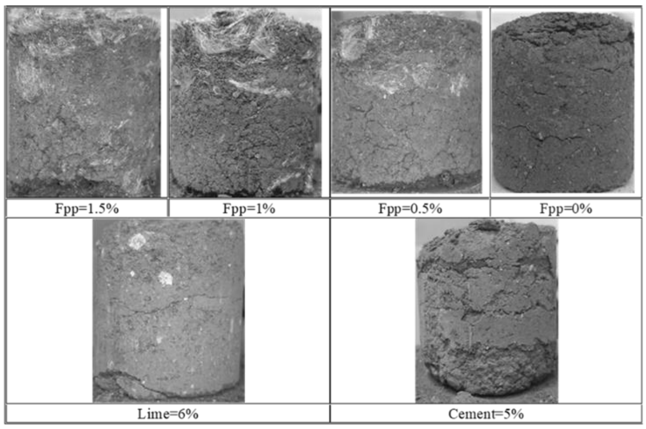

Fig. 6 Generated cracks/volume change at the fourth drying cycle

After that, all samples were subjected to the drying/wetting cycles, where all samples were initially exposed to the drying process in the oven at (50°C) for 24 hours. After 24 hours of drying, the samples were submerged with distilled water for another 24 hours at room temperature, and this was repeated for four cycles. Fig. 5 shows a schematic chart for the volume change (dry/wet cycles) test.

As it is shown in Fig. 5, volumetric changes and the developed cracks of each sample were measured at the end of each drying cycle, where the width and approximate length of the developed cracks on the peripheral surface was measured, then the total area of cracks can be calculated and multiplied by four (the number of samples for each situation) to obtain the total area of cracks generated on the peripheral surface of the sample. Cracking is estimated relatively by using the digital processing method (Abhishek 2015), as the area of generated cracks on the peripheral surface (perimeter surface) is attributed to the

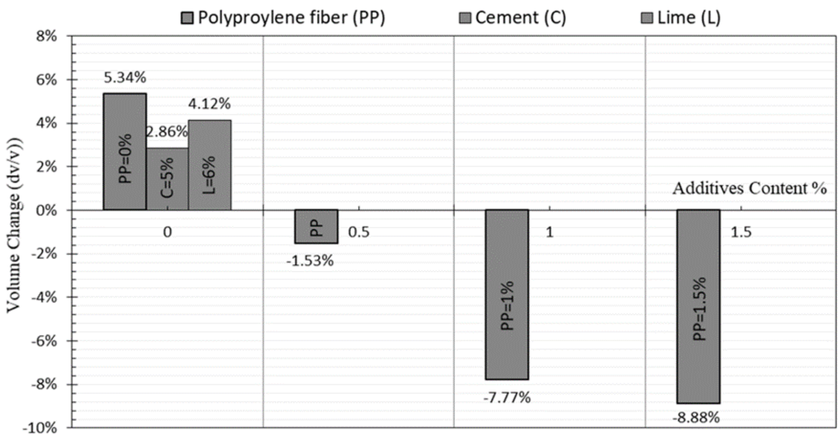

Fig. 7 Summary of experimental results of the dry/wet cycles test

area of the cylinder face. Regarding the volumetric changes, they are connected to the initial cylinder volume (sample cylinder's volume) as well. Fig. 6 shows the generated cracks/volume change at the sample surfaces for each treatment case.

After conducting the measurements during the testing phase, the final volume change for each studied case can be obtained by subtracting the final measured volume (at last drying cycle) from the initial volume (cylindrical can volume) and dividing the result to the initial volume. Fig. 7 summarizes the experimental results of the dry/wet cycles test.

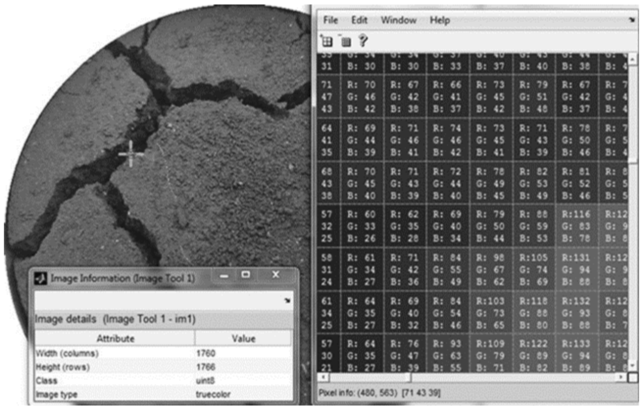

Fig. 8 Digital processing by using MATLAB

4. Results and discussions

4.1 Evaluation of fiber effect and other chemical additives on cracks resisting

Referring to Fig. 2, it can be noticed easily that the evaporation rate for all studied cases (untreated, reinforced, cement stabilized, lime stabilized) is almost the same, and this indicates that the used treatment method did not affect the rate of evaporation, and therefore the method of treatment did not affect the time required for the appearance of cracks/cracks' development. Even though there were some differences in the values of the evaporation rate at the last stage of drying, this can be attributed to the generated cracks that have affected the evaporation rate.

To identify the area of generated cracks in each sample for all cases, the digital processing (through MATLAB program) method was applied. The digital processing method can be summarized by capturing high-resolution images of the sample’s surface during different stages of the drying process. To calculate the area of the developed cracks, the captured image at the final stages of the drying process was inserted into the MATLAB program for analysis. MATLAB Analyzing procedure depends on dividing the image into an array of elements, and the number of lines and columns (number of elements) in this matrix depends on the resolution of the used camera which affects the calculation accuracy/analysis. After dividing the image into an array of elements, each element takes specific values for each color (Red, Green, Blue) as shown in Fig. 8. So thus, by identifying the range of color that cracks are located in (through applying a set of programming commands), the number of elements that meet specific values of each color (color ranges) can be found, therefore, the area of the generated cracks in each image and for each studied case can be determined by using the equation Eq. (1) which was derived from the aforementioned image analysis method (Abhishek 2015). However, It was noticed that by using this method, the areas of shrinkage/contraction were considered cracks. Table 3. summarizes the results of digital processing in terms of cracks area for each studied case during the drying process.

$$A_{cracks}(cm^2) = A_{sample} \times \frac{N_{cracks-elements}}{N_t} \quad (1)$$

Where, $N_{crack\text{-}elements}$ is the number of elements that represent the cracks, N_t is the total number of image elements, and A_{sample} is the area of the pictured sample (38.48 cm^2).

From the above table, it can be noticed easily that the area of the developed cracks, for reinforced cases, was decreased with the increase of the fiber content, and this can be attributed to the role of the fibers that creates additional bonding between the soil particles, wherein due to the drying, the soil shrinks, and desiccation cracks tend to develop, and at this stage, the tensile force starts to be

Table 3 Results of digital processing

Additives type	Additives Content	Array size (Pixel)	$N_{crack\text{-}elements}$ (Pixel)	A_{crack}/A_{sample}
No Additives	0%	1760×1766	310356	12.7% *1
Polypropylene fiber	0.5%	1730×1735	209626	9.0%*1
Polypropylene fiber	1%	1900×1880	135879	4.8%*1
Polypropylene fiber	1.5%	2160×2090	94659	2.8%*1
Cement	5%	2066×2020	67881	2.0%*2
Lime	6%	1960×1926	40164	1.4%*2

*1 Note: cracks were noticed for reinforced and unreinforced samples during the drying process.
*2 Note: both contraction and cracks have been resulted, while for the chemical stabilized samples the effect was limited to contraction.

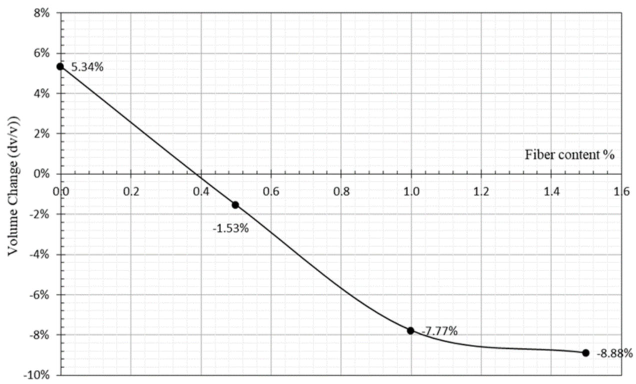

Fig. 9 Optimal fiber content for resisting volume changes

mobilized in the fibers and only adhesion restrains the fibers from the pullout, and thus allows for its tensile resistance to develop and create additional bonding effect to resist the formation of the cracks. Regarding the cement and lime stabilized samples, it was noticed that no cracks were developed during the drying process, and it was limited to the sample contraction only. However, this behavior can be explained due to the cementitious effect/pozzolanic effect that increases the cohesion between the soil particles which led, in turn, to the sample contraction only, and high resistance of cracks development.

From the experimental observations, it was noticed as well that the samples' structure for cement/lime stabilized can be easily broken or crushed at the end of the drying process, while for reinforced samples, the structure was more coherent, and this can be attributed to the absence of water which plays a vital role in chemical reactions that let to high cohesion in the soil, while for fiber additives the water absence didn't have that effect.

4.2 Evaluation of fiber effect and other chemical additives on volume changes

Referring to Fig. 6, it can be noticed (by using the aforementioned image digital analysis method) that no remarkable cracks appeared on the cylindrical surface for all cases. However, small cracks were observed but their width and depth were very small and can be ignored.

Referring to the outputs of the related test which were summarized in Fig. 7, it was noticed that the volume changes, at the last cycle, for untreated samples and cement/lime stabilized samples were swelling type. In addition, the cement stabilized samples exhibited lower volume change in comparison with lime stabilized one. In contrast, reinforced samples exhibited a volumetric change of contraction/compression type, and the change was increased with the increase of fiber content. However, this behavior can be attributed to the effect of polypropylene fiber in resisting the swelling pressure during the wetting cycles which was more efficient in comparison with the swelling resistance effect of cement and lime. Likewise, the high crack formation resistance also contributed to reducing the changes during the drying cycles. To identify the optimum fiber content for the reinforced samples in which the volume change was increased with the increase of fiber content, regardless of the change type (swelling or contraction), the volume changes values for all fiber contents (0%, 0.5%, 1%, 1.5%) were represented as shown in Fig. 9 where it can be found that the optimum fiber content for resisting the volume changes is 0.38%.

5. Conclusions

This study demonstrates the influence of polypropylene fiber on resisting desiccation cracks, where it is found that cracks' resistance increases with the increase of fiber content. Furthermore, the efficiency of polypropylene fiber utilization to reduce the volume changes is investigated, and different behaviors were observed between the unreinforced samples and reinforced ones. As such, the results highlight the contraction behavior for fiber stabilized soil, while it was swelling behavior for both lime/cement stabilized soil and unstabilized soil. Therefore, the optimum fiber content is identified as 0.38% for improving the resistance of volumetric changes. Besides, the most appropriate ground improvement techniques were assessed, taking into account, the selected contents for the conventional materials (Lime of 6% and cement of 5%), and the studied fiber contents which varied from 0% to 1.5% (by the dry weight of the soil), where it was observed high efficient of fiber influence in comparison with lime and cement stabilization techniques, and fiber contents between 1% to 1.5% are considered the most effective and suitable contents, after applying proper mixing techniques to ensure the homogeneity of the soil-fiber matrix in the field.

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