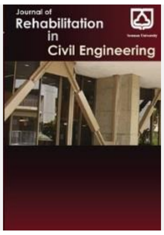
Journal of Rehabilitation in Civil Engineering 14-1 (2026) 2240



Journal of Rehabilitation in Civil Engineering

Journal homepage: https://civiljournal.semnan.ac.ir/

Improving Landfill Liner Performance through Mitigating Desiccation Cracking Using Fiber and Nanocomposite Materials: A Laboratory Study

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ARTICLE INFO

Article history:
Received: 02 January 2025
Revised: 11 February 2025
Accepted: 04 March 2025

Keywords:
Liner of the landfill;
Improvement;
Composite materials;
Reduce of crack width;
Soil clay.

ABSTRACT

Landfill liners are critical components of waste management infrastructure, designed to prevent the migration of leachate into the surrounding environment. However, the long-term performance of these liners is significantly influenced by their susceptibility to desiccation cracking. This study investigated the effectiveness of incorporating polypropylene composites, micro-silica, and nano-silica as additives within the clay liner material to mitigate cracking and enhance overall liner performance. Three distinct clay types were evaluated: local soil, soil excavated from the landfill site, and a synthetic clay mixture. Laboratory experiments were conducted to assess the impact of the additives on crack formation and by extension, the hydraulic conductivity of the liner material. The results demonstrated a significant reduction in crack formation across all clay types with the addition of 0.8% polypropylene. Similarly, incorporating 20% micro-silica exhibited a marked decrease in cracking, suggesting a potential improvement in the long-term hydraulic performance of the liner. These findings indicate that the inclusion of these additives can enhance the resistance of the clay liner to desiccation, thereby minimizing the risk of leachate migration and contributing to the environmental integrity of the landfill site. This research has important implications for the design and construction of more robust and environmentally sound landfill liners. Further research is warranted to optimize the concentration and combination of these additives, evaluate their long-term performance under field conditions, and assess their cost-effectiveness in improving the overall durability and environmental performance of landfill liners.

E-ISSN: 2345-4423

How to cite this article:
Dehestani, H. and Haddad, A. (2026). Improving Landfill Liner Performance through Mitigating Desiccation Cracking Using Fiber and Nanocomposite Materials: A Laboratory Study. Journal of Rehabilitation in Civil Engineering, 14(1), 2240
https://doi.org/10.22075/jrce.2025.36411.2240

1. Introduction

Improving landfill liners using composite materials in order to reduce cracking is one of the effective methods to prevent the infiltration of contaminated leachate from landfill into the ground [1]. The liners are made to protect the soil and groundwater around landfill from the infiltration of toxic leachate and dangerous waste. Due to financial limitations or lack of access to materials with low permeability, it may not be possible to build engineering liners or use prefabricated geosynthetic coatings in developing countries such as Iran, especially in smaller cities. Given the relatively easy access to fine-grained materials and lower costs compared to synthetic liners as GCL, clay liners are the most used for the construction of landfill and are often used in a single-liner system along with a collection and drainage system for leachate. If there is not enough clay in the site, it is possible to obtain suitable materials for the construction of the waterproof lining by supplying clay from borrow pits. Using the soil of landfill, if it has suitable geomechanical properties, is the most convenient and economical way to build a liner [2].

As a result, this movement and displacement of particles causes desiccation cracking or volumetric shrinkage in clay on a macroscopic scale [3]. Usually, the cracks that form after the main cracks are called sub-cracks [4]. With the presence of montmorionite in clay, higher volumetric shrinkage occurs [5]. The higher the soil shrinkage, the greater the effect on desiccation cracking [6]. Among the factors affecting the behavior of desiccation cracking, are soil properties, environmental factors, and the effect of additives on soil [7]. Important and key parameters related to the properties of the soil and its effect on the cracks include the constituent minerals, the amount of clay in the soil, the density and hardness of the soil, and the effect of soil salinity [8]. Smectite is one of the minerals affecting the cracking of clay soils, so that the shrinkage of clay increases by increasing smectite. Smectite has high water absorption compared to other clay minerals, and before the clay particles are completely in contact with each other, it causes more soil shrinkage. Considering the high percentage of smectite in bentonite, desiccation cracking in bentonite are significant compared to other soils [6]. Vail et al. showed that the higher the mineral content of illite, kaolinite and quartz in the soil, the lower the shrinkage in the soil [9]. A study by Tang found that the higher the value of plastic index in clay, the higher the width, dimension and size of the crack in this soil [10]. According to the experiments conducted by Omidi et al., the volume changes in montmorionite was equal to 16.4% and the volume changes in illite was equal to 11.7% [11]. Accordingly, the volume contraction of montmorionite was higher than that of illite. Expansive soils have a high potential of desiccation cracking due to the amount of clay [12]. According to a study by Fang and Chaney, desiccation cracking in clay samples with complex structure is much higher than clay samples with dispersed structure. Also, by increasing compaction energy, the volume contraction of the soil decreases [13]. In order to analyze the effect of ambient temperature on desiccation cracking, Shi et al. conducted tests to determine the cracks on clay at ambient temperatures of 30, 40, and 50 C with relative humidity of 52, 32, and 22 %. The results showed that changes in ambient temperature have a great effect on desiccation cracking, so that by increasing the ambient temperature, the crack pattern becomes simpler and the crack development increases in depth [14]. Uday and Singh investigated the effect of ambient humidity on desiccation cracking. Accordingly, the humidity of the tested samples was checked from 40% to 90% by the same temperature. The results showed that by increasing the humidity of the environment, the rate of evaporation and crack development reduced [15].

To investigate the behavior of cracks and determine the characteristics of cracks such as length, size, shape, depth and the crack intensity factor, various studies have been conducted. For this purpose, direct and indirect methods can be used. The direct methods of crack measurement include linear survey and window extraction, which provides the approximate results. Indirect methods also include electrical and electromagnetic methods. Also, to calculate the dimension and size of the crack, image processing was used to measure and analyze the changes in the dimensions of the crack, and various studies have been conducted in this field [16,17]. In this regard, Shit et al. presented a simple method for digital image processing to determine the crack intensity factor in dense clay soils [18]. Also, one of the effective and low-cost methods of imaging is the use of a digital camera, a suitable light source and stable framing [19]. To get more accurate results, the resolution and accuracy of the camera should be between 5 and 10 million pixels [20]. Also, the camera should be placed at a suitable distance from the soil surface so that the cracks can be processed accurately and appropriately [20].

In a studies, Raihan Taha, Sarand et al., Changizi and Haddad investigated the effect of nanomaterials on reducing the size of cracks and in improving geotechnical properties of soils [21–23]. In this study, the effect of different percentages of aluminum and copper nanoparticles on reducing the number and dimensions of cracks has been evaluated [24]. In another study, Harianto et al. investigated the effect of fiber additives on the behavior of cracks in dense clay soils for use as a cover in landfill. According to the results, cracks have developed rapidly in the soil with no fiber additive added with humidity less than 50% [25]. According to Haryanto and Shukla, polypropylene fibers are hydrophobic and the ingredients of this type of fiber do not absorb soil moisture and leachate, nor do they react with soil moisture and leachate [25,26]. Polypropylene fibers have very high resistance to acidic, alkaline, salt, detergent, micro-organisms and even water reactions. Considering that sewage usually has an acidic environment with salt or alkali and also contains various chemicals and micro-organisms, the use of polypropylene fibers is effective in dealing with sewage and its technical performance is not reduced [26]. Mehdi Nikbakht and colleagues investigated the effect of leachate on permeability, geotechnical properties, and crack reduction on clay modified with nanoclay and nanofibers and the combination of these materials in the Tabriz landfill [27]. According to the results, by combining nanoclay and nanofibers in clay in the presence of leachate, in addition to not reducing the performance of the fibers, the geotechnical properties of the modified soil increased with the increase in additives and the permeability of the soil also decreased. Adding nanoclay, nanofibers and the combination of these two additives reduced the permeability of the Tabriz clay liner [27]. Flamke et al. investigated the effect of pit leachate on the mechanical behavior and cracking of a clay liner reinforced with polypropylene fibers [28]. As a result, the fibers perform well in the presence of water and sewage and reduce cracks [28]. In another study, Tao et al. evaluated permeability and cracking of compacted clay liner improved by nano-SiO2 and sisal fiber in a case study [29]. In a study, Kalkan investigated the effect of micro-silica (silica foam) on desiccation cracking in dense clay layers and the permeability of clay soils [30]. Given that clay has low permeability, it is used as a cover and liner in landfill and support systems, but cracks caused by shrinkage increase soil permeability. After performing the relevant tests, it was found that the width and depth of the crack in the samples improved by micro-silica has reduced significantly compared to the natural clay samples [30]. Another reason for using micro-silica is the reasonable price of this material compared to other chemicals and nano materials. Given that large volumes of chemicals may be used to remediate soil in landfills, it is essential to examine the economic aspect of the issue. In this research, given that the price of microsilica is significantly lower than nanosilica, the choice of microsilica is considered one of the main advantages of this chemical due to its economic efficiency. These cases regarding the improvement of soil cracks with micro-silica have been confirmed in past researches.In 2022, Bahari and Hataf investigated the reduction of soil permeability using the microbial induced carbonate precipitation (MICP) method, a case study of Shiraz landfill soil [31]. Farqian et al. investigated soil reinforcement with waste tire textile fibers through small-scale experimental tests [32].

This study emphasized that by adding chemicals and fibers to the studied soil, while improving and stabilizing it in order to reduce hydraulic permeability, cracking caused by the process of compaction and drying of the waterproof lining layer will also be reduced. The samples in this study were selected from the real sample of the soil of Mashhad landfill to evaluate the accuracy of the assumptions and the method used in a real case. In this study, two types of soil 1 and 2 are related to the location of landfill and its surroundings, and soil 3, which is a combination of kaolinite and montmorionite, was used. Given that in most of previous studies, the effect of additives alone on desiccation cracking of clay in landfill have been investigated [1], Given that most previous research has examined the effect of additives alone on cracks caused by drying of clay in landfills, in this study, in addition to examining the effect of polypropylene fiber, microsilica, and nanosilica on cracks caused by drying in Mashhad landfills, the simultaneous effect of polypropylene fiber and microsilica has also been examined as a new innovation and challenge. Also, most of the research on the floor covering of landfills is related to the time of landfill exploitation, but in the leading research, the investigations and studies are related to the time of landfill construction and the aim is to prevent the formation of cracks due to drying before the waste is placed in the landfill.

2. Materials and methodology

2.1. Soil samples

In this study, three types of soil have been studied. The soil clay type 1 is related to the soil around 9 km from the main landfill of Mashhad, which is used as a clay depot for the Mashhad landfill. The soil clay type 2 is related to the soil of the main landfill of Mashhad. The soil clay type 3 as the selected soil is a combination of Montmorillonite (MMT) and kaolinite at a weight ratio of 3:1, respectively. Figure 1 shows the location of landfill and the used borrow pit. Table 1 shows properties of these three types of soil. Figure 2, 3 and 4 shows the soil samples used in this study.

Fig. 1. The location of landfill in mashhad.

Table 1. Properties of three types of soil.

Properties	Clayey soil 1	Silt soil 2	Clayey soil 3
Specific gravity, Gs	2.61	2.59	2.55
USCS Classification	CL	ML	CH
Particle size analysis			
Gravel	-	-	-
Sand %	5	8	-
Silt %	43	61	21
Clay %	52	31	79
Atterberg limits			
Liquid limit %	38	44	64
Plastic limit %	16	18	31
Plasticity index %	22	26	33
Shrinkage limit %	11	12	17
Specific surface area m^2/gr	235.4	207.3	201.8
Optimum water content %	10	12	15
Maximum dry unit weight gr/cm^3	1.85	1.81	1.71
Hydraulic conductivity E-06 cm/s	2.00	8.35	0.985
Percent of swelling with swelling pressure 1 Kpa	19.22	21.51	36.94

Fig. 2. The sample of soil 1 used in this study.

Fig. 3. The sample of soil 2 used in this study.

Fig. 4. The sample of soil 3 used in this study.

Figure 5 shows the result of compaction test for soils 1, 2 and 3. As shown, the maximum dry weight of soil 1 was equal to 1.85 g/cm³, 1.81 g/cm³ for soil 2, and 1.71 g/cm³ for soil 3. Also, the optimum moisture content for soil 1 is 10%, 12% in soil 2 and 15% in soil 3.

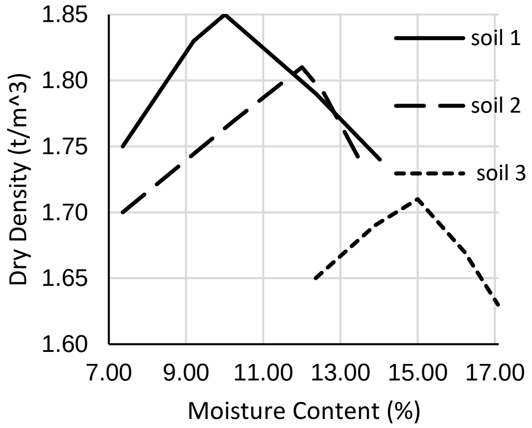


Fig. 5. The result of compaction test for soils used in this study.

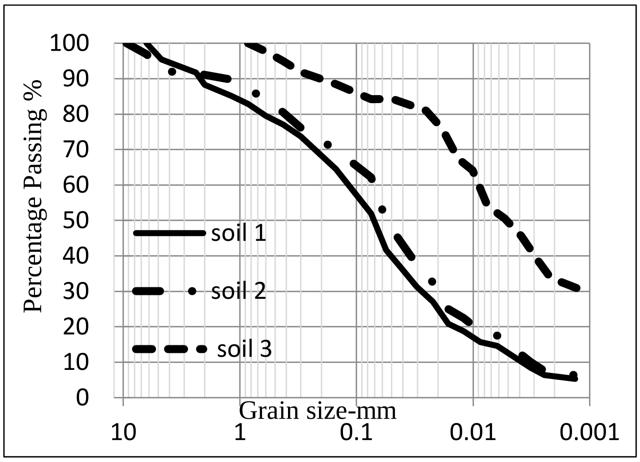


Fig. 6. The result of grain size for soils used in this study.

Figure 6 shows the grain size distributions of soils 1, 2 and 3. As shown, the grain size of soils 1 and 2 is almost the same, and the grain size of soil 3, which consists of kaolinite and montmorionite, has greather finer grain size than others.

For a better comparison of the physical properties of the soils used in this study, the Atterberg limits and free swelling index of each of these soils are presented and compared with each other in Figures 7 and 8. According to the presented results, soil 3 has higher plasticity index and plasticity property and has higher free swell index. Also, soils 1 and 2, which are related to the borrow pit and the main site of landfill, have almost similar plasticity properties, but plasticity index and plasticity properties of the soil of the main site of landfill are slightly higher than the soil of the borrow pit.

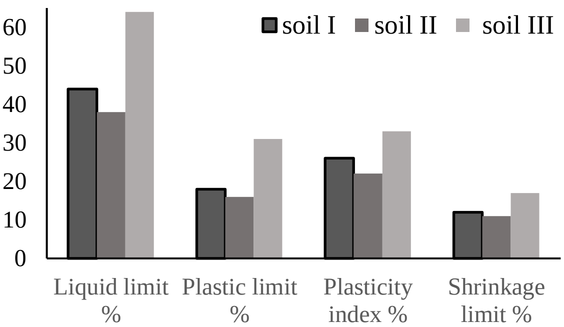


Fig. 7. The result of Atterberg limits for soils used in this study.

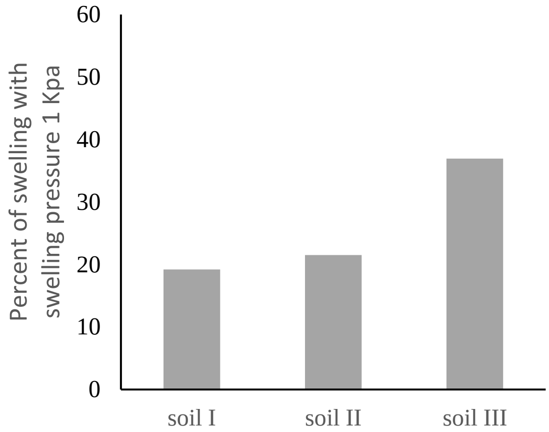


Fig. 8. The result of free swelling index for soils used in this study.

Also, Table 2 shows chemical properties of soil 1, 2 and 3.

Table 2. Chemical properties of three types of soil.

Property	Clayey soil 1	Clayey soil 2	Clayey soil 3
SiO2 %	58.13	61.26	53.74
Al2O3 %	20.12	21.93	18.15
Fe2O3 %	5.02	3.79	6.63
MgO %	4.17	2.26	4.94
CaO %	2.45	1.54	4.48
SO3 %	0.12	0.08	0.45
K2O %	1.23	0.44	1.96
Na2O %	1.74	0.68	3.95
TiO2 %	0.36	0.50	0.85
L.O.I %	6.66	7.52	4.85

2.2. Additives material

Polypropylene fiber, nanosilica and micro-silica fiber additives have been used to improve the desired properties of soils. The properties and reasons for using these compounds are discussed below.

2.2.1. Polypropylene fibers

In this study, polypropylene fibers were used to reinforce the soil. The reason for this choice is easy access, economic efficiency, high resistance in acidic and alkaline environments and knowledge of valuable experiences obtained from previous studies. Fibers mobilize the resistance in the soil mass against the contraction phenomenon [6]. Also, the volume changes in compacted soil samples are reduced by adding fibers [25]. In the present study, fibers were added to the soil samples once alone and once with other additives, to evaluate the effect of fiber performance on soil mass response to volumetric shrinkage and cracking. Table 3 shows physical and mechanical properties of these fibers.

Table 3. Properties of polypropylene fiber used in this study.

Property	Values
Specific gravity	0.95
Tensile strength - MPa	300 – 500
Elongation at break %	90 -130
Melt point (°C)	150
Diameter (micron)	20
Length - mm	5,10,15 and 20

2.2.2. Micro silica

In this study, micro-silica has been used to improve the geotechnical properties of the soil, so that adding micro-silica reduces the development of desiccation cracking. Also, the size and dimensions of the cracks in the samples improved with micro-silica have decreased significantly compared to the natural clay samples [30]. Tables 4 and 5 show the chemical and physical properties of micro-silica, respectively.

Table 4. Chemical properties of micro-silica and nanosilica in this study.

Property	micro-silica	Nanosilica
SiO_2 %	93.14	99.965
Al_2O_3 %	2.85	-
Fe_2O_3 %	0.84	-
MgO %	1.63	-
CaO %	0.92	-
SO_3 %	-	-
K_2O %	-	-
Na_2O %	-	-
TiO_2 %	-	-
Ti %	-	0.016
Ca %	-	0.010
Na %	-	0.006
Fe %	-	0.003
L.O.I %	0.62	-

Table 5. properties of micro-silica and nanosilica in this study.

Property	micro-silica	nanosilica
The main chemical composition	SiO_2	SiO_2
Density	2 – 2.5 (mg/m^3)	0.35 (gr/cm^3)
Particle size between 0.002 mm and 0.075 mm	20 %	0
Particle size less than 0.002 mm	80 %	100 %
Specific surface area m^2/gr	20.12	720
Purity	98 %	99 %
Color	Gray	White

2.2.3. Nanosilica

In this study, nanosilica has been used due to the positive performance on improving the geotechnical properties of the soil. Nanoclays have a crucial role in enhancing the mechanical and chemical characteristics of soil samples due to their high porosity and huge surface area. Intercalated and exfoliated nanoclay formations, on the other hand, substantially increase the mechanical and physical characteristics of samples [33]. The use of the appropriate amount of nanomaterials reduced the size and dimension of cracks. For soils with high plasticity, the crack dimension with 0.1% amount of nanomaterials is the minimum [21]. This was also confirmed in previous studies regarding the improvement of soil cracks using nanosilica. Tables 4 and 5 show the chemical and physical properties of nanosilica, respectively. Also, Figures 9, 10 and 11 show samples of chemicals and fibers used in this study.

Fig. 9. The samples of nanosilica used in this study.

Fig. 10. The samples of micro-silica used in this study.

Fig. 11. The samples of polypropylene fibers used in this study.

2.3. Methodology

The main objective of this study was to reduce the volume changes in clay and as a result the cracking in the waterproof lining layer of the bottom of landfill. For this purpose, the additives, including polypropylene fiber, micro-silica and nanosilica should be mixed with the desired soil samples. To investigate the effect of fibers and chemicals on the studied clay, the variables were considered and analyzed as shown in Table 6.

The test box made in this study was 1000 × 600 × 300 mm in length, width and height, respectively, as shown in Figure 12. In the test box, the camera should be placed at a suitable distance above the soil surface to be able to take pictures of the soil surface to check surface cracks.

For pounding and compacting the layer, a metal hammer made with the following specifications was used as shown in Figure 13. The weight of the hammer is equal to 10 kg. The dimensions of the hammer plate are equal to 25 × 15 m^2 with a thickness of 12 mm to achieve 90% compaction of soil layers.

Table 5. Quantity and percentage of composite materials for making samples and performing tests.

Parameter	Quantity
Polypropylene fibers in four sizes	5, 10, 15 and 20 mm
Eight different weight ratios for polypropylene fiber	0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.4 and 1.6 % of dry weight of soil
Eight different weight ratios for micro-silica	5, 10, 15, 20, 25, 30, 35 and 40 % of dry weight of soil
Eight different weight ratios for nanosilica	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8 and 1 % of dry weight of soil

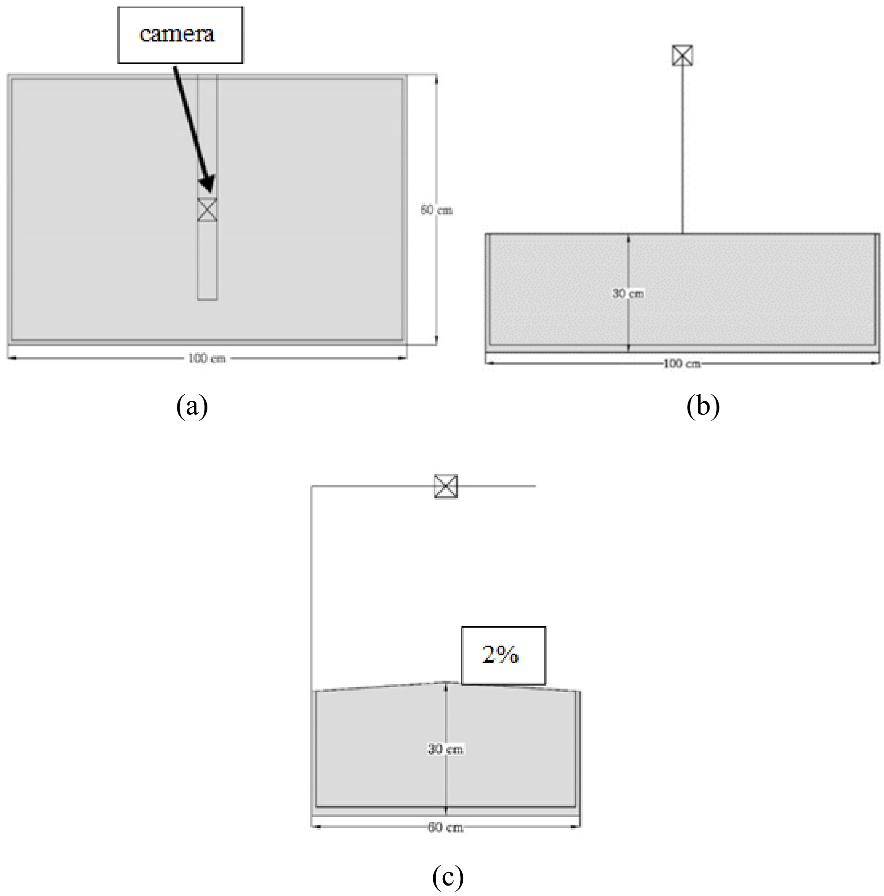


Fig. 12. Schematic of the test box made for crack evaluation through image processing, a. view from above, b. longitudinal section of the device, c. transverse section of the box.

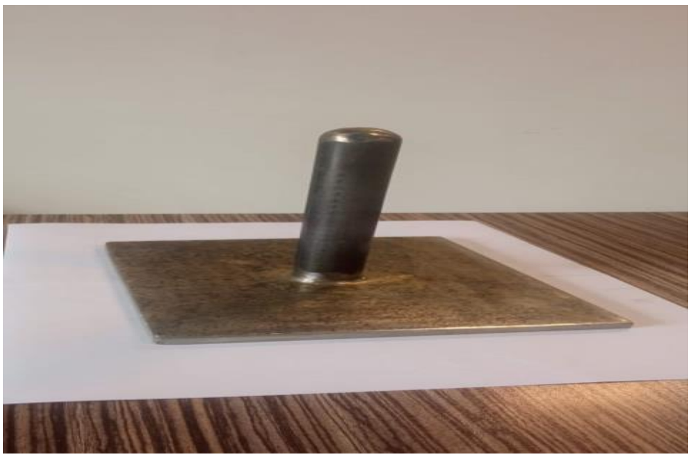


Fig. 13. The metal hammer made for compacting the layer.

Next, water, chemicals and fibers were prepared to be added to the soil inside the test box. These values were determined based on the results of the density test, the maximum dry weight and the optimal moisture percentage as shown in Figure 5 and the volume of the test box. Chemicals and fibers were added to the soil and mixed. Opening and separating the fiber particles before mixing greatly helps in making homogeneous samples. To make homogeneous samples, chemicals and fibers are added to the soil in stages and the mixing operation is performed. An attempt has been made to ensure that the number of stages and type of adding chemicals and fibers are such that the samples are as homogeneous as possible. Also, from the results and images of electron microscope analysis, it can be concluded that the fibers and chemicals are mixed homogeneously with the soil. Given that the density of soil layers in landfills must be at least 90 percent, the density of soil layers in the test box used was selected to be 90 percent. The percentage of soil compaction inside the test box is equal to 90%. Further, after several trials and errors, it was found that filling the test box in 5 layers with a thickness of 6 cm and compacting it with 25 blows by a special hammer led to achieving 90% relative density. Different layers of soil were manually poured into the test box. Each 5 cm layer that is poured into the test box was first leveled and then compacted by a hammer. After preparing the soil along with chemicals and fibers in the test box, the image of the surface of the soil cracks was taken. Figure 14 shows the method of filling the test box and compacting the soil by a hammer.

Fig. 14. Filling the test box and compacting the layers of soil to reach the given density.

Figures 15 and 16 shows the test box after filling, immediately after compaction and 24 hours after the test and the formation of surface desiccation cracking.

Fig. 15. The test box after filling, immediately after compaction.

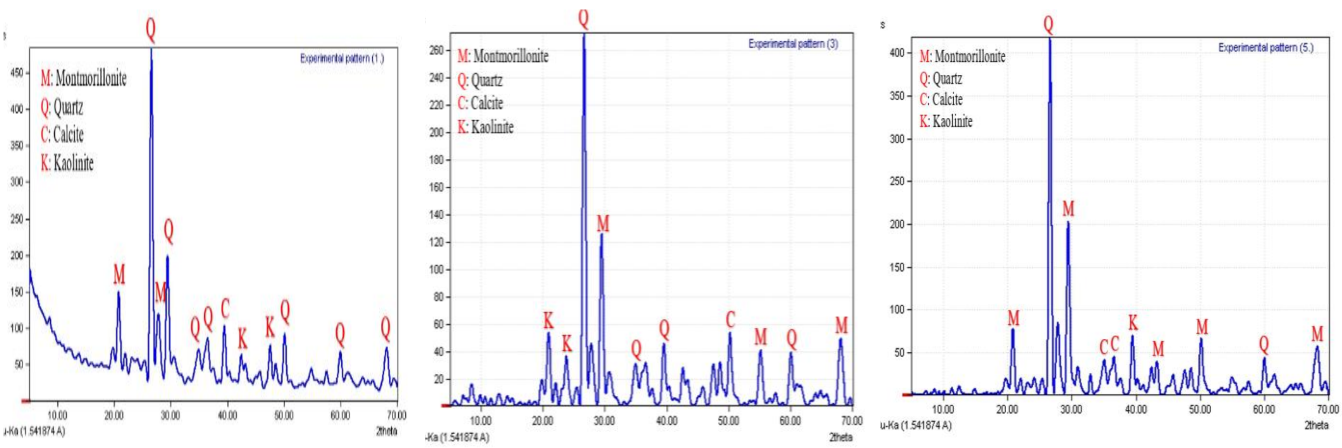
Fig. 16. The test box after filling and 24 hours after the test and the formation of surface desiccation cracking.

3. Results

3.1. Microscopic and microstructural study of soil improved by additives

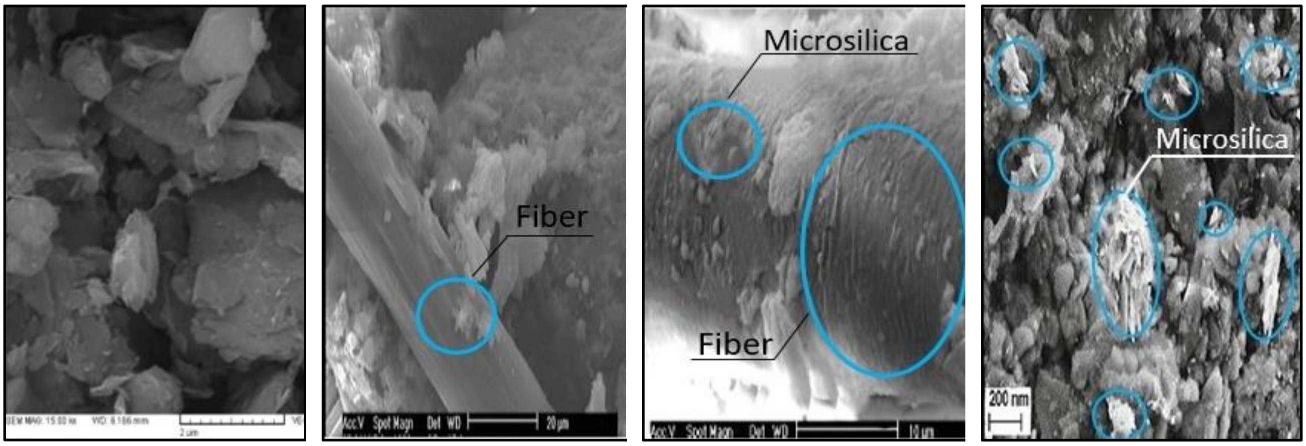
SEM images were used to for the surface, hole size and crystal structure of the constituents of soil samples and additives. Images taken by this method are presented at 500 magnification. As shown in Figures 17 and 18 SEM and XRD tests were performed on soil 2. To better compare the effect of additives on the desired clay, SEM and XRD were performed on clay 2 containing polypropylene fiber, micro-silica and nanosilica, the results of which are presented below.

As shown in Figure 18, the presence of polypropylene fiber in clay creates more cohesion between soil particles and makes clay particles more resistant. Also, the addition of micro-silica to the soil containing polypropylene fiber in clay creates more cohesion between the soil particles and the fiber and fills the empty space and soil porosity. As a result, as shown in Figure 18 and the adhesion and continuity, soil desiccation cracking is reduced.



(a) (b) (c)

Fig. 17. Results of XRD for soil 2, a. without additives , b. containing fiber and micro-silica, c. containing nanosilica.



(a) (b) (c) (d)

Fig. 18. Results of SEM for soil 2, a. without additives , b. containing fiber, c. containing fiber and micro-silica, d. containing micro-silica3-2-Evaluation of Cracks through the imaging processing.

In order to evaluate the behavior of cracks and determine the properties of cracks such as crack width, photography and image processing methods have been used to measure and analyze changes in crack dimensions. The objective of this method is to provide an applicable method based on image processing, in order to identify and analyze the cracks in the clay in vitro.

LabView was used to identify the crack and determine the crack severity factor. This program is a graphical programming language that is used in many branches of engineering. One of the important features of this program is data collection and processing, analysis of measurement systems, control and simulation of processes. This program can provide information input and output facilities and signal processing, which can be any type of filtering operations, noise removal, performing complex mathematical operations, and audio or image processing. In this study, the LabView image processing is used. The camera used to record images in this study is a canon camera with 18 megapixels accuracy, which is very fast and accurate. The desired camera is placed at a suitable distance from the soil surface.

(a) (b) (c)

Fig. 19. Surface cracks in soil 1, a. improvement of cracks in soil 1 using 15% micro-silica and 0.8% fiber and 15% moisture, b. cracks in soil 1 with 0.4% fiber and 15% moisture, c. cracks in soil 1 without additives and 15% moisture.

(a) (b) (c)

Fig. 20. Surface cracks in soil 2, a. improvement of cracks in soil 2 using 15% micro-silica and 0.8% fiber and 15% moisture, b. cracks in soil 2 with 0.4% fiber and 15% moisture, c. cracks in soil 2 without additives and 15% moisture.

(a) (b) (c)

Fig. 21. Surface cracks in soil 3, a. improvement of cracks in soil 3 using 15% micro-silica and 0.8% fiber and 15% moisture, b. cracks in soil 3 with 0.4% fiber and 15% moisture, c. cracks in soil 3 without additives and 15% moisture.

The camera is placed on the surface and immediately after preparation, the samples are photographed. After 24 hours, photography was done again to evaluate desiccation cracking.

Given that the thickness of the liners in landfill was usually between 30 and 50 cm, 30 cm layers were prepared from soils 1, 2, 3 and additives,including micro-silica, polypropylene fiber, and nanosilica. added to the three mentioned types of soil and the results were analyzed. The evaluated parameter includes the average crack width, which was accurately measured through digital photography and image processing, examples of which are shown in Figures 19, 20 and 21. These figures show some samples of soils 1, 2 and 3 before and after soil improvement.

3.3. Effect of soil improvement on the crack width average

By performing tests and adding different percentages of the composite materials, the effect on the width of the cracks has been investigated. The average crack width is shown by CWA (Crack Width Average). The numerical value of the crack width average on the surface of the soil is obtained from the sum of all the crack widths in the given area divided by the number of surface cracks, which is presented by

Equation 1 [34]. Where CWA shows the average crack width, Wsum shows the sum of all crack widths in the given area, and Nseg shows the number of surface cracks. The number of surface cracks is as the distance between two adjacent points or nodes which is defined in the software coding and the width of the crack is calculated [19].

$$CWA = W_{sum} / N_{seg} \quad (1)$$

According to the method of calculating the crack width, Figures 22-25 show the crack width average for different situations.

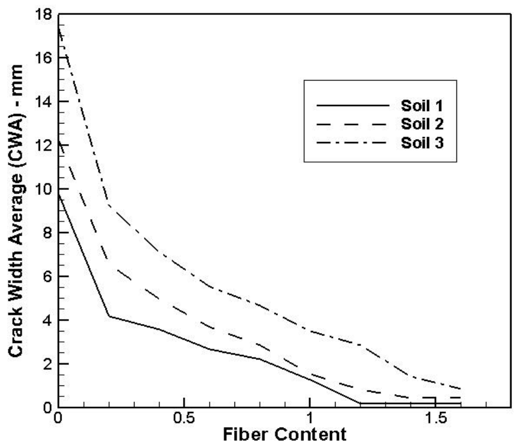


Fig. 22. Changes in the crack width average of soils 1, 2 and 3 according to different fiber percentages.

As shown in Figure 22, the results show that for soil 2 and 1 by adding 0.8% polypropylene fiber, the crack width average reduced from 12 and 10 mm to 2.22 and 2.85 mm. Also, for soil 3 by adding 0.8% polypropylene fiber, the crack width average reduced from 17 mm to 4.68 mm. According to the results, by adding 0.8% polypropylene, cracks in soil 2 have been reduced by 81%, 71% in in soil 1, and 72% in soil 3. By adding more than 1% of polypropylene fiber, changes in the crack width average will be almost uniform.

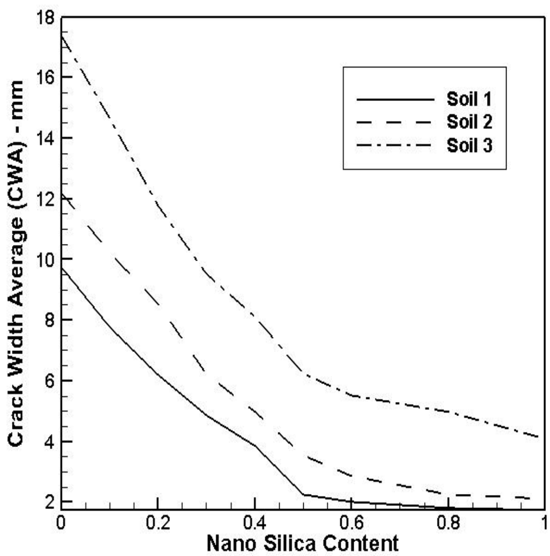


Fig. 23. Changes in the crack width average of soils 1, 2 and 3 according to different nano silica percentages.

In Figure 23, the results show that for clay 1, 2 and 3, by adding 0.4% nanosilica, the crack width average decreased from 10, 12 and 17 mm to 3.85, 4.96 and 8.12 mm, respectively. By adding 0.4% nanosilica, cracks in soil 2 have reduced by 59%, 61% in soil 1, and 52% in soil 3.

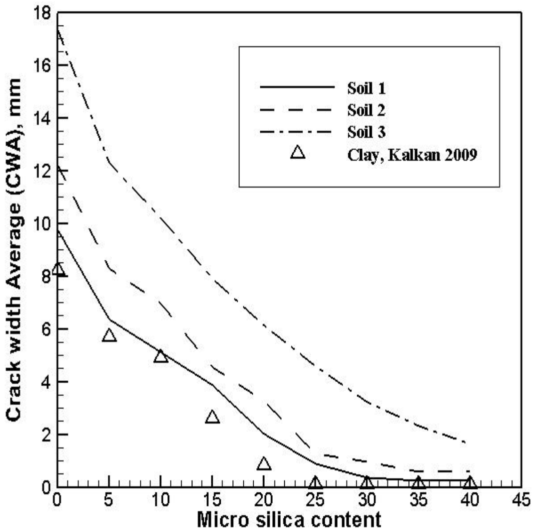


Fig. 24. Changes in the crack width average of soils 1, 2 and 3 according to different micro-silica percentages.

As shown in Figure 24, for soil clay types 1 and 2 used in the landfill, by adding 20% micro-silica, the crack width reduced from 12 and 10 mm to 2.02 and 3.26 mm, respectively. For soil clay type 3, by adding 20% of micro-silica, the crack width reduced from 17 mm to 6.12 mm. Also, according to the results, by adding 20% micro-silica, cracks in in soil clay type 2 reduced by 83%, cracks in in soil clay type 1 reduced by 67%, and cracks in in soil clay type 3 reduced by 64%. Also by adding about 10% of micro-silica the changes in crack width are significantly reduced by about 50%. Also, the results have been compared with the study results of Kalkan which are consistent with these results as shown in Figure 24 [30]. According to the results, adding micro-silica or silica foam improved the soil clay and reduced desiccation cracking on the surface. The reason for the reduction in desiccation cracking when using micro-silica is that the non-plastic properties and pozzolanic nature of micro-silica improve the properties of the clay so that it reduces the dry-bulk density and increases the optimum moisture content of the clay.

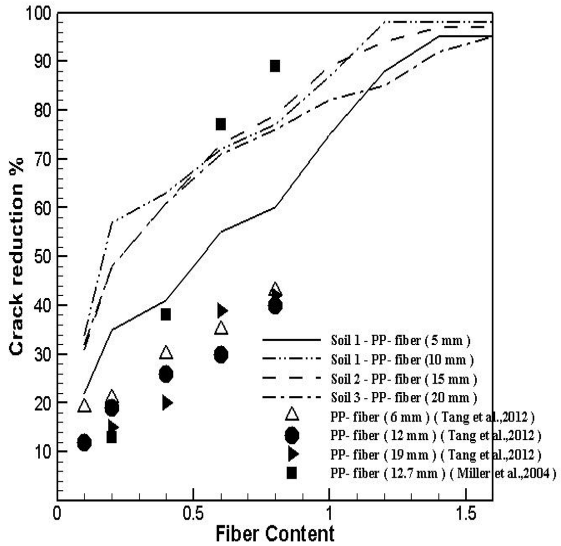


Fig. 25. Trend of reducing the crack width in soils 1, 2 and 3, according to different lengths and different fiber percentages.

As shown in Figure 25, the changes in crack reduction in soil clay types 1, 2, and 3 and studies by Tang et al and Miller et al are presented in terms of different percentages and lengths of polypropylene fibers [35][36]. As shown by increasing fibers the cracks on the surface of the sample are significantly reduced.

The fibers strengthen and improve the soil and the high tensile strength of the fibers increases the resistance properties of the soil and thus reduces the cracks caused by reducing moisture. Adhesion and surface friction between fiber and soil matrix is the determinant of improved soil properties.

3.4. Effect of soil improvement on the crack intensity factor

By performing tests and adding different percentages of the composite materials, the effect on the crack intensity factor has been investigated. The crack intensity factor is shown by CIF (Crack Intensity Factor). The value of the crack intensity factor on the surface is obtained from the area of cracked parts of the soil divided by the total area of the soil, which is presented by Equation 2. Where CIF shows the crack intensity factor, AC shows the area of cracked parts of the soil, and A shows the total area of the soil.

$$CWA = Ac / A \tag{2}$$

According to the method of calculating the crack intensity factor, Figures 26-29 show the crack intensity factor for different situations.

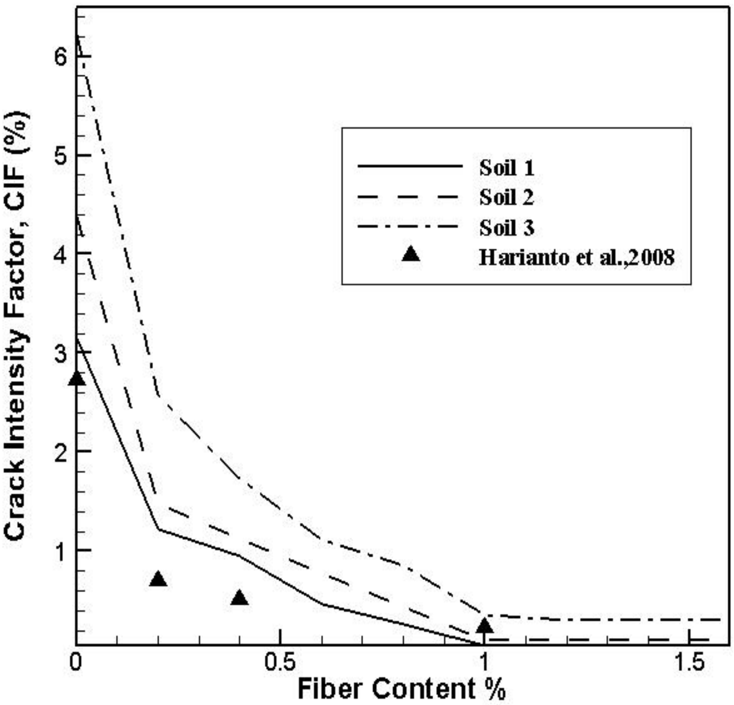


Fig. 26. Changes in the crack intensity factor of soils 1, 2 and 3 according to different micro-silica percentages.

As shown in Figure 26, the results show that for soil 1, 2 and 3, by adding 0.6% polypropylene fiber, the crack intensity factor decreased from 3.15, 4.38 and 6.22% to 0.47, 0.77 and 1.11%, respectively. By adding 0.6% polypropylene fiber, cracks in soil 2 have reduced by 82%, 85% in soil 1, and 82% in soil 3. As shown in Figure 26, the results show that in soil 1, if fiber is not used, the crack intensity factor will be 3.15%. Also, in the same soil, if 0.4% fiber soil is not used, the crack intensity factor is reduced by 0.95%. Further, if the fiber percentage is increased by 0.8%, the crack intensity factor is reduced by about 0.26%. And increasing the percentage of fiber again does not have much effect on the crack intensity factor and remains constant. Given that the total strain of the improved soil is lower than the total strain of the initial soil, adding the amount of fiber reduces the crack intensity factor. Also, the results have been compared with the study results of Harianto which are consistent with these results as shown in Figure 26 [25].

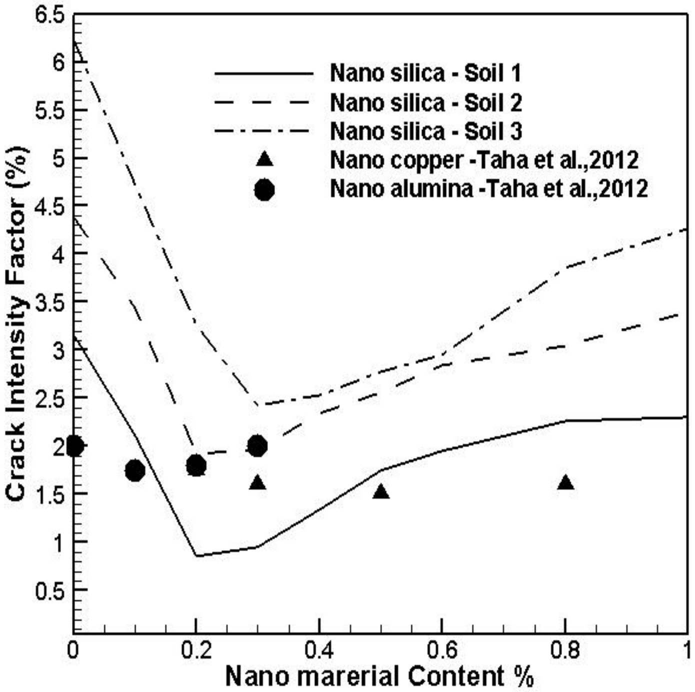


Fig. 27. Changes in the crack intensity factor of soils 1, 2 and 3 according to different nano silica percentages.

In the following, Figure 27 shows the changes in the crack intensity factor in terms of different percentages of nanosilica in soils 1, 2, 3 with 15% moisture.For soil 1, if we do not use nanosilica, the crack intensity factor will be 3.15%. If the amount of nanosilica is increased by 0.2%, the crack intensity factor is reduced by 0.85%. Further, if the amount of nano-silica is increased by 1%, the crack intensity factor is increased by 2.3%. Therefore, the optimal amount of nanosilica used in this soil is 0.2%. As shown in Figure 27, the results show that for soil 1, 2 and 3, by adding 0.1% nanosilica, the crack intensity factor decreased from 3.15, 4.38 and 6.22% to 2.12, 3.44 and 4.72%, respectively. By adding 0.1% nanosilica, cracks in soil 2 have reduced by 21%, 33% in soil 1, and 24% in soil 3. In Figure 27, the results show that for soil 1, 2 and 3, by adding 0.2% nanosilica, the crack intensity factor decreased from 3.15, 4.38 and 6.22% to 0.85, 1.92 and 3.26%, respectively. By adding 0.2% nanosilica, cracks in soil 2 have reduced by 56%, 73% in soil 1, and 48% in soil 3. Also, the results have been compared with the study results of Taha which are consistent with these results as shown in Figure 27 [24]. Adding 0.1% to 1% nano-silica improved the soil properties and reduced desiccation cracking on the surface. The reason for the reduction in desiccation cracking when using 0.1% to 0.2% nano-silica is that the non-plastic properties and pozzolanic nature of nano-silica improve the properties of the clay so that it reduces the dry-bulk density and increases the optimum moisture content of the clay. When the amount of nanosilica exceeds 0.2%, the pozzolanic and non-plastic properties do not have the same effect as before, and the crack intensity factor. increases slightly compared to the case of 0.1% to 0.2%. It should be noted that ultimately adding more than 0.2% nanosilica will reduce the crack intensity factor compared to the case where nanosilica is not added.

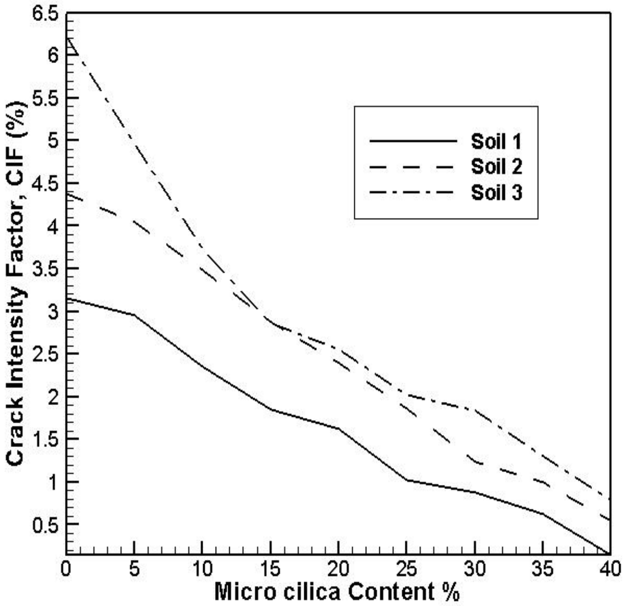


Fig. 28. Changes in the crack intensity factor of soils 1, 2 and 3 according to different micro-silica percentages.

Figure 28 shows the changes in the crack intensity factor in terms of different percentages of micro-silica in soils 1, 2 and 3 with 15% moisture. The results show that in soil 1, if we do not use micro-silica, the crack intensity factor will be 3.15%. If the amount of micro-silica is increased by 20%, the crack intensity factor is reduced by 1.62%. Also, if the amount of micro-silica is increased by 40%, the crack intensity factor will be 0.15%. The results show that the addition of micro-silica causes a significant reduction in the crack intensity factor.As shown in Figure 28, the results show that for soil 1, 2 and 3, by adding 20% micro-silica, the crack intensity factor decreased from 3.15, 4.38 and 6.22% to 1.62, 2.39 and 2.56%, respectively. By adding 20% micro-silica, cracks in soil 2 have reduced by 45%, 49% in soil 1, and 59% in soil 3.

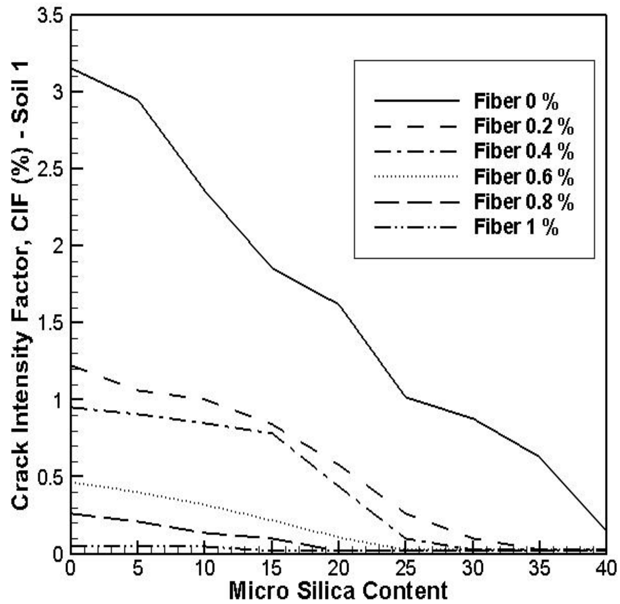


Fig. 29. changes in crack intensity factor for type 1 soil in terms of different percentages of fiber and micro-silica.

Figure 29 shows the changes in crack intensity factor for type 1 soil in terms of different percentages of polypropylene fiber and micro-silica. The results show that for type 1 clay used in landfill, by adding 0.6% of polypropylene fiber with a length of 10 mm, the value of crack intensity factor reduced by 0.47 mm. Also, by adding 0.8% of polypropylene fiber with a length of 10 mm, the crack intensity factor reduced by 0.26.Also, The results show that for soil 1, by adding 0.6% polypropylene fiber along with 20% micro-silica, the crack intensity factor reduced from 3.15% to 0.11%, i.e. by 96%. Also, for soil 2, by adding 0.6% of polypropylene fiber along with 20% of micro-silica, the crack width average reduced from 4.38% to 0.21%, i.e. by 95%. Next, for soil 3, by adding 0.6% of polypropylene fiber along with 20% of micro-silica, the crack width average reduced from 6.22% to 0.44%, i.e. by 92%.

As mentioned earlier, the simultaneous addition of fibers and micro-silica in soils 1, 2 and 3 had a significant effect on reducing the crack intensity factor, the reason for which is that the contraction strain in the improved soil was less than the contraction strain in the natural soil.

Also, fibers increase compressive and shear strength in soft soils and by reducing the soil shrinkage increase its plasticity. The crack intensity factor in soil without fiber is much higher than soil containing fiber. Fibers mobilize the resistance of the soil mass against shrinkage. Adding fibers to the soil reduces the specific surface area of the soil and, as a result, reduces the volumetric shrinkage strain (VSS) of the soil.

3.5. Effect of changing soil moisture on desiccation cracking through the imaging processing

One of the factors affecting the creation and expansion of surface cracks in fine-grained and sticky soils is the change in clay moisture. In this section, the trend of changes in surface cracks by changing moisture content in different samples of soils 1, 2 and 3 has been investigated. Figures 30,31 and 32 show the different states of cracks with different moisture content on soils 1, 2 and 3, which were evaluated through the imaging processing. Table 6 shows these changes. Figures 30-32 show the evaluation of the change in shape, amount and pattern of cracks by reducing moisture during the desiccation.

Figures 30, 31 and 32 show cracks created and developed from the borders and weak points of the soil and near the edges and borders. Its development continues to the inner zones of the soil and ends after the intersection of these cracks. These initial cracks are known as the main cracks, which after the final desiccation and the lowest amount of moisture, have higher crack width average. Secondary cracks are formed after the primary and main cracks and end when they connect to other main cracks. As shown in Figures 30-32, a large number of small cracks and the intersection of cracks divides the soil sample into a polygon. As the number of cracks increases, the polygon becomes smaller. Finally, according to the above, by reducing moisture in the soil and increasing the shrinkage strain, desiccation cracking increased significantly.

Table 6. Changes in width average of desiccation cracking based on humidity changes.

moisture	crack width average for soil 1 (CWA)	crack width average for soil 2 (CWA)	crack width average for soil 3 (CWA)
37 %	0.1 mm	0.2 mm	0.6 mm
30 %	0.45 mm	0.77 mm	1.15 mm
22 %	0.7 mm	0.98 mm	1.8 mm
15 %	2.85 mm	3.21 mm	5.5 mm
10%	6.77 mm	7.56 mm	10.75 mm
3 %	9.2 mm	11.5 mm	16.3 mm

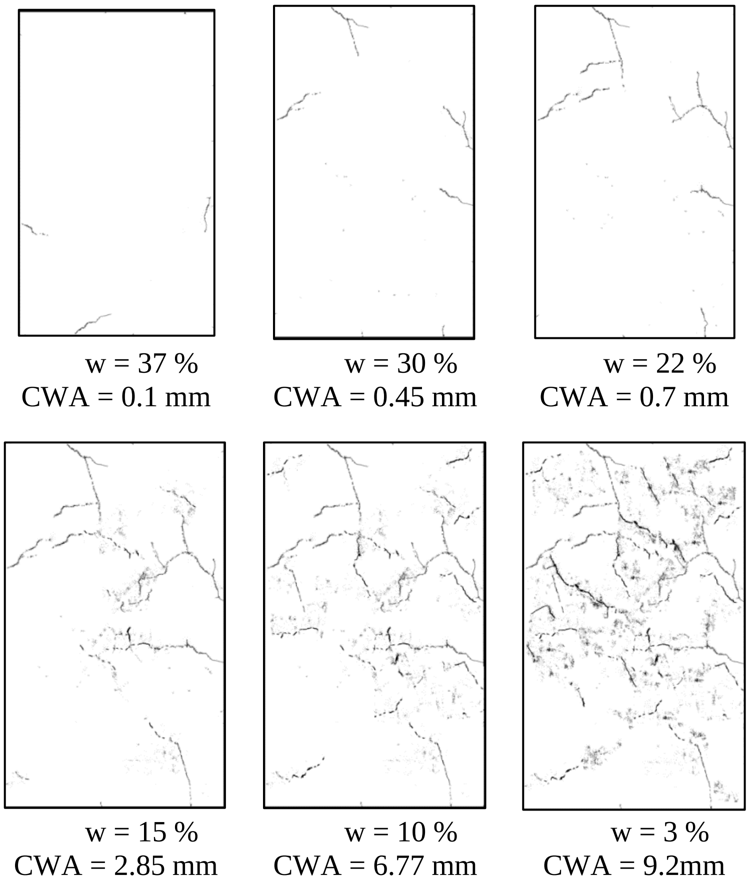


Fig. 30. Changes in width average of desiccation cracking based on humidity changes in soil 1.

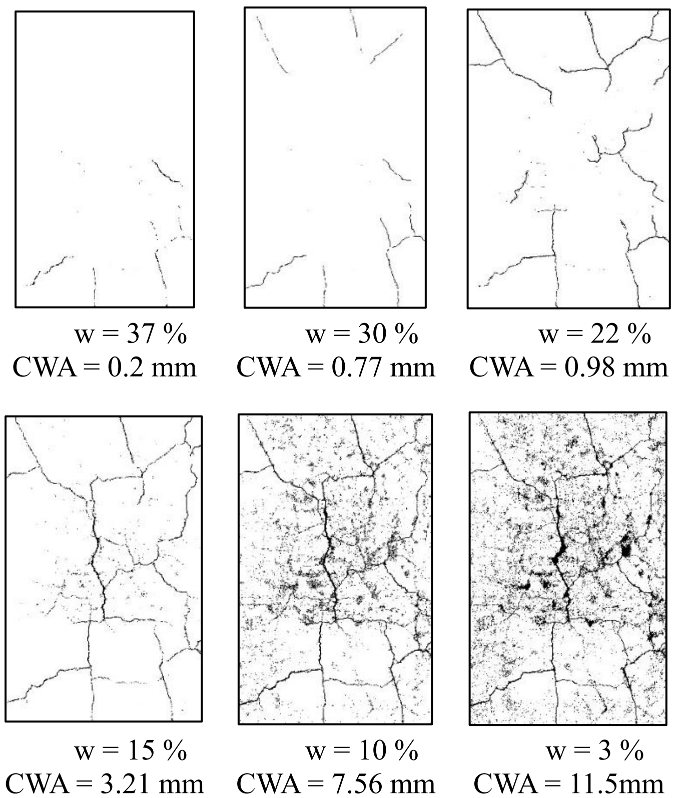


Fig. 31. Changes in width average of desiccation cracking based on humidity changes in soil 2.

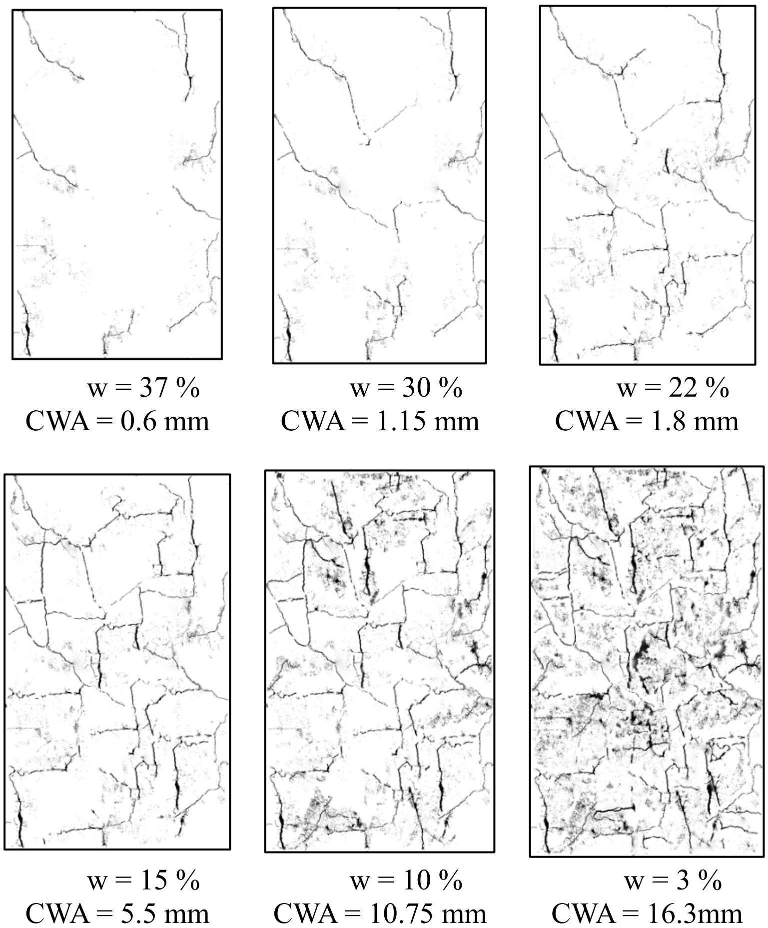


Fig. 32. Changes in width average of desiccation cracking based on humidity changes in soil 3.

3.6. Determining the range and proposed equations for fiber, microsilica and nanosilica with respect to cracking parameters

According to the figure 22 for crack width average, the symbol CWA and for the amount of fibers, the symbol FBC is determined. Figure 33 shows the range and proposed equations based on CWA and FBC.

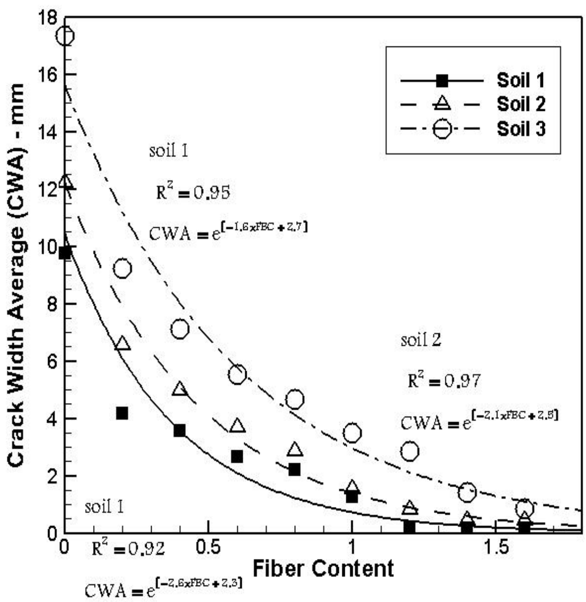


Fig. 33. The range and proposed equations based on CWA and FBC.

As shown in Figure 33, proposed equation based on CWA and FBC is illustrated in Equation 3.

$$CWA = e^{(-2.1\ FBC + 2.5)} \quad (3)$$

Next, According to the figure 23 for the amount of nanosilica, the symbol NSC is determined. Figure 34 shows the range and proposed equations based on CWA and NSC.

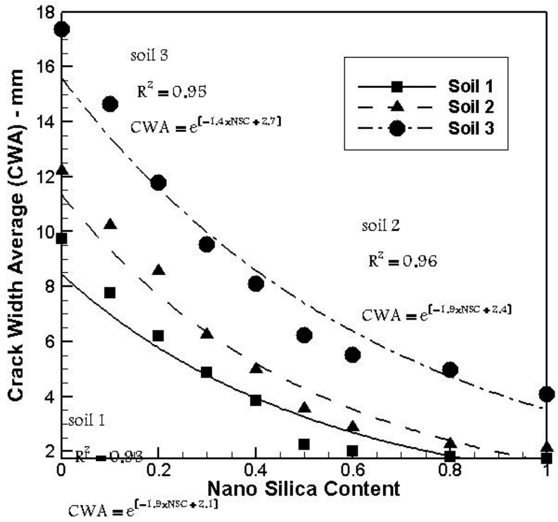


Fig. 34. The range and proposed equations based on CWA and NSC.

As shown in Figure 34, proposed equation based on CWA and NSC is illustrated in Equation 4.

$$CWA = e^{(-1.9\ NSC + 2.4)} \quad (4)$$

According to the figure 28 for crack intensity factor, the symbol CIF and for the amount of micro-silica, the symbol MSC is determined. Figure 35 shows the range and proposed equations based on CIF and MSC.

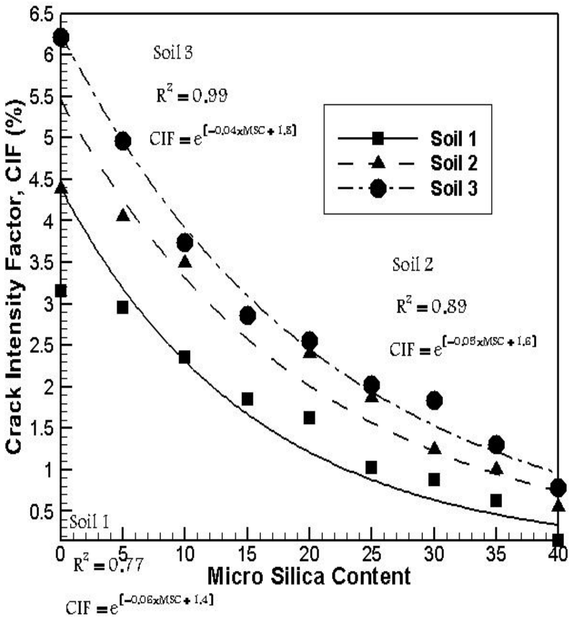


Fig. 35. The range and proposed equations based on CIF and MSC.

As shown in Figure 35, proposed equation based on CIF and MSC is illustrated in Equation 5.

$$CIF = e^{(-0.05\ MSC + 1.6)} \quad (5)$$

Conclusions

Due to financial limitations or lack of access to materials with low permeability, it may not be possible to build engineering liners or use prefabricated geosynthetic coatings in developing countries such as Iran, especially in smaller cities. If there is not enough clay in the site, it is possible to obtain suitable materials for the construction of the waterproof lining by supplying clay from borrow pits. According to the reports presented and the presence of surface cracks, the existing clay in the Mashhad landfill site is not suitable for use as a liner at the bottom. Therefore, using such soil and the site soil along with additives of polypropylene fiber, microsilica and nanosilica has been raised as an option.

According to the results for soil 2 and 1 by adding 0.8% polypropylene fiber, the crack width average reduced from 12 and 10 mm to 2.22 and 2.85 mm. Also, for soil 3 by adding 0.8% polypropylene fiber, the crack width average reduced from 17 mm to 4.68 mm. According to the results, by adding 0.8% polypropylene, cracks in soil 2 have been reduced by 81%, 71% in in soil 1, and 72% in soil 3. By adding more than 1% of polypropylene fiber, changes in the crack width average will be almost uniform. According to the results, the crack width average for lengths of 10, 15, and 20 mm of polypropylene fiber has significantly reduced compared to the length of 5 mm and was almost similar. Therefore, it is suggested to use 10 mm long polypropylene fiber for the soil in terms of cost optimization.

In soil 1, if we do not use micro-silica, the crack intensity factor will be 3.15%. If the amount of micro-silica is increased by 20%, the crack intensity factor is reduced by 1.62%. Also, if the amount of micro-silica is increased by 40%, the crack intensity factor will be 0.15%. The results show that the addition of micro-silica causes a significant reduction in the crack intensity factor.As shown in Figure 28, the results show that for soil 1, 2 and 3, by adding 20% micro-silica, the crack intensity factor decreased from 3.15, 4.38 and 6.22% to 1.62, 2.39 and 2.56%, respectively. By adding 20% micro-silica, cracks in soil 2 have reduced by 45%, 49% in soil 1, and 59% in soil 3.

As mentioned earlier, the simultaneous addition of fibers and micro-silica in soils 1, 2 and 3 had a significant effect on reducing the crack intensity factor, the reason for which is that the contraction strain in the improved soil was less than the contraction strain in the natural soil. Also, fibers increase compressive and shear strength in soft soils and by reducing the soil shrinkage increase its plasticity. The crack intensity factor in soil without fiber is much higher than soil containing fiber. Fibers mobilize the resistance of the soil mass against shrinkage. Adding fibers to the soil reduces the specific surface area of the soil and, as a result, reduces the volumetric shrinkage strain (VSS) of the soil.

Adding the optimal amount of nano materials (0.4%) and the ratio of polypropylene fiber and microsilica (0.6:20%) had a significant effect on reducing the crack width average in soil samples 1 and 2.

According to these results, it was found that the effect of polypropylene and microsilica fibers and the combination of these two compounds was more effective on reducing the crack width average compared to nanosilica. As a result, the use of polypropylene fibers and microsilica are cost-effective compared to nanosilica in high volumes. Hence, for practical purposes, it is suggested to improve the clay in the waterproof lining layers in landfill using the combination of polypropylene fiber and microsilica.

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