The effect of hollow polyester fiber additive on expansive clay soil

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Abstract. Controlling the swelling of expansive clay soils is always challenging for geotechnicians. In this study, the effect of hollow polyester fiber as an additive on the free swelling percentage and pressure reduction of bentonite clay is investigated experimentally. The fibers are employed in two forms of spread and concentrated. Fiber dosages of 0.2, 0.5, 1, and 1.5 are employed for the spread form and fiber columns with diameters of 1.2, 2 and 3.2 cm, are considered for the concentrated form with fiber column densities of 30 and 60 kg/m³. The obtained results show a significant improvement in the swelling behaviour of bentonite for both the spread and concentrated forms, with better performance for the later form. In which, higher densities and larger diameters of the fiber columns generally decrease the swelling percentage and pressure. The best improvement was observed in the concentrated form sample, with 60 kg/cm³ density and 3.2 cm diameter, with 19 and 57 percent reduction in swelling percentage and pressure, respectively.

1. Introduction
Clay soil swelling control has become a great concern for geotechnical engineers since the first United States Federal Highway Administration (FHWA) report about the damages caused by clay swelling in 1938 [1]. This phenomenon is mostly observed in cohesive clay soils. This type of soil is sensitive to water content fluctuations, which can be a result of water table level variation, flood, and sewage pipe leakage. This leads to shrinkage in the case of losing water and swelling during the absorption process [2]. Clay-based soils are widely distributed around the world, causing severe damages and injuries [3]. The economic loss in the United States due to the soil swelling is two times more than the losses from natural disasters, such as floods, earthquakes, typhoons, and tornadoes [4]. According to the official reports, the damage cost by this phenomenon is yearly 1000 million dollars in the United States, 150 million pounds in England, and billion dollars worldwide [5].

The swelling and shrinkage behaviour of soils can be experienced by the uplift pressure and induced stress. While the uplift pressure is not able to be converted to expansion due to the high surface structure weight, it will cause crack generation and propagation in lightweight structures [6]. Studies show that many crack types on road pavements and embankments are a result of this phenomenon [7]. Recent foundation design guidelines give more attention to clay soil expansion and swelling pressure [8, 9]. As a result, studies are performed on preventing swelling using various chemical and physical additives, such as cement, lime, fly ash, gypsum, calcium carbide, and natural and synthetic fibers (10-19). In addition to the additive type, the distribution arrangement of these additives was also

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investigated. Where the use of spreadly distributed fibers in clay soil structure, improving the mechanical characteristics, has been proven and utilizing additives such as geofoams and fly ash with a local distribution as columns in clay soil are investigated in previous studies [12, 16, and 21]. Behbahani et al. (2016), studied the effect of uniformly distributed polyester fiber on the plasticity and strength characteristics of two types of clay soils, CL and CH [22]. The results show that adding 0.5% of these fibers will decrease the plasticity and increase the compressive strength of the samples, 35 and 83 percent, respectively. In another study, the effect of polyester, fly ash, and lime additives on the geotechnical parameters of clay were investigated. To investigate the effect of these additives on the strength parameters of the soil, 0.5, 1, 1.5, and 2 percent of these fibers with 3, 6, and 12 mm lengths are added to the mixture with 15 percent fly ash and 8 percent lime. The results show a significant increase in the compressive and tensile strength of the soil mixture [12]. Selvam, et al. (2018), performed a study on polyester fibers as additives in clay soils to overcome the shrinkage and volumetric deformation of the clay soil. The polyester fiber is added to the clay soil mixture in 0.25, 0.5, 0.75, and 1 percent. The uniaxial compressive strength test and Atterberg limits tests to determine the solid limit, plastic limit, and liquid limit are done. The results showed a decreasing percentage on shrinkage and plastic limit by adding polyester fiber [23]. Selvakumar et al., (2019), studied the geofoam in the form of columns as additives to swelling clay particles. To investigate the effect of the geofoam column diameter and density, holes with 25, 40, 50, and 75 mm are created and filled by geofoams with 15 and 20 kg/m3 densities, in compressed clay mixtures in optimum moisture and maximum dry density. The large scale swelling percentage and pressure test is performed in CBR mold. The results showed that with diameter increase and density decrease in geofoam columns, the swelling percentage and pressure decreases. The maximum swelling reduction occurs for 75 mm diameter with 15 kg/m3 density, in which the free swelling percentage and swelling pressure drop, 2.6 and 200 kPa, respectively, compared to the witness sample [21]. Due to the extended use of bentonite in geomechanical projects and engineering structures, the swelling control of this material is still a concern. On the other hand, the improvement of clay swelling performance using geofoams, and polyester fibers additives in concentrated and spread form is proved in previous studies. Therefore, in the current study, the effect of hollow polyester fibers, in two forms of spread and columns, on the swelling performance of bentonite soils are investigated. It is expected that hollow polyester fibers, as water-absorbent structures, would compensate for the water lack of the soil structure during the swelling procedure.

2. Material

- **Bentonite**

Bentonite is a commonly used material with a high swelling tendency. The Sodium-based bentonite clay with the highest swelling potential among bentonite types is used in this study with characteristics presented in Table 1. With attention to the high liquid limit (LL) value, there would be a considerable water absorption potential for this type of bentonite, making it sensitive to shrinkage and swelling.

| Parameter                      | Value  |
|--------------------------------|--------|
| Maximum Dry Density (gr/cm³)  | 1.6    |
| Optimum Moisture content (ω) (%) | 28    |
| Liquid Limit (LL) (%)         | 150    |
| Plastic Limit (PL) (%)        | 49     |
| Plastic Index (PI) (%)        | 101    |

- **Fibers**

The polyester fibers are a type of synthetic fibers created from the polymerization of an ester. Moreover, these fibers have a circular section, high resistance to moisture, chemicals, and flammability. Previous studies show the improving effect of polyesters additive in controlling the
swelling phenomenon, in other material [12, 24, and 25]. Hollow polyester fibers as a type of polyester fibers with higher water absorption capacity and lower density compared to ordinary polyesters are employed in this research to reduce the water content fluctuation content of the bentonite clay soil. A Picture of the used Hollow Polyester Fibers and its water absorption mechanism presented in Figure 1 [26]. During the water absorption procedure, the penetrated water is spread and confined in the hollow section and could be released to compensate for the water lake of the soil mixture [27]. The detailed properties of the utilized fibers are presented in Table 2.

![Picture of the used Hollow Polyester Fibers and its water absorption mechanism](image)

**Figure 1.** Picture of the used Hollow Polyester Fibers (left) and its water absorption mechanism (right - modified from Wada and Takatera 1984).

### 3. Sample Preparation

As noted, samples in both the spread and column forms are studied. To prepare these samples, first, the optimum moisture content and the corresponding density values are obtained from the compaction test. The consolidation test mold with 75 mm diameter and 20 mm height is utilized for the free swelling and swelling pressure tests. The mold gets smeared with silicon oil to reduce the friction between the mixture and the mold wall. In the first method, the fibers with 0.2, 0.5, 1, and 1.5 percentages are mixed with the soil in a spread form in optimum moisture content. The prepared mixtures are kept in a plastic bag for 24 hours curing. Then the mixtures are compacted in the testing mold to reach the corresponding density of the optimum moisture content.

**Table 2.** Physical characteristics of the hollow polyester fibers.

| Parameter                              | Value (Type) |
|----------------------------------------|--------------|
| Length (mm)                            | 1-4          |
| Cross Section Shape                    | Hollow Circle|
| Longitude Section Shape                | Wavy         |
| Water Absorption (%)                   | Hollow       |
|                                        | 12-13        |
|                                        | Ordinary     |
|                                        | 2-3          |
| Density (gr/cm³)                       | 1.23         |
| Diameter µm                            | 40           |

For the second method, the fibers are placed with various densities in column form within the created central hole with 1.2, 2, and 3.2 cm diameters. In this procedure, first, the soil with the optimum moisture content is mixed, and a tube with the considered diameter is placed in the middle of the mold. The soil is poured homogeneously around the tube and compacted until it reaches its corresponding...
density related to the optimum moisture content. After compaction, the smeared tube with silicon oil is twisted and detached from the soil. Then the polyester fibers are located in the created hole, in which the density reaches 30 and 60 kg/m³. To evaluate the swelling behavior improvement of each modified sample, the witness samples with empty holes are also prepared (HC1.2, HC2, and HC3.2). For instance, Figure 2 illustrates the created witness specimens with 2 cm and the fiber-filled sample with 3.2 cm diameters and 60 kg/cm³ density. The considered parameters for all the specimens in the first and second methods are presented in Table 3.

![Figure 2. Witness specimen with 2 cm hole diameters (left), and modified specimen with fiber column of 3.2 cm diameter (right).](image)

4. Method
The free swelling percentage and swelling pressure are the two factors considered to compare the swelling behavior of samples in this study. In this regard, the free swelling test and swelling pressure test in the constant volume are performed. A brief description of these tests, according to ASTM standard, are presented below.

- **Free swelling test**
To measure the swelling percentage according to ASTM D-4546 the sample is placed in the consolidation test mold, and a one kPa load is applied on the top. Then the specimen is allowed to swell by water absorption, and the gauge value is then recorded at 0, 0.1, 0.5, 1, 2, 5, 10, 15, 30 minutes, and 1, 2, 4, 8, 24, 48, 72 hours. The recorded swelling values are plotted against time (logarithmic scale), which illustrates three swelling stages, namely initial, primary, and secondary.

- **Swelling Pressure test in Constant Volume**
In the constant volume, the specimen is located in the consolidation mold, and after adding water, a 5 kPa surcharge is applied to prevent swelling. The test is continued with a five kPa increase in the surcharge load, in each stage until the soil sample overcomes all the applied loads; thus, the swelling gauge displays zero. The final load amount is called the swelling pressure. Figure 3 illustrates the experimental procedure of the performed free swelling and swelling pressure tests.

5. Results
Two sets of results are obtained from the experimental tests, the swelling percentage and swelling pressure for various fiber-bentonite mixtures (presented in Table 3) in the two spread and concentrated forms.
Table 3. Sample specifications in the first and second methods.

| Method | Specimen | Column Diameter (cm) | H/D | Soil and Water mass (gr) | Density (kg/cm³) | Applied Fiber (gr) | Applied Fiber (%) |
|--------|----------|----------------------|-----|--------------------------|----------------|-------------------|------------------|
| -      | SB       | -                    | -   | 140                      | -              | -                 | -                |
| 1      | HPF0.2   | -                    | -   | 139.72                   | -              | 0.28              | 0.2              |
| 1      | HPF0.5   | -                    | -   | 139.3                    | -              | 0.7               | 0.5              |
| 1      | HPF1     | -                    | -   | 138.6                    | -              | 1.4               | 1                |
| 1      | HPF1.5   | -                    | -   | 137.9                    | -              | 2.1               | 1.5              |
| 1      | HC 1.2   | 1.2                  | 1.67>1 | 138                    | -              | 0                 | 0                |
| 2      | PFC 1.2-30 | 1.2                   | 1.67>1 | 138                   | 30             | 0.068             | 0.049            |
| 2      | PFC 1.2-60 | 1.2                   | 1.67>1 | 138                   | 60             | 0.136             | 0.098            |
| 2      | HC 2     | 2                    | =1   | 131                     | -              | 0                 | 0                |
| 2      | PFC 2-30 | 2                    | =1   | 131                     | 30             | 0.19              | 0.145            |
| 2      | PFC 2-60 | 2                    | =1   | 131                     | 60             | 0.38              | 0.29             |
| 2      | HC 3.2   | 3.2                  | 0.625<1 | 115                  | -              | 0                 | 0                |
| 2      | PFC 3.2-30 | 3.2                   | 0.625<1 | 115                 | 30             | 0.48              | 0.42             |
| 2      | PFC 3.2-60 | 3.2                   | 0.625<1 | 115                 | 60             | 0.96              | 0.84             |

Note: H.C. is the pure bentonite sample with hole specimens, PFC is the modified samples with column, HPF is the sample modified with hollow polyester fiber in the spread form, and S.B. is the pure bentonite specimen.

Figure 3. The experimental setup for swelling pressure (left) and free swelling tests (right)

- Spread Form

The swelling percentage versus time (logarithmic scale) for the fiber-modified samples in the spread form (HPF) and bentonite (SB) in 72 hours are recorded from the aforementioned tests and plotted in Figure 4. It can be seen that for all samples, the swelling percentage follows the same trend with significant growth after 100 minutes, and a noticeable disband is observed after 72 hours. To accurately compare the swelling behavior of the samples,
Figure 4. The swelling percentage versus time.

Figure 5 presents the final swelling percentages and pressure recorded for the modified samples. The figure depicts that all modified samples experienced a lower swelling percentage than the bentonite sample. The minimum value was observed for the sample with 0.2% fiber (HPF0.2) in which the swelling percentage drops from 31.4 to 26.27. This value gradually grows by implementing higher fiber percentages and stays almost constant. A similar trend is observed for the swelling pressure, where the maximum decrease is obtained for the HPF0.2 sample, from 210 to 160 kPa. This phenomenon can be explained by the tensile strength increment generated by the fibers; however, higher fiber dosages may decrease this positive effect due to the inhomogeneity of the mixture.

- Concentrated form (column)

As discussed, fibers are implanted as columns with various diameters and densities in the concentrated mode. To investigate the effect of fiber-filled column samples, it is necessary first to evaluate the effect of hollow columns on the swelling behavior. Fig. 6 illustrates the swelling percentage for the three hollow column diameters of 1.2, 2, and 3.2 cm along with the SB sample against time.
(logarithmic scale) through 72 hours. It is expected that the swelling percentage would amplify with higher water accessibility for the samples with larger hole diameters. However, in these samples, the lower clay soil volume leads to limited swelling potential. For the HC1.2 sample, the contrary effect of these two phenomena is almost equal, resulting in no change compared to the SB sample (~30%). While in the HC2 sample, the impact of water accessibility is dominant, thus with hole diameter growth for the HC3.2 sample, the effect of soil volume leads to a drop in the swelling percentage (~37%). To assess the effect of fiber-filled columns on the swelling behavior, the columns are filled with fibers in two densities of 30 and 60 kg/m³. The swelling percentage versus time is plotted for the fiber-modified samples in Figure 7. In comparison with the hollow samples, it is obviously observed that the swelling percentage of the fiber-filled samples are significantly lower. To accurately inspect the fiber-filled sample's behavior, the final swelling percentage against column diameter in considered densities are plotted in Figure 8. Generally, a decreasing trend is observed for the swelling percentage of 30 and 60 kg/m³ against the hole diameter with lower values for the later density. Moreover, the swelling percentage is 60 kg/m³ is lower compared to 30 kg/m³ density. This can be explained by the fact that the water accessibility of the sample for the higher density is limited compared to the 30 kg/m³ and hollow column sample.

The simultaneous impact of the column diameter (considering the H/D ratio) and density on swelling percentage reduction derived from Eq. 1 is illustrated in Figure 9. As shown, the swelling percentage reduction, increases in higher densities and lower H/D ratios (larger column diameters).

$$PS_{r} = \frac{PS_{SB} - PS_{PFC\text{ sample}}}{PS_{SB}} \times 100$$  \hspace{1cm} (1)

To evaluate the effect of fiber column diameter on the swelling pressure, the test is performed on the samples. The results are presented in Fig. 10. As shown, there is a significant reduction in swelling pressure for the fiber-filled samples compared to the witness sample (HC), in which the column diameter increase leads to lower swelling pressure. Despite the swelling percentage, the swelling pressure is higher in higher density. This due to the fact that by applying the load on the sample, less lateral expansion occurs for the samples with higher fiber-filled density, which leads to higher required pressure to overcome the axial expansion. Therefore, the highest reduction in swelling pressure is observed for PFC3.2-60, which was about 57 percent.

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**Figure 6.** The swelling percentage versus time for empty column samples.
Figure 7. The effect of the fiber column diameter with a density of 30 and 60 kg/m$^3$ on the swelling percentage.

Figure 8. Effect of hole diameter on the swelling percentage for HC, PFC30, and PFC60.

Figure 9. Relation of fiber column density and swelling percentage.

Figure 10. The effect of the fiber column diameter with a constant density of 60 kg/m$^3$ on the swelling pressure.
6. Conclusion
The effect of polyester fiber additive on bentonite clay swelling performance is evaluated. The fibers are implemented in two forms of spread and columns. For the spread form, 0.2, 0.5, 1, and 1.5 percentages are mixed with the bentonite clay, and columns with 1.2, 2, and 3.2 cm diameter with 30 kg/m³, and 60 kg/m³ are inserted in the samples for the column mode. Free swelling and swelling pressure tests are performed and then compared with the results from the prepared witness samples. The conclusions are as follows:
- In general, adding polyester fibers in spread and column forms results in less swelling percentage and pressure. This reduction was more significant in column form modification.
- For the modified sample with 0.2 percent of fibers in spread form, the swelling percentage and pressure are decreased, 16 (31.4 to 26.27), and 24 (210 to 160 kPa) percent, respectively.
- At a specific density, the column diameter increment generally leads to a lower swelling percentage for all specimens.
- In all samples with constant fiber-filled column diameter, density growth up to 60 kg/m³, results in swelling percentage reduction. In which the highest reduction is from 36.75 (for HC2) to 29.41(for PFC 3-60) is observed.
- The optimum H/D ratio for the swelling percentage value is assessed to be 1:1. This value is observed for the PFC 2-60 specimen with a maximum swelling reduction of 22% compared to the unmodified sample.
- As for the lightweight surface structures, the swelling pressure is a critical factor. Among the investigated specimens, the PFC3.2-60 has the best performance, with 57% reduction in swelling pressure compared to the SB sample.

7. References
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