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Experimental study of the effect of the glass fibers on reducing collapse of a collapsible soil

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Abstract. Collapsible soil presents a porous unsaturated structure, its sudden settlement after humidification, without supplementary charge, can be of a big nuisance for the foundations and therefore for the constructions built on it. To improve its structure and limit its instability, samples of laboratory reconstituted soil, with different percentages of water contents and compacted at different compaction energies, were treated with glass-fiber. The study of the mechanical behavior was performed by oedometer tests. The microstructure was explored by the Scanning Electron Microscope (SEM). The results obtained show clearly the efficiency of the treatment with glass fiber on reducing the collapsibility of such soil.

Keywords: collapsible soil; arid zones; glass-fiber; oedometer; SEM

1. Introduction

The treatment of collapsible soils in arid and semi-arid regions is a major issue in both economic and security aspects. Indeed, the collapse of this type of soil can be of a big nuisance for the foundations and consequently for the constructions built on it. Several researchers have focused on the study of the parameters of identification of such soils, while others were interested by the treatment of this type of soil with the aim of exploiting it without any danger.

Collapsible soil is metastable and unsaturated, it has an open and a porous structure due to the grain size of this type of soil and the nature of the cementing grains, occurring in the form of deposit. Such soil can support heavy loads in the dry state, however, its humidification, even without additional loading, causes the disintegration of the connections giving a denser structure followed by the collapse of the soil.

The loess, dunes and other aeolian deposits form soils with a loose structure. Studies claim that the loess covers about 17% of the United States, about 17% of Europe, 15% of Russia and Siberia, and large areas of China (Clemence and Finbarr 1981). This type of soil is also encountered in South America and Southern Africa. We can find calcareous windblown dune sands in Kuwait and some parts of the Arabian Peninsula (Ismael *et al*. 1987). A study by Nouaouria *et al*. (2008) showed that the properties of loess in southern Algeria are similar to those existing in other regions

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such as the soil of Iowa (USA) and Libya. This kind of soil can be classified as a silty loess.

In the general case, collapse occurs because of mechanical constraints that broke the cementing links. However, in the case of collapsible soils, capillary suction between grains and fine particles vanishes when water is added (Dudley 1970). Clemence and Finbarr (1981) claims that collapse velocity depends on the link nature. Indeed, collapse velocity is high, low or very slow if the links are respectively capillary suction, chemical cementing or clay buttresses.

Because of the damage caused by the collapse, this type of soil is considered unstable for foundations of structures. Collapse occurs if the dry density and the initial water content are low (Cui *et al*. 1999, Loiseau *et al*. 2001). However, if the relative density is greater than 0.65%, the water content is close to the optimum moisture content and the percentage of the clay fraction exceeds 30%, there is no risk of collapse (Abbeche *et al*. 2007).

An identification method using ultrasonic testing has been proposed recently on reworked or undisturbed samples, and has led to a relationship between the propagation speed of the waves and the susceptibility of a soil to collapse, as if $V \leq 400$ m/s collapse occurs, and if $V > 1000$ m/s the risk of collapse is discarded (Abbeche *et al*. 2010b). Between these two limits, depending on the initial water content and the state of soil compaction, subsidence can occur or not.

Salehi *et al*. (2015) have contributed by a study carried out on loess samples of Golestan province (North of Iran), to the estimation of the collapse potential by a neural network and neuro-fuzzy systems. They proposed than, several neural network architectures and training algorithms to evaluate the collapse potential and at last they give the optimal performance of the estimation given by the best network.

Abbeche and Ziani (2014) studied the effect of the hydraulic gradient and the vertical load on the collapse potential of soils. They have conclude that the collapse reaches its maximum for a vertical load of 400 kPa, and that one of the mechanisms of collapse is the displacement of the fine particles from an horizon to another through the soil matrix.

To solve the problem of collapsible soils, several treatment methods have been proposed; a method using lime proved its efficiency in the case of a minimum rate of 6% lime, a water content of 8% and a minimum compaction energy (Abbeche *et al*. 2009). However, this method is unusable in the arid and semi-arid areas, where the need to minimize the amount of water and soil compaction is required. In Lahmadi *et al*. (2012) soil was treated with cement using double consolidation. This study showed that for a minimum compaction, a cement content of 4% and a water content of 6%, the soil is not collapsible. However, the author has concluded that the water remains high in view of the specificity of the areas to be treated. But the treatment of collapsible soil by sulfur cement, increases its compressive strength by about three times than ones stabilized by Portland cement (Mohamed and El Gamal 2012).

A method of treatment with salts (ammonium sulfates $(NH_4)_2SO_4$ and potassium chlorides KC1) using the double consolidation method, was carried on samples of soil at different concentrations (0.5, 1.0, 1.5 and 2.0 mol/l) and compaction energies shows that the rate of collapse can be reduced appreciably (Abbeche *et al*. 2010a). Fattah *et al*. (2013, 2014, 2015) affirm by their study that the treatment of undisturbed collapsible gypseous samples with acrylate liquid, with different properties and with various gypsum contents, can reduce the collapse potential by more than 50-60%.

Bara (1976) gives by a table, a summary of current, past and possible future treatment methods. These methods were classified following the amount and the type of treatment depending on the depth of the collapsible soil and the support requirements for the proposed structure.

In this paper, a new treatment is proposed, which will be carried out with a milled glass-fiber with different percentages. The soil will be subject to different compaction levels and different water contents in order to find the needed rate to reduce the soil subsidence, and thus to improve security level for the structures built on this type of soil.

2. Characteristics of materials

Tests were conducted on soil samples reconstituted in the laboratory with the composition of 80% of sand (D < 2 mm), and 20% of kaolin as fine particles (grains size < 80 μm). The stream

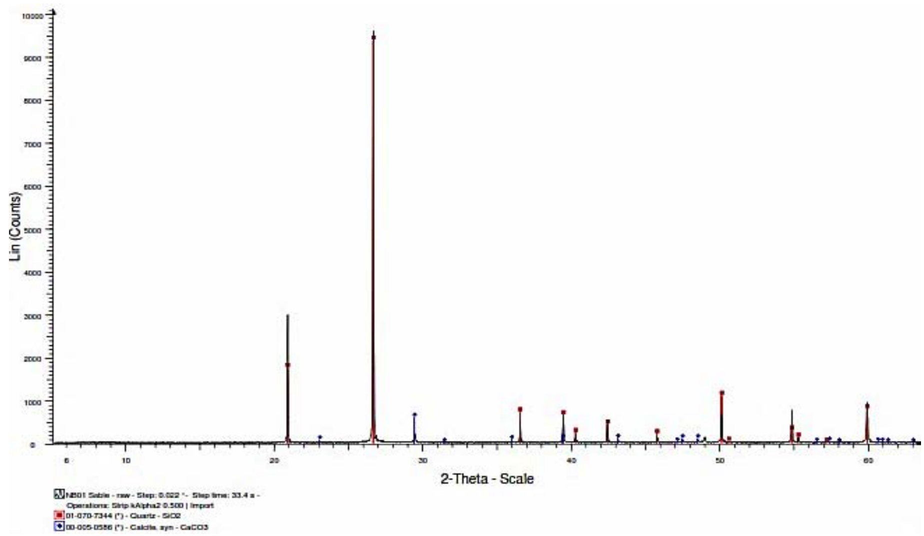


Fig. 1 X-ray diffractogram of sand

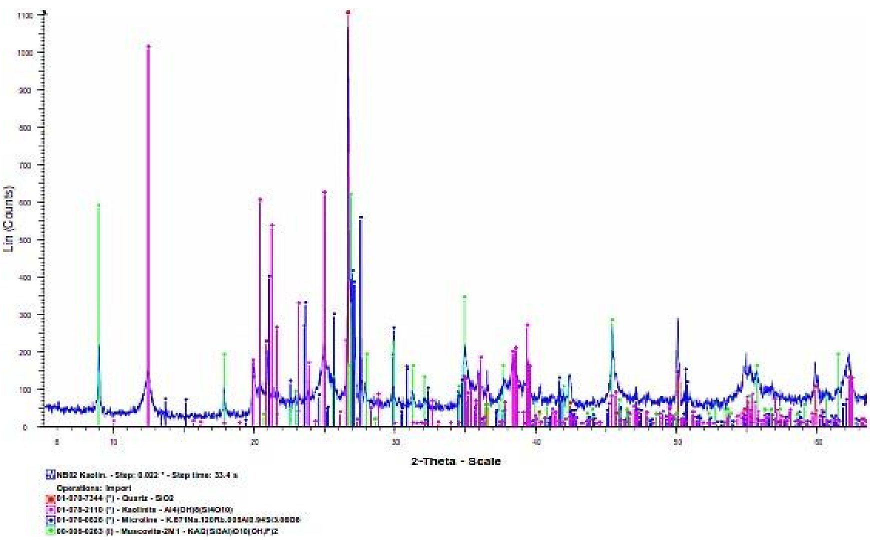


Fig. 2 X-ray diffractogram of kaolin

sand is from Oued Maitar at Boussaâda (Algeria) and the clay is kaolin of Elmilia region located in Mila (eastern Algeria). The characteristics of the sand and the fine particles are summarized in Table 1.

The treatment is carried out with a milled glass-fiber (F_g) often used for its mechanical, thermal and chemical resistance (E-glass, product specification 1320 K, fiber length: 180 μm).

The X-Ray Diffractometer, XRD is used to characterize the microstructure and crystallographic properties of the different compositions. This test was carried out on the sand and the kaolin. The

Table 1 Characteristics of the sand and the fine particles (< 80 μm)

Liquid limit, $W_{L\%}$	18.53
Plastic limit $W_{p\%}$	13.13
Specific density, G_S	2.63
Coefficient of uniformity, C_u	9.44
Coefficient of curvature, C_c	2.64
Maximum dry density γ_{opt} (g/cm^3)	1.91
Optimal water content $W_{opt\%}$	10

Table 2 Geotechnical characteristics of reconstituted soil

Materials	Characteristics
Sand	Sand equivalent, SE (%) = 70%
	Grain size distribution (0.08-2 mm) with 1% of particles < 80 μm
	Coefficient of uniformity, C_u = 2.63
	Coefficient of curvature, C_c = 1.62
	Specific density, G_S = 2.61
Kaolin	Grains size < 80 μm
	Liquid limit, W_L = 48.9%
	Plastic limit W_p = 29.7%
	Specific density, G_S = 2.65

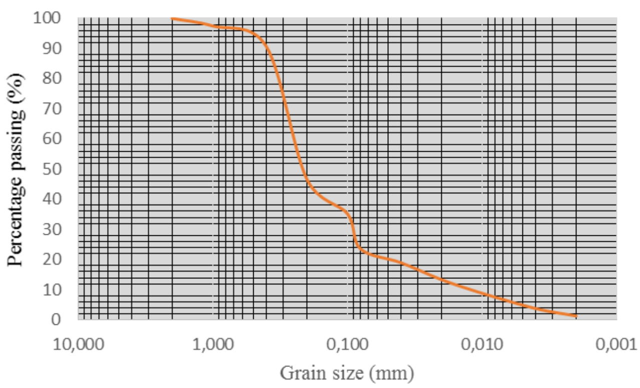


Fig. 3 Grain size distribution curve of the reconstituted soil

Table 3 Collapse potential values (Jennings and Knight 1975)

C_p (%)	Severity of disorders
0-1%	No problem
1-5%	Moderate trouble
5-10%	Trouble
10-20%	Severe trouble
> 20%	Very severe trouble

results show that the essential constituent of the sand is the quartz with traces of calcite. The kaolin consists essentially of kaolinite, some of muscovite, microline and quartz, all this is illustrated by Figs. 1-2.

The geotechnical characteristics of the laboratory reconstituted soil are summarized in Table 2 and its particle size distribution curve is shown in Fig. 3.

3. Experimental program

The study consists in consolidation in the oedometer (ASTM D5333), of samples of a laboratory reconstituted soil with 80% sand and 20% kaolin, according to the procedure of Jennings and Knight (1975), samples were prepared at different moisture contents and compaction energy. Then, the same test will be carried on samples of soil treated with different percentages of milled glass-fiber. Content in glass-fiber is varied in order to determine the rate beyond of which the collapse C_p becomes without any danger for the structure “no damages” according to the classification of Jennings and Knight (1975), Table 3. The reserved parameters are:

- Initial water contents: 2, 4 and 6%;
- Energy of compaction 20, 40 and 60 blows;
- Contents in glass-fiber: 0, 3, 4, 5 and 6%.

After finishing the oedometer tests samples were observed by the scanning electron microscope (SEM). The first pictures were taken on samples before saturation, with or without treatment with glass-fiber, the last ones were taken after saturation in order to explore the microstructure of this type of soil and see what happens at the microstructure.

4. Test procedure

The first stage of sample preparation is to mix the two components (sand and kaolin), to obtain a well homogenized soil. The soil is then compacted at given water content in a standard oedometric mold in one layer due to the small height of the ring (20 mm). The equipment used for the compaction procedure, which was made at the laboratory (see Fig. 4), is composed of a disk having a diameter slightly smaller than that of the ring, which is fixed to a stem of guidance and a disk shaped weight. The weight of 121 g, sliding along the stem and falling from 15 cm height, comes to strike the disk, compacting thereby the material in the oedometer ring. The total compaction energy E_c at stake for a soil specimen, being the work of the mass M (kg) at a height h (m), is expressed by the equation

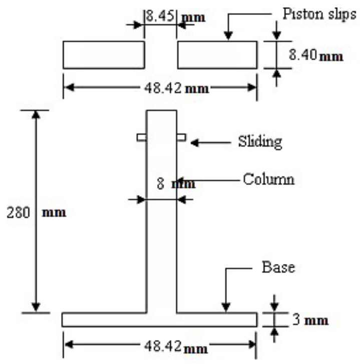


Fig. 4 Compaction tamper

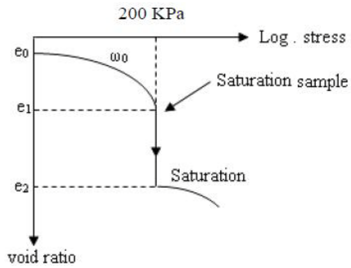


Fig. 5 Typical simple oedometer curves for a collapsing soil (Jennings and Knight 1975)

$$Ec = M\ g\ h\ n \text{ (joules)} \tag{1}$$

Where n is the number of strokes of the mass M, and g the acceleration gravity.

The oedometer tests are made according to Jennings and Knight's (1975) procedure which consists in the application of loads: 25, 50, 100 until 200 kPa, then the sample is flooded with water and a new settlement value is recorded, afterwards the loading is increased up to 400 kPa. During the test, the settlements are recorded after 15 s, 30 s, 1 min, 2 min, 5 min, 10 min and 24 h. The resulting curve of this test is shown in Fig. 5 and the collapse potential (C_P) is defined as

$$C_p\,(\%) = \left[\frac{\Delta e}{1+e_0}\right] \times 100 \tag{2}$$

$\Delta e = e_1 - e_2$,
e_1 : void ratio before flooding
e_2 : void ratio after flooding
e_0 : initial void ratio.

5. Results and discussion

5.1Test results without treatment

5.1.1 Soil's consolidation properties (*oedometer test*)

To verify the collapse of the laboratory reconstituted soil, oedometer consolidation tests were executed at different moisture content and compaction energy. The results showed that the coefficient of collapse C_p varies according to compaction from 11.95 to 7.3 for an initial water content of 2%, from 8.74 to 6.59 for an initial water content of 4% and from 7.47 to 5.26 for an initial water content of 6%. These values show a clear tendency of the untreated soil to collapse, they correspond to the variation of the state of the soil from severe to a moderate disorders according to the classification of Jennings and Knight (1975) given in Table 3.

In these tests, which were carried to verify the collapsibility of the laboratory reconstituted soil, we noted that the ratio of the instant collapse is about 80% and the remaining one occurs slowly. The sudden collapse is due probably to the elimination of the capillary tension by the addition of water, the other part (slow collapse) is caused by the impermeability of the clay bridges making links between the soil grains. This confirms the mechanisms of collapse postulated by Morgenstern and de Matos (1975), Ganeshan (1982), Knight (1961) and Booth (1975).

The influence of the variation of initial water content, for different compaction energy, is clearly visible in Fig. 6.The same observation can be noted for the compaction energy. Indeed, we notice that the value of C_p decreased with increasing energy of compaction (Fig. 7). This result confirms the work of Barden *et al*. (1969), Lefebvre and Belfadhel (1989) and Lawton *et al*. (1989).

Consequently, we can notice that the laboratory prepared soils have an analogous behavior to those met in situ.

5.1.2 Microscopic structures using (*SEM*)

The results given above were confirmed by the SEM images made on samples with 2%

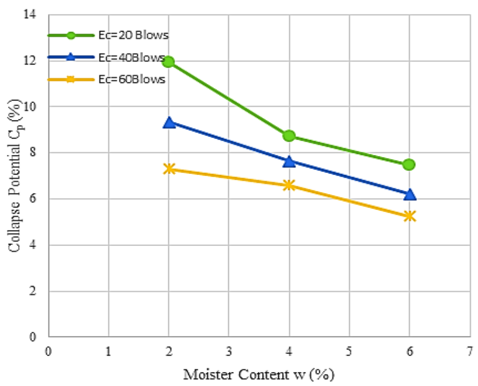


Fig. 6 Variation of the collapse potential against moister content

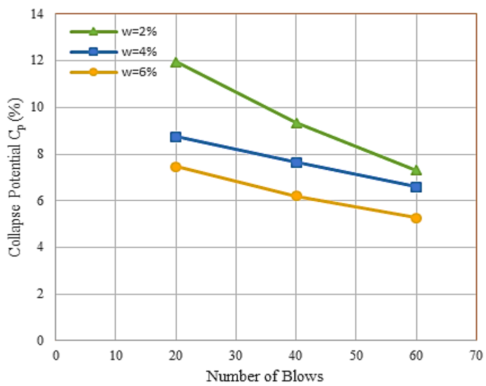
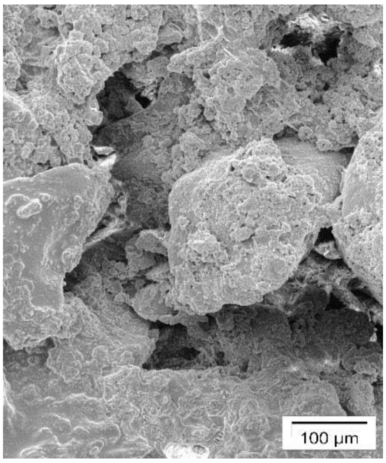
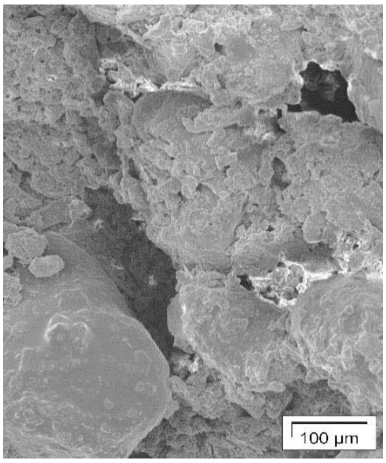


Fig. 7 Variation of the collapse potential against number of blows

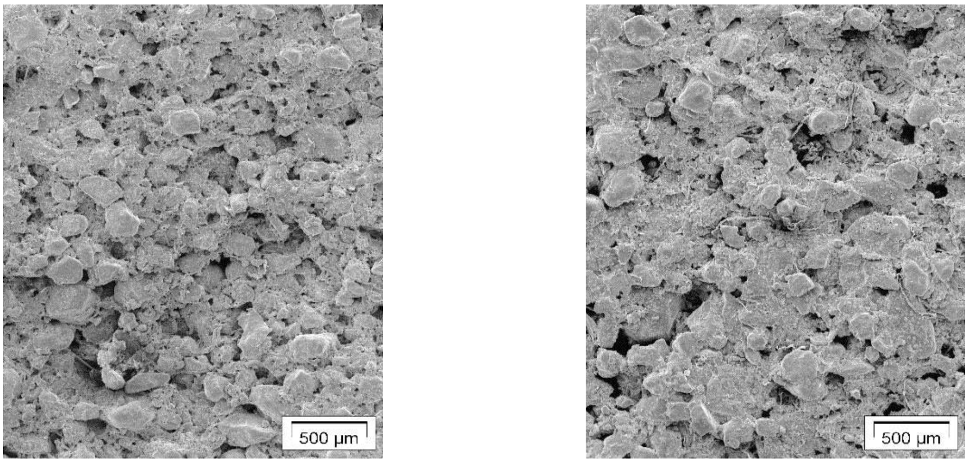


(a) w = 2%, E_c = 20 Blows, F_q = 0%



(b) w = 2%, E_c = 60 Blows, F_q = 0%

Fig. 8 SEM observation before saturation



(a) w = 2%; E_c = 20 Blows, F_q = 0% (b) w = 2%; E_c = 60 Blows, F_q = 0%

Fig. 9 SEM observation after saturation

moisture content (w) and 20 blows of compaction energy, then with w = 2% and 60 blows of compaction energy. In the obtained photos (Figs. 8(a)-(b)), we can see the loose soil structure, in which the large grains of sand are attached by fine particles composed of kaolin. The open structure of the soil is very pronounced in the first case, highlighting the importance of compaction on the reduction of the voids size.

After finishing oedometer tests, we observe the samples at the scanning electronic microscope and we see the images presented in Figs. 9(a)-(b), which show the modification occurred in the microstructure after flooding. The reduction of the voids size in both cases can be explained by the rearrangement of the granular skeleton, the elimination of capillary suction and then the destruction of clay bridges between the large grains. All this produced by the flooding of the soil.

5.2 Test results after treatment

5.2.1 Soil's consolidation properties (*oedometer test*)

The results illustrated by Figs. 10, 11 and 12, represent the variation of the collapse potential (C_p) against the treatment of the soil with different percentage of glass-fiber at different moister content.

We notice for the addition of 3% of glass-fiber a little decrease of the collapse, C_p decreases of 14.7% for 2% of water content and compaction energy of 20 blows, until reaching 48.12% for the same previous water contents and a compaction energy of 60 blows. For the addition of 6% of glass-fiber, C_p decreases of 55.2% for 2% of water content and a compaction energy of 20 blows, until 70.88% for the same previous water contents and a compaction energy of 60 blows (Fig. 10). That is to say, that soil state passes from severe to moderate disorders according to the classification of Jennings and Knight (1975), given in Table 3.

When the water content is 4% (Fig. 11), the results of treatment by 3% and 4% of glass-fiber (energy of compaction of 20 blows) seem to be close. The results go then from a decrease of 7.67% of C_p, for 3% of glass-fiber (F_q) and 20 blows, until reaching 8.12% for 4% of F_q and 20 blows as compaction energy. The same remark can be done for the treatment with 5% and 6% of glass fiber for 40 blows of compaction energy.

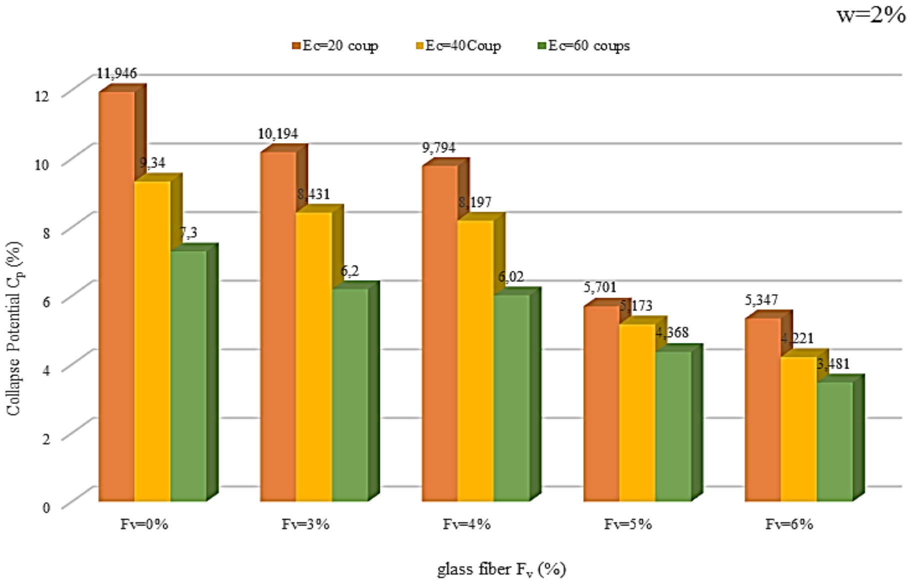


Fig. 10 The collapse potential of soils compacted at various number of blow against glass fiber contents (w = 2%)

For 6% of water content (Fig. 12), the collapse becomes insignificant until it vanishes from treatment with 5% of glass fiber especially for 60 blows of compaction energy. The C_p value is 1.62% for 6% of glass fiber and 60 blows.

According to the obtained results, we can notice clearly the influence of the treatment of the

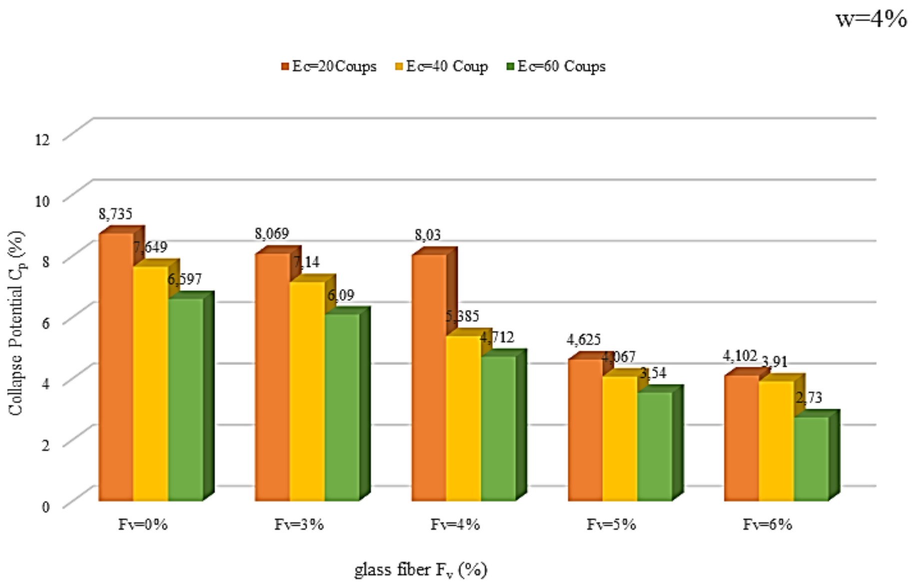


Fig. 11 The collapse potential of soils compacted at various number of blow against glass fiber contents (w = 4%)

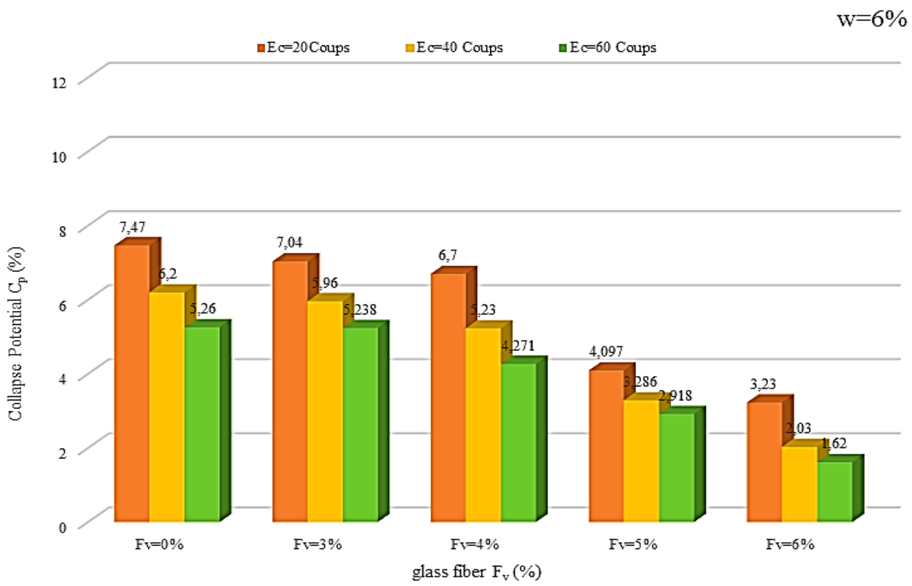


Fig. 12 The collapse potential of soils compacted at various number of blow against glass fiber contents, w = 6%

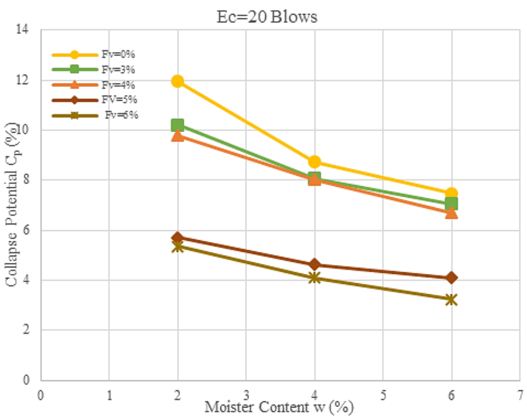


Fig. 13 The collapse potential of soils treated with glass fiber versus initial moister content (E_c = 20 blows)

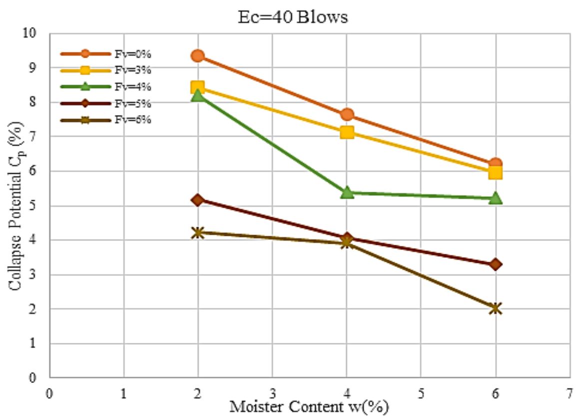


Fig. 14 The collapse potential of soils treated with glass fiber versus initial moister content (E_c = 40 blows)

soil by glass-fiber and its efficiency in reducing, or eliminating the danger of collapse of the soil and therefore structures built on it.

Figs. 13, 14 and 15, present the variation of the collapse potential C_p of soils treated with the milled glass fiber versus initial moister content under different compaction energy. In each one of these figures we can remark that the effect of the treatment can be appreciate when its amount is by 5%, then 6%. The value of the collapse is then 1.62%, which Jennings and Knight (1975), classify as a soil with moderate disorder. We can also note that the collapse decreased for increasing energy of compaction and water content.

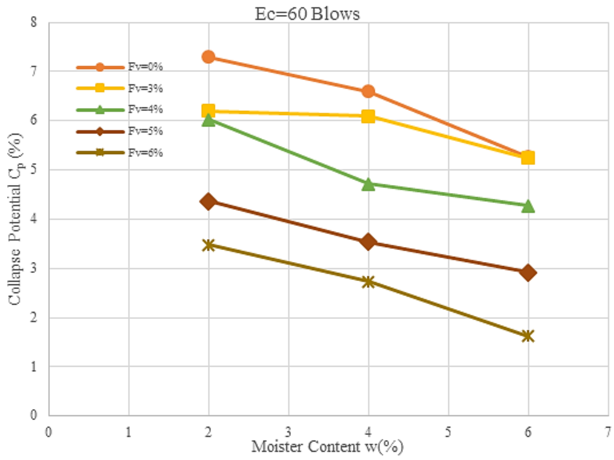


Fig. 15 The collapse potential of soils treated with glass fiber versus initial moister content (E_c = 60 blows)

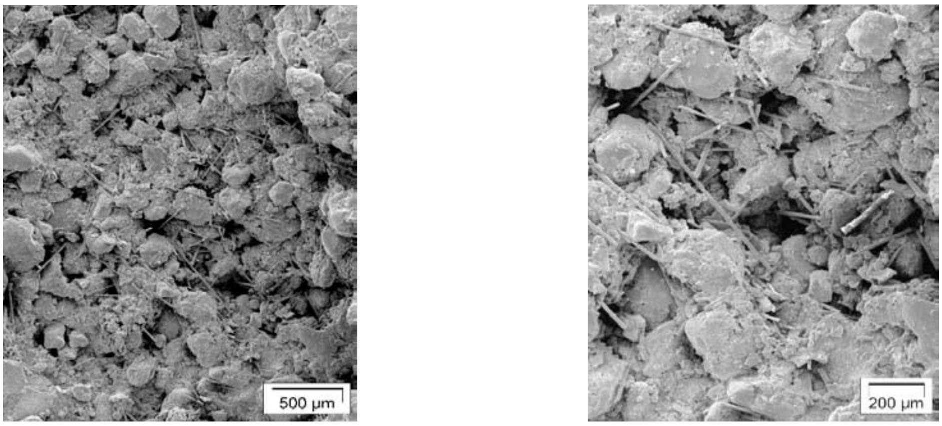


Fig. 16 SEM observation before saturation with (F_q = 2%; w = 2%; E_c = 60 blows)

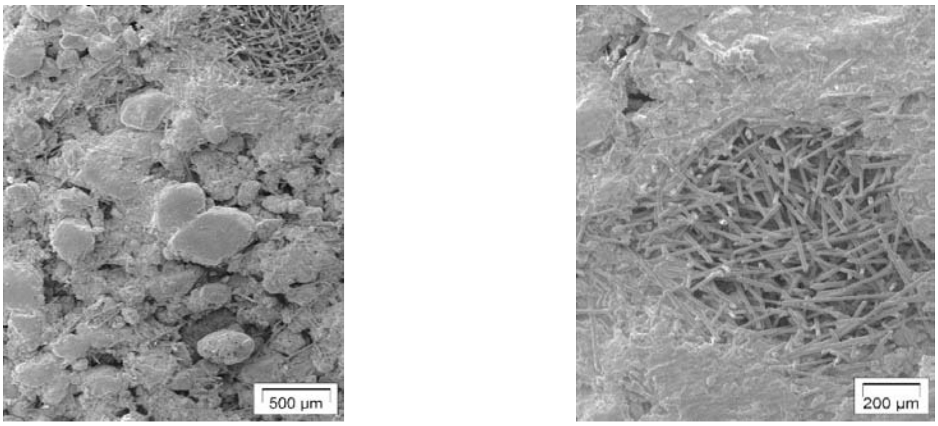


Fig. 17 SEM observation before saturation with (F_q = 4%; w = 6%; E_c = 60 blows)

5.2.2 Microscopic structures (*SEM*)

In the SEM photos (Fig. 16), for the case of the treatment by 2% of milled glass-fiber for a soil with 2% moisture content and a compaction energy of 60 blows, we can say that probably the distribution of glass-fiber in the area confers the soil a certain resistance, decreasing consequently the risk of collapse. In the photo taken for 4% of glass-fiber and 6% of moisture content (Fig. 17), the image shows clearly the tangle of glass-fiber, their gathering in the empty spaces and their distribution on the remaining part in order to make the soil more resistant.

6. Conclusions

In this work, soil samples were prepared at the laboratory with 80% sand and 20% kaolin, they were treated with different percentages of glass-fiber in order to improve their mechanical characteristics and to eliminate the collapse problem. The interpretation of the results of this study leads to the following conclusions:

- The results of physical and mechanical tests show that the laboratory reconstituted soil, with a water content lower than the optimum of Proctor and moderate compaction energy, manifests the same physical and mechanical characteristics of a natural collapsible soil.
- Photos taken by the scanning electron microscope SEM, show the porous loose structure of the collapsible soil before saturation, and a condensed state after flooding with no supplementary charge.
- Mechanical tests clearly show the variation of the collapse according to the augmentation of water content percentage and compaction energy.

The oedometer results confirm the efficiency of the treatment with the glass fiber, and show that we can get a soil with moderate disorders since adding 5% of glass fiber at different cases of water content and compaction energy. Then we can conclude that for the evolution of the reduction of collapse with the addition of glass fiber, soil without disorder can be obtained for a treatment upper to 6%.

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