4
Results and Analysis

In this chapter the results and analysis of the tests performed in this research will be presented, with the pure soil and the PET-soil mixtures. These results will help a better comprehension of the mechanic characteristics of the soil mixtures, and how the addition of fine crushed PET and PET flakes could improve the strength parameters.

4.1
Physic Characterization Tests

4.1.1
Sand

4.1.1.1
Physics Index

The material studied is characterized as an average sand, clean and with uniform particle size. During the material characterization, it was not observed the presence of organic material. The physics index are shown on Table 4.1.

Table 4.1 – Physics index of the sand.

Physics Index	**Sand**
Specific Weight (Gs)	2,65
Uniformity Coefficient (*Cu*)	1,76
Coefficient of Curvature (*Cc*)	1,1
Effective Diameter (D_{10})	0,33 mm
Average Diameter (D_{50})	0,55 mm
Minimum voids index (e_{min})	0,51
Maximum voids index (e_{max})	0,74

4.1.1.2
Particle Size Test

The particle size test has the aim to obtain the constituent fractions of the soil and so its classification. The Figure 4.1 presents the particle size curve.

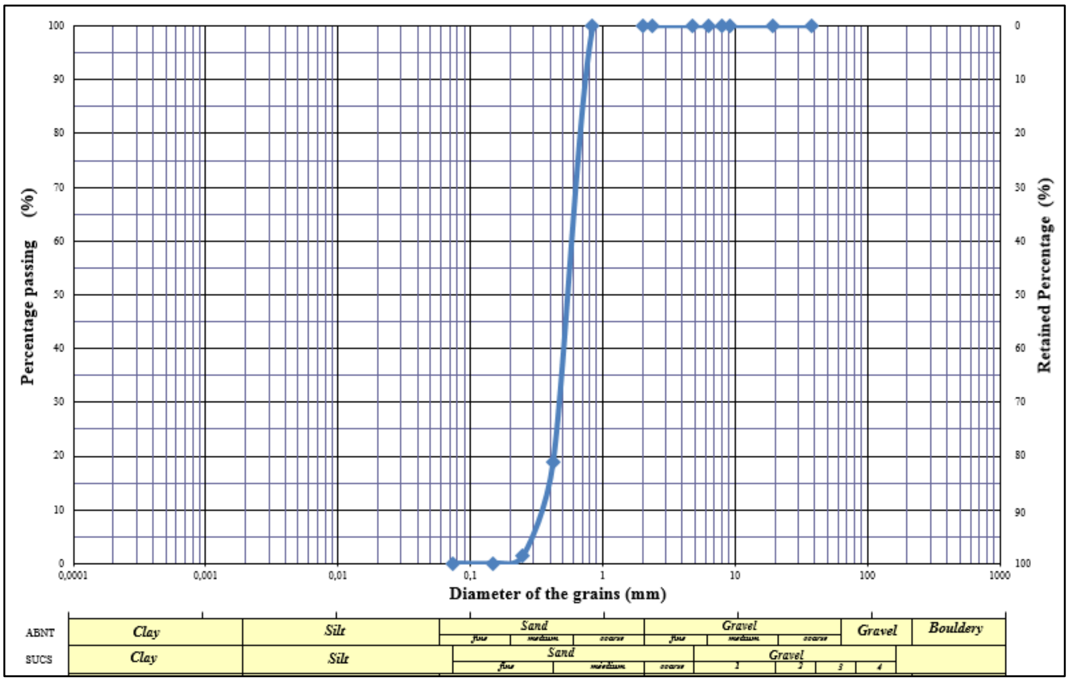

Figure 4.1 - Particle size curve of the sand.

According to the Unified System of Soil Classification (SUCS), the sand that shows less than 5% of fines, presenting Cu < 6 and/or Cc < 3, as the material used, are classified as SP, so it is a poorly graded sand.

4.1.2
Clayey Soil

4.1.2.1
Specific Weight (Gs)

The value of Gs for the clayey soil was obtained through the arithmetic average for determinations, and the maximum variation was 1,1%. The value of Gs found was 2,72.

4.1.2.2
Particle Size Test

For samples located at similar depths, the percentages of material that pass through the #200 sieve and the ones that are retained, are about the same. Figure 4.2 shows the particle size curve of the clayey soil.

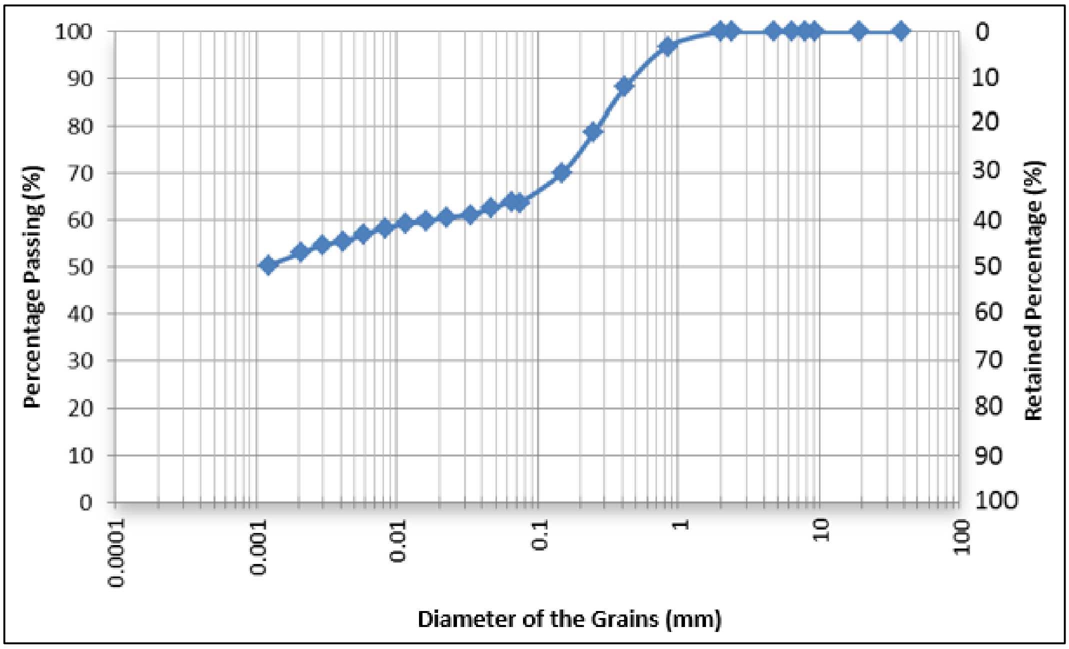

Figure 4.2 - Particle size curve of the clayey soil.

4.1.2.3
Atterberg Limits

Through the results achieved in the laboratory for the clayey soil, it was found a Liquid Limit of 53% and a Plastic Limit of 39%, resulting in a Plastic Index (IP = LL – PL), equal to 14%. According to the Unified System of Soil Classification (SUCS), the studied soil is classified as CH, corresponding to a sandy clay with medium plasticity.

4.1.3 Bentonite

4.1.3.1 Specific Weight (Gs)

The value of Gs for the Bentonite was obtained through the arithmetic average of for determinations, and the maximum variation was 1,1%. The value of Gs found was 2,90.

4.1.3.2 Particle Size Test

The particle size curve of the bentonite, was reached through the sedimentation test and it is presented in the Figure 4.3.

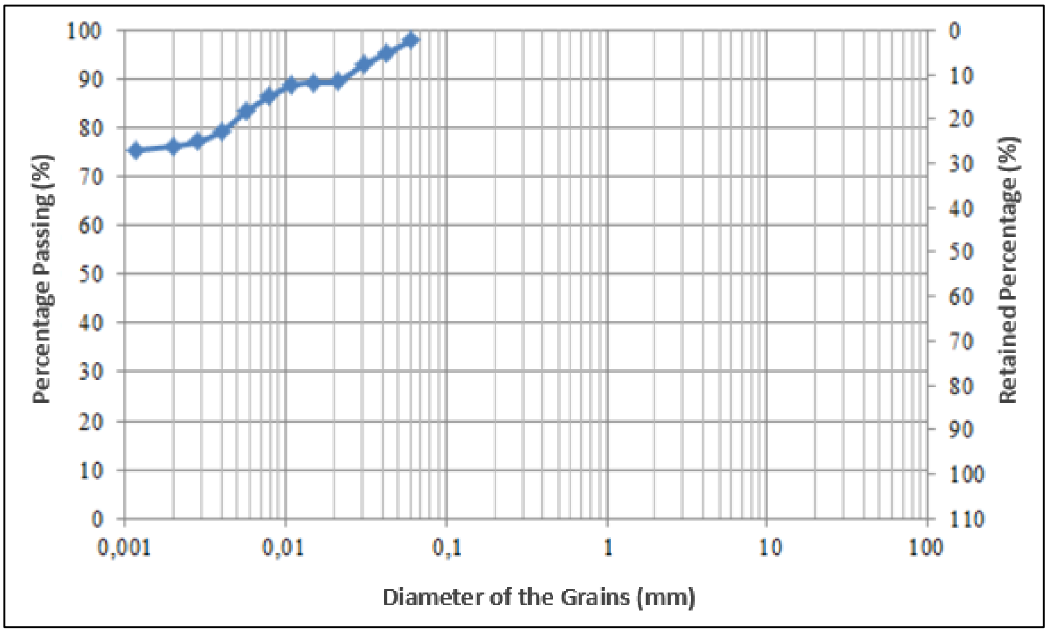

Figure 4.3 - Particle size curve of the bentonite.

4.1.3.3 Atterberg Limits

Through the results achieved in the laboratory for the clayey soil, it was found a Liquid Limit of 368,4% and a Plastic Limit of 53,7%, resulting in a Plastic Index (IP = LL – PL) equal to 314,7%.

4.1.4
Fine Crushed PET

4.1.4.1
Physics Index

The fine crushed PET studied is characterized as very thin material, which came from a micronization process. The physics index are shown on Table 4.2.

Table 4.2 - Physics index of the fine crushed PET.

Physics Index	Fine Crushed PET
Specific Weight (Gs)	1,44
Uniformity Coefficient (*Cu*)	14
Coefficient of Curvature (*Cc*)	4,6
Effective Diameter (D_{10})	0,01 mm
Average Diameter (D_{50})	0,12 mm
Minimum voids index (e_{min})	0,69
Maximum voids index (e_{max})	1,27

4.1.4.2
Particle Size Test

The particle size curve of the fine crushed PET and PET flakes, was reached through the screening test, once the material is very light, it was not possible to perform the sedimentation test on it. The particle size curve is presented in the Figure 4.4.

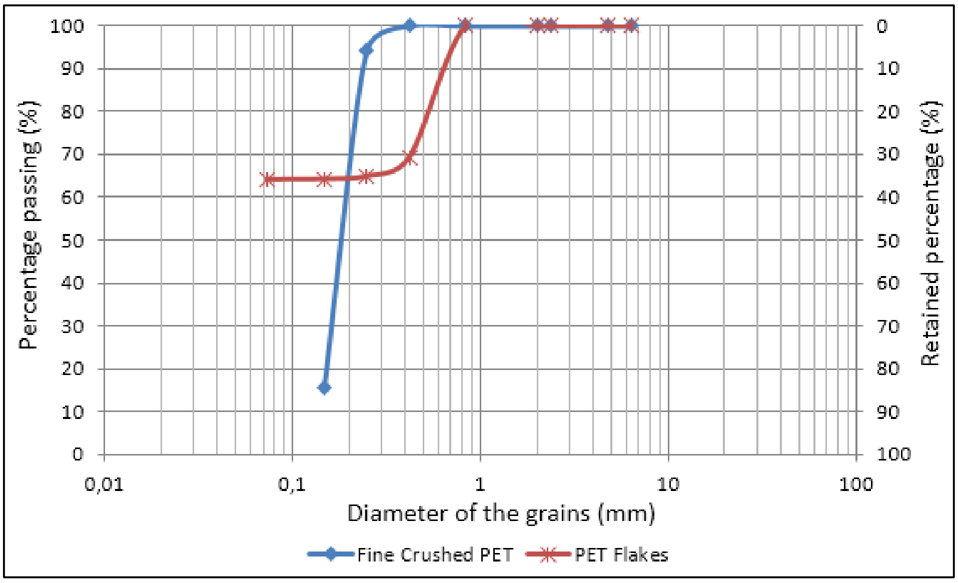

Figure 4.4 - Particle size curve of the fine crushed PET and PET flakes.

4.2
Chemical Characterization Tests

The tests of chemical composition were carried out in the laboratory of the Department of Chemical Engineering from PUC-Rio. They were performed for the fine crushed PET and for the mixture S70P30, and the results are presented in terms of the oxides and also by the chemical elements. The results were compared with the values determined in the Brazilian standard NBR 10004:2004 and no hazard material was found and also none of the substances have the contents above the ones established by the standard.

The Table 4.3 shows the results of the chemical analyses in term of oxides for 30g of pure fine crushed PET.

Table 4.3 - Chemical Analysis in terms of oxides for the PET.

Chemical Compound	Name	Quantity (%)
SiO_2	Silicon Dioxide (Silica)	0,223
SO_3	Sulfur Trioxide (Sulfuric Oxide)	0,198
CaO	Calcium Oxide (Lime)	0,017
Cl	Chlorine	0,015
Fe_2O_3	Iron Oxide (Hematite)	0,013
Tm_2O_3	Thulium Oxide	0,006
CuO	Copper Oxide	0,003
$(C_{10}H_8O_4)n$	Polyethylene Terephthalate	99,524

In the same sample was also performed the chemical analysis in terms of the chemical element separately (Table 4.4).

Table 4.4 - Chemical analysis in terms of the chemical elements for the PET.

Chemical Element	Name	Quantity (%)
S	Sulfur	0,223
Si	Silicon	0,198
Cl	Chlorine	0,017
Ca	Calcium	0,015
Fe	Iron	0,013
Tm	Thulium	0,006
Cu	Copper	0,003
C	Carbon	99,524

It was also performed the chemical analyses in terms of oxides for 30g of the mixture C70P30 and the results are shown in Table 4.5. It is relevant to highlight that the equipment used in the tests, joins the result of substances that have carbon in their composition and also water, resulting in a high percentage of the CH element.

Table 4.5 - Chemical Analysis in terms of oxides for the mixture C70P30.

Chemical Compound	**Name**	**Quantity (%)**
Al_2O_3	Aluminum Oxide	15,729
SiO_2	Silicon Dioxide (Silica)	12,758
Fe_2O_3	Iron Oxide (Hematite)	2,311
SO_3	Sulfur Trioxide (Sulfuric Oxide)	0,327
TiO_2	Titanium Dioxide	0,276
CaO	Calcium Oxide (Lime)	0,059
K_2O	Potassium Oxide	0,052
V_2O_5	Vanadium Pentoxide	0,018
ZrO_2	Zirconium Dioxide (Zirconia)	0,012
ZnO	Zinc Oxide	0,007
CuO	Copper Oxide	0,007
CH	Organic Matter, PET, Carbon, Water	68,443

As well as in the PET, for same sample of C70P30, was also performed the chemical analysis in terms of the chemical element separately (Table 4.6).

Table 4.6 - Chemical analysis in terms of the chemical elements for the mixture C70P30.

Chemical Element	**Name**	**Quantity (%)**
Al	Aluminum	2,319
Si	Silicon	1,903
Fe	Iron	0,834
Ti	Titanium	0,085
S	Sulfur	0,048
K	Potassium	0,021
Ca	Calcium	0,021
V	Vanadium	0,005
Zr	Zirconium	0,005
Zn	Zinc	0,003
Cu	Copper	0,003
C	Carbon	99,752

4.3
Mechanical Characterization Tests

4.3.1
Standard Compaction Test

4.3.1.1
Clayey Soil

The Figure 4.5 and Figure 4.6 show the standard compaction curves for the clayey soil and the mixtures. It can be noticed that, the insertion of the fine crushed PET decreases the maximum specific dried mass of the material.

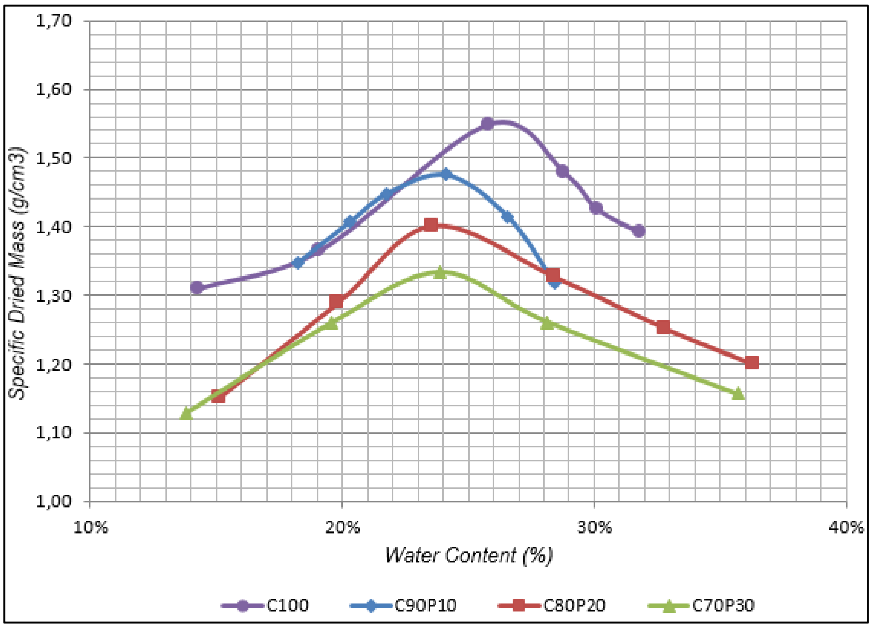

Figure 4.5 - Standard compaction curves of the clayey soil and the fine crushed PET mixtures.

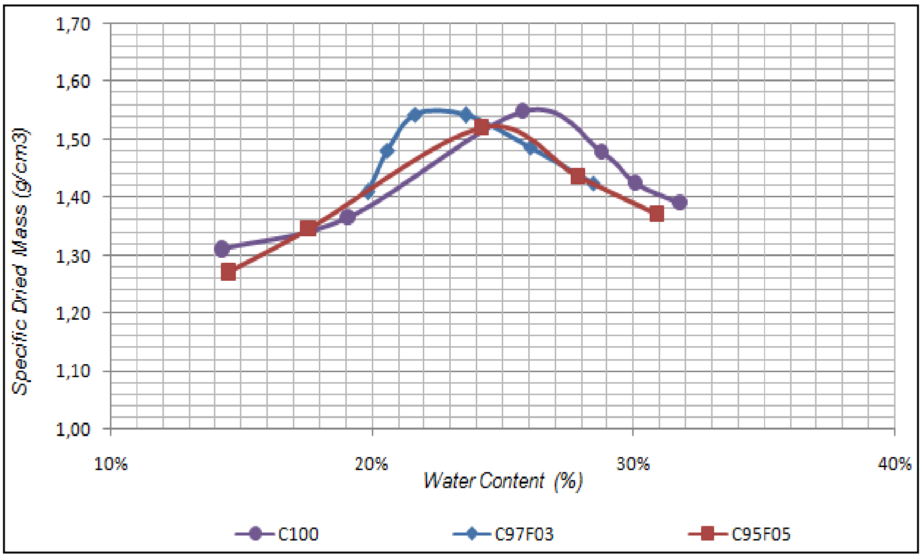

Figure 4.6 - Standard compaction curves of the clayey soil and the PET flake mixtures.

In the Table 4.7 is summarized the results of moisture content and specific dried mass for the clayey soil and mixtures, found through the analysis of the graphics.

Table 4.7 - Results of standard compaction test for the clayey soil and mixtures.

Material/Mixture	**Moisture Content (%)**	**Maximum Specific Dried Weight (g/cm^3)**
C100	26,5	1,55
C90P10	24,1	1,48
C80P20	23,6	1,40
C70P30	23,5	1,33
C97F03	22,3	1,55
C95F05	24,0	1,52

This clayey soil was also studied by other authors, such as, Ramírez (2012), Szeliga (2011), Quispe (2013), Calheiros (2013) and Beneveli (2002) it was noticed the same behavior in the standard compaction test as the ones found in this research.

4.3.2
Triaxial Tests (CID)

The triaxial test (CID) was performed for the soils and mixtures samples. The sand was mixed with 10 and 20% of the fine crushed PET and the clayey soil was mixed with 10, 20 and 30% of fine crushed PET and 3 and 5% of PET flakes, all the contents were calculated in relation to the dry weight of the soil. The effective stresses applied in all cases were 50, 150 and 300 kPa.

The stress paths, the strength envelopes and shear strength parameters of all materials will be presented in this section, as well as an analysis of the influence of the insertion of the fine crushed PET and the PET flakes in the shear behavior of the soil.

4.3.2.1 Sand and fine crushed PET

i. Deviator Stress and Volumetric Variation vs Axial Strain Behavior

In Figure 4.7, are presented the curves of deviator stress (σ_d) and volumetric variation (ε_v) versus axial strain (ε_a), which correspond to the triaxial (CID) tests performed in a series of mixtures with confining stress of 150kPa, in order to find an initial percentage of PET.

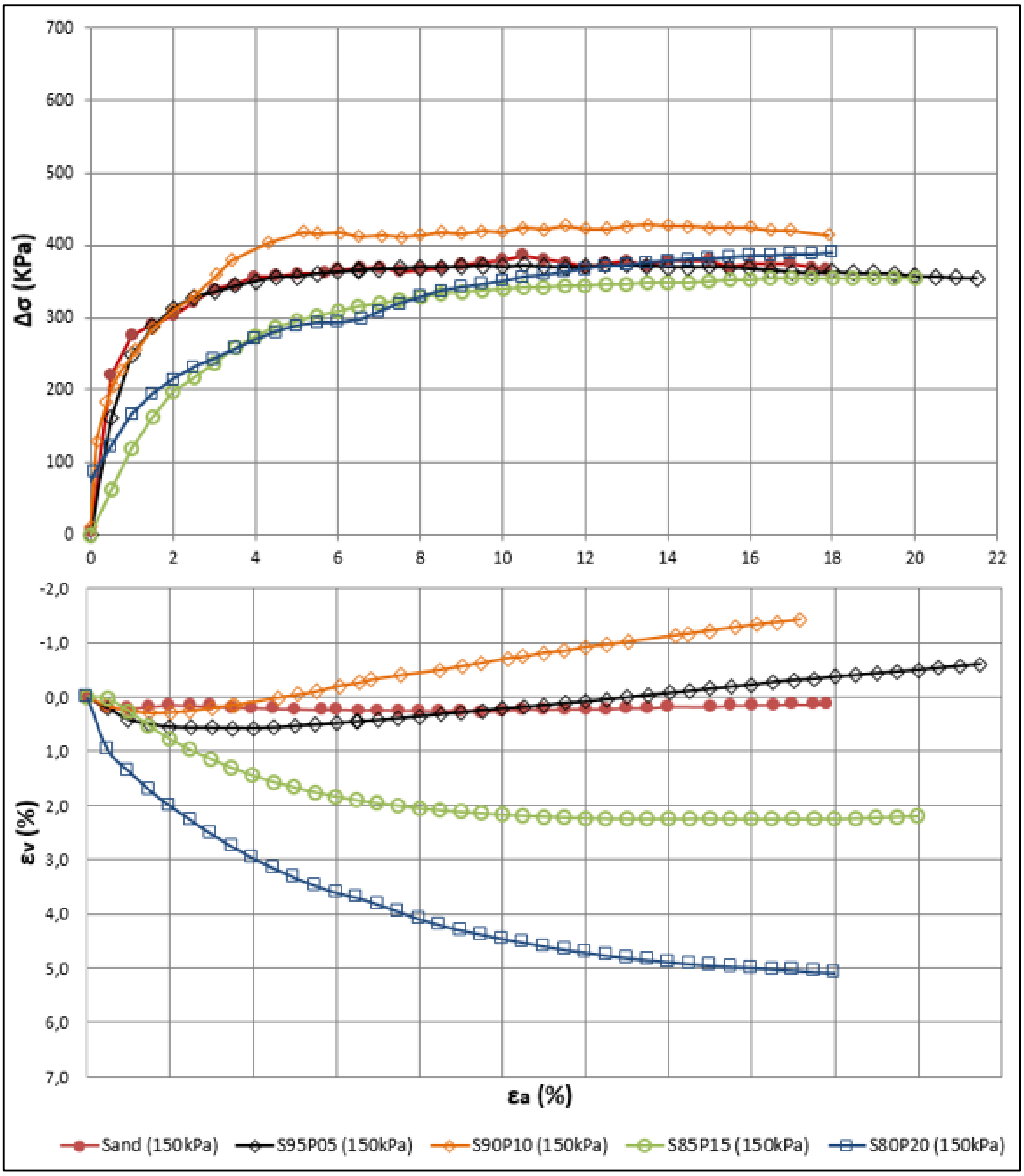

Figure 4.7 - Curves of deviator stress (σd) and volumetric variation (εv) versus axial strain (εa) for the sand and mixtures in triaxial tests.

In Figure 4.8, are presented the curves of deviator stress (σ_d) and volumetric variation (ε_v) versus axial strain (ε_a), which correspond to the triaxial (CID) tests performed in the sand and in the mixture S90P10 with confining stress of 50, 150 and 300kPa.

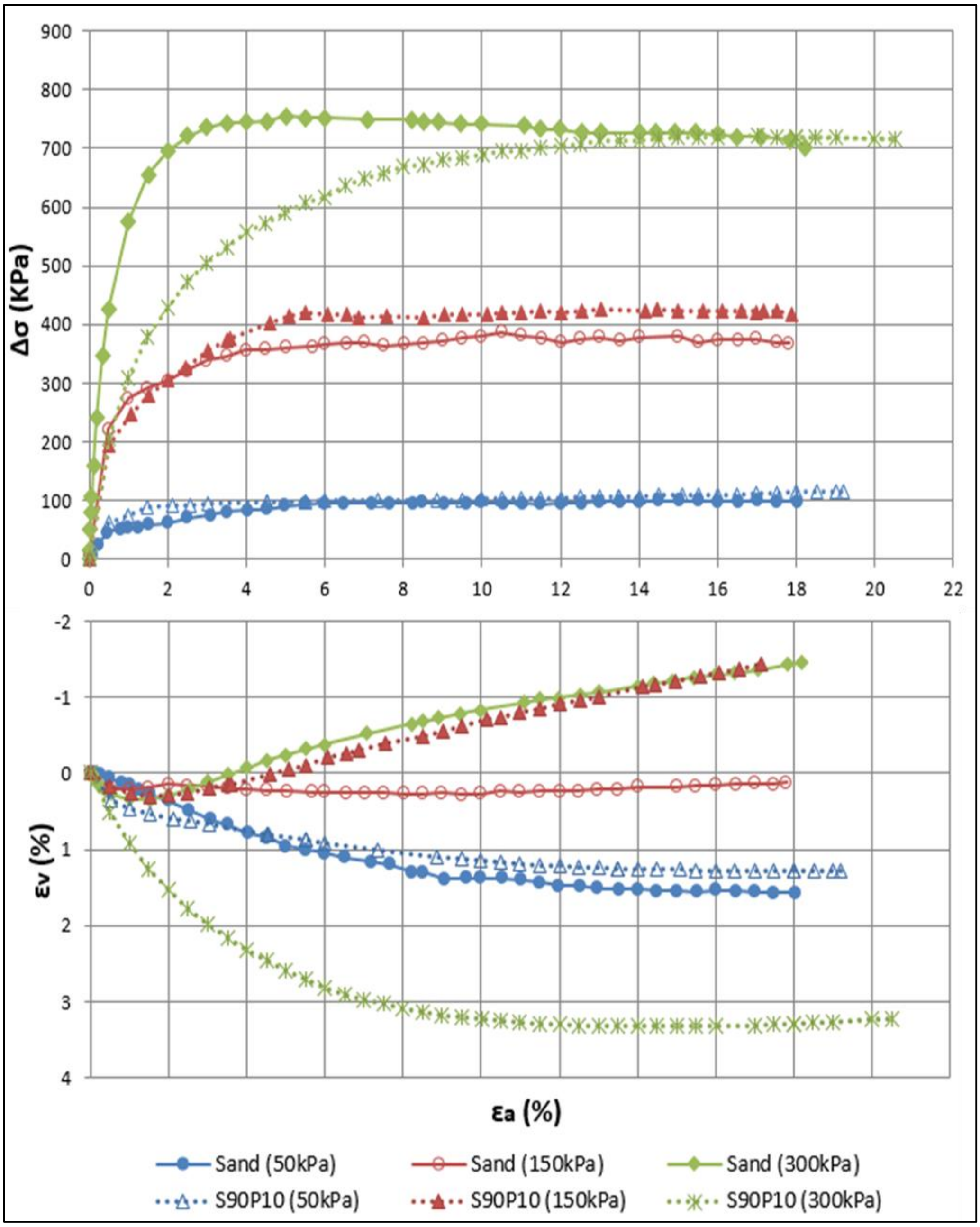

Figure 4.8 - Curves of deviator stress (σd) and volumetric variation (εv) versus axial strain (εa) for the sand and S90P10 in triaxial tests.

In Figure 4.9, are presented the curves of deviator stress (σ_d) and volumetric variation (ε_v) versus axial strain (ε_a), which correspond to the triaxial (CID) tests performed in the sandy soil and in the mixture S80P20 with confining stress of 50, 150 and 300kPa.

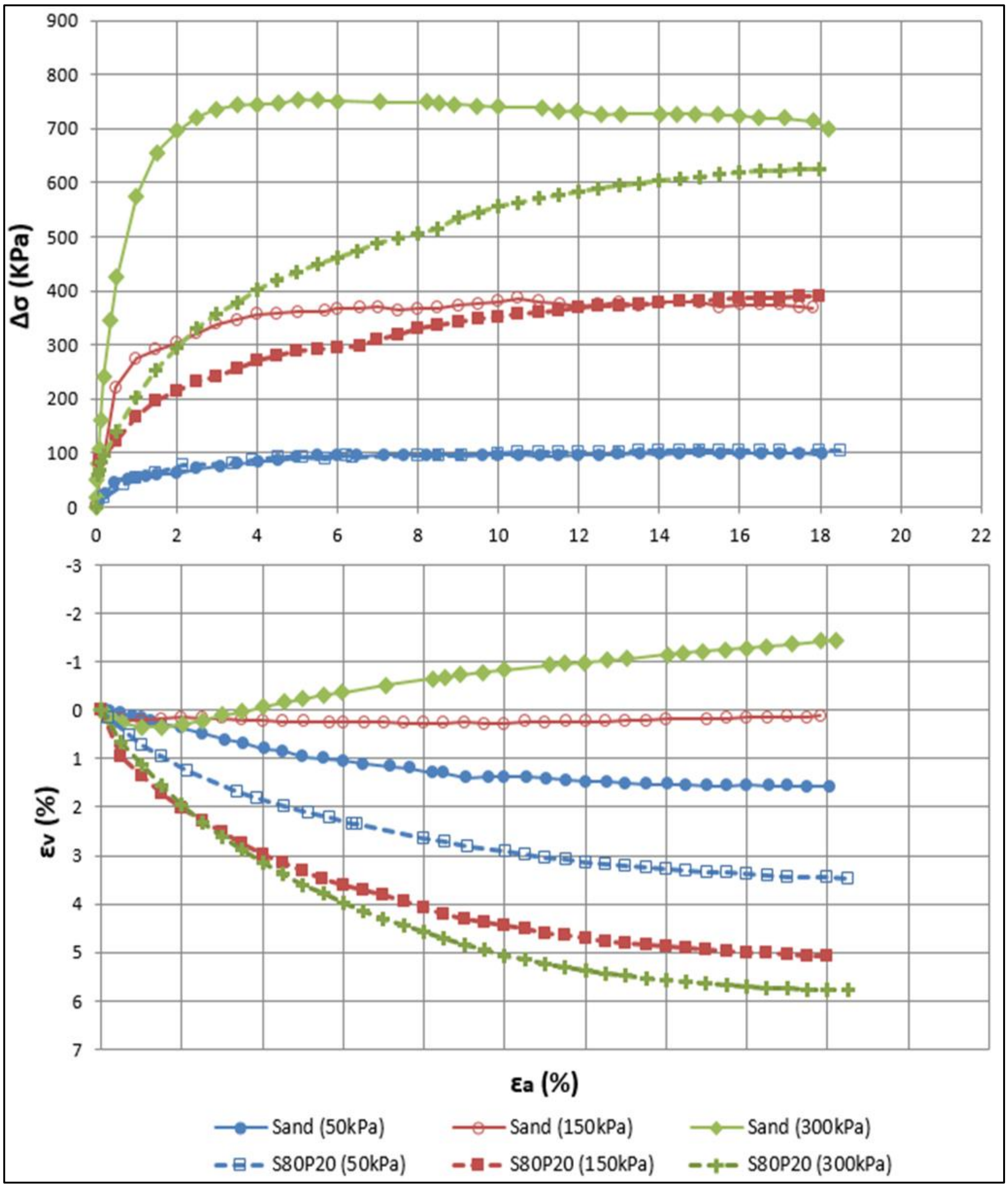

Figure 4.9 - Curves of deviator stress (σd) and volumetric variation (εv) versus axial strain (εa) for the sand and S80P20 in triaxial tests.

ii. Influence of the Fine Crushed PET content in the Sand.

The behavior of deviator stress (σ_d) and volumetric variation (ε_v) versus axial strain (ε_a), which correspond to the triaxial (CID) tests performed in the sandy soil and in the mixtures, are presented in the Figure 4.10.

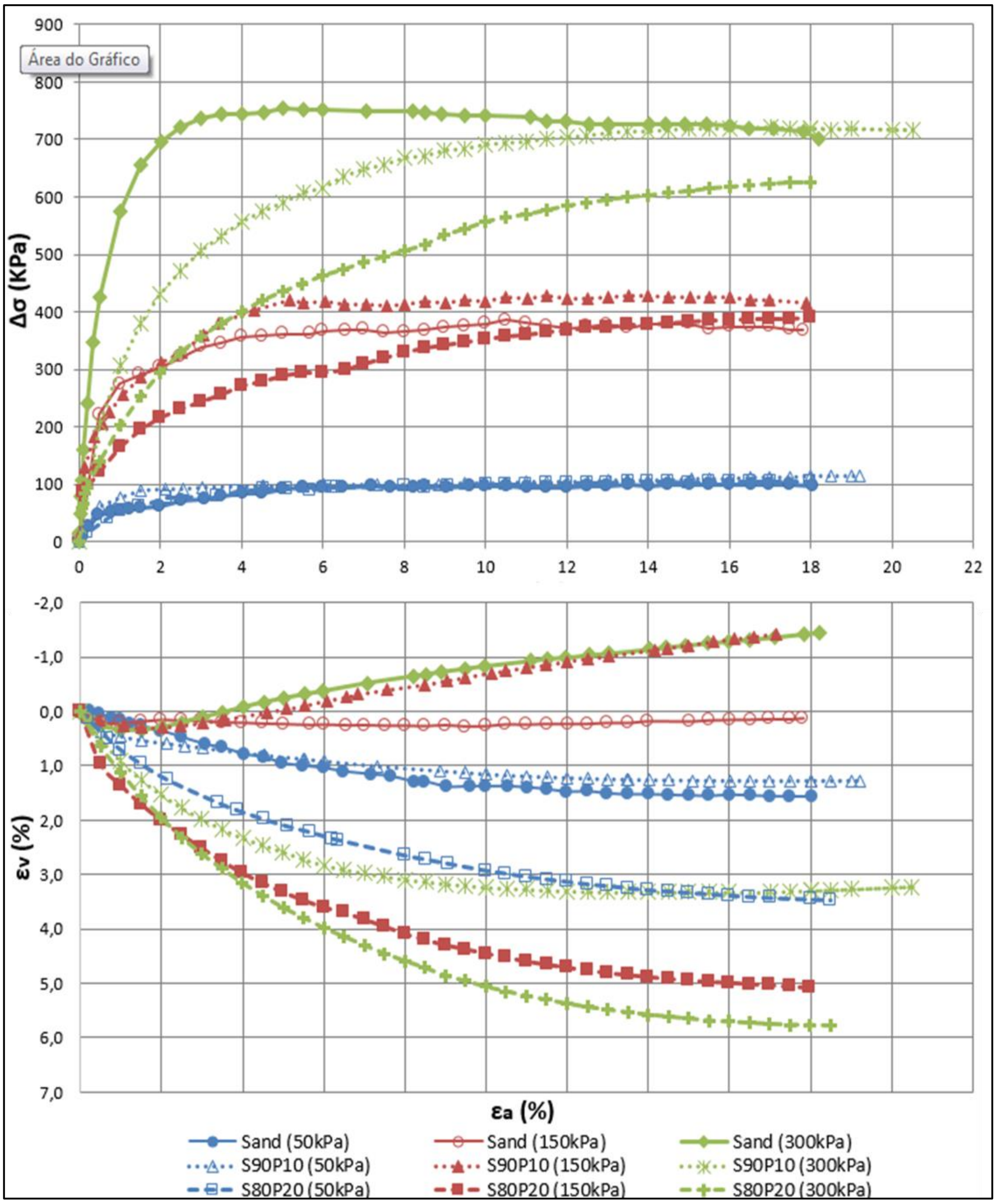

Figure 4.10 - Curves of deviator stress (σd) and volumetric variation (εv) versus axial strain (εa) for the sand and mixtures in triaxial tests.

It is observed that for higher confining stress (300kPa) the addition of fine crushed PET did not improve the behavior of the soil in lower strain, however after 14% of axial strain, the mixture S90P10 tends to equalize with the pure soil having the same strength at 18% of axial strain. The mixture S80P20 had the same behavior as the mixture S90P10 comparing with the sandy soil, but it did not reach the same strength at 18% of axial strain. None of the materials have a well-defined peak strength. Through the curve of volumetric strain versus axial strain can be noticed that, the pure soil firstly decreased the volume and then after 4% of axial strain it starts to increase. On the other hand the mixtures (S90P10 and S80P20) suffered a continuous decreasing in the volume.

For confining stress of 150kPa, the sandy soil and the mixtures had no well-defined peak strength. At this level of confinement the mixture S90P10 presented a better behavior than the pure soil, supporting higher loads at smaller and bigger strains. The behavior of the mixture S80P20 only equalizes with the sandy soil after 13% of strain. About the volumetric strain, the pure soil remained with almost no volume changes, while the mixture S90P10 suffers a shrinkage at the begging and after 5% it starts to swell.

At the confining stress of 50kPa the sandy soil and the mixtures have the same behavior, reaching the same value deviator stress at the same level of axial strain. In the curves of volumetric strain versus axial strain they all suffer a swell, where the sandy soil and the mixture S90P10 had a smaller swell than the mixture S80P20.

A possible explanation to these phenomena, where the mixtures did not improve the behavior of the sandy soil, is related to the shape and interaction between the grains of sand and fine crushed PET. As the tests were performed in a beach sand, it was observed through a microscopy that the sand’s grains are very rounded, that explain the lack of interaction between them and the fine crushed PET. The material added do not react with the soil creating a cementation process, it fill the voids of the soil, but the poor interaction among the particles does not help the bearing capacity of the soil. In a lower confining stress the fine crushed PET are not direct in contact with the particles of the pure soil, so there are more soil-soil interaction, what explains why the curves from the soil and the mixtures have the same behavior. However, the opposite happens with higher confining stress, where there are contact soil-PET, the sand’s particles are too rounded, so they do not interact properly with the fine crushed PET particle, causing the decrease in the support capacity of the mixture.

iii. Envelopes and Shear Strength Parameters

The Figure 4.11, 4.12 and 4.13 show the shear strength parameters of Mohr-Coulomb criterion and the strength envelopes, plotted in the p':q space, of the sandy soil and the mixtures. Because of the different behavior of the materials and also the lack of peak strength, all the envelopes were plotted at 18% of axial strain, once the materials have the tendency to equalize at higher strains and it was able to reach this level of strain in all tests.

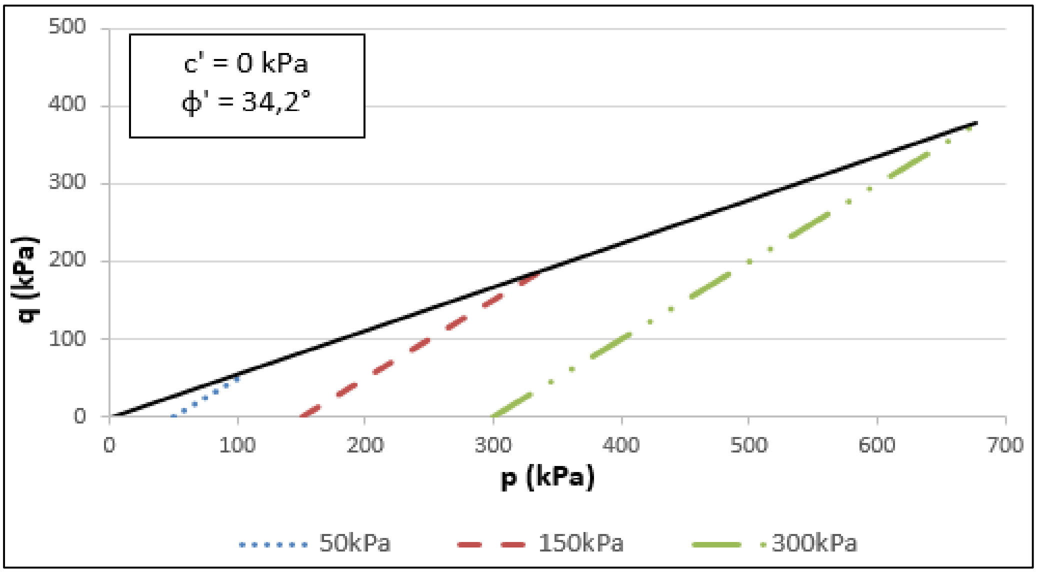

Figure 4.11 - The shear strength parameter and the strength envelope of the sand.

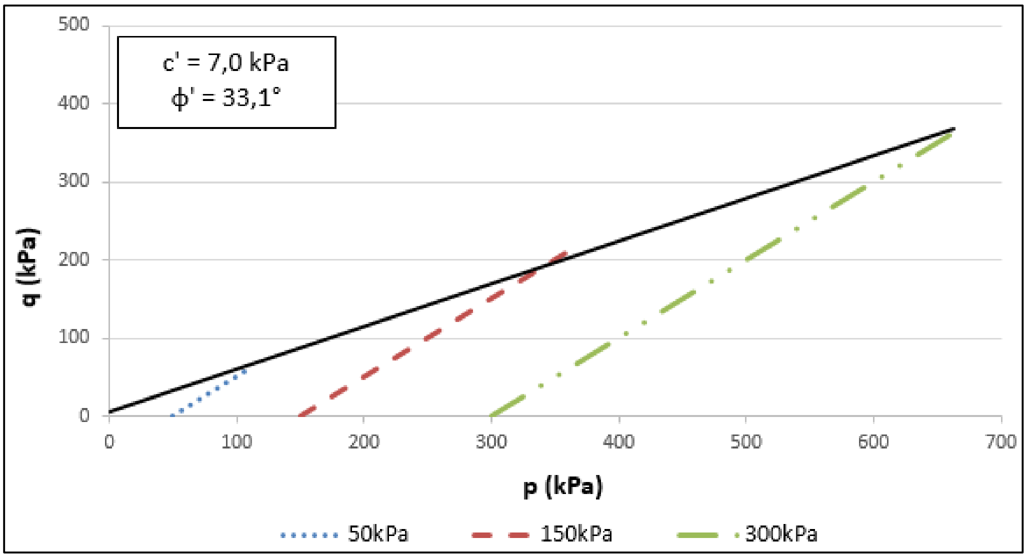

Figure 4.12 - The shear strength parameter and the strength envelope of the mixture S90P10.

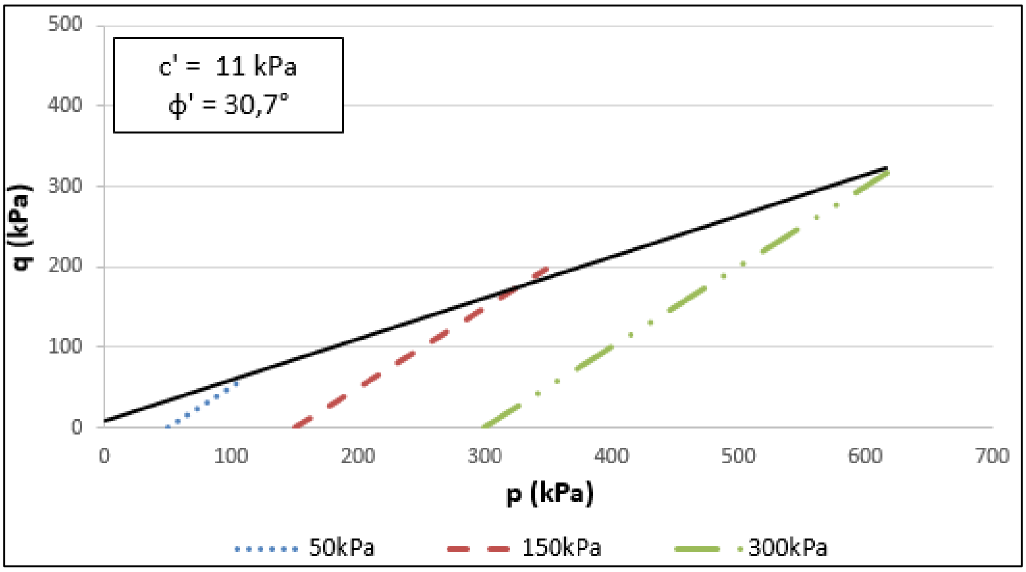

Figure 4.13 - The shear strength parameter and the strength envelope of the mixture S80P20.

The Table 4.8 summarizes the values of cohesion and friction angle of the pure soil and the mixtures at 18% of strain.

Table 4.8 - Results of shear strength parameters for the sandy soil and mixtures.

Material/Mixture	Cohesion (kPa)	Friction Angle (°)
S100	0	34,2
S90P10	7,0	33,1
S80P20	11,0	30,7

It can be inferred from the graphics that, as much as the amount of PET is raised, an improvement in the cohesion is observed, and consequently the values of friction angle decrease.

Although the insertion of fine crushed PET has raised the value of cohesion, it weakened the bearing capacity of the soil. Because the fine crushed PET has more angled particles and also it fills the remaining gaps in the soil, it helps the improvement in the cohesion, and on the other hand a slight decrease happens in the friction angle.

The mixture S90P10 has the best relation between the improvement of the parameter and the load capacity of the soil, where the cohesion increased from 0kPa to 7kPa and the friction angle has just decreased 1 degree (approximately 3,5% of decrease). It can be noticed that for the mixture S90P10 at 300kPa of confining stress, the behavior of the mixtures has more tendency to reach the pure soil at higher strains, and even overpassing at 150kPa, showing that even though the bearing capacity decreased, the strength parameters did not suffer a major change.

4.3.2.2
Clayey Soil and Fine Crushed PET

i. Deviator Stress and Volumetric Variation vs Axial Strain Behavior

In Figure 4.14, the curves of deviator stress (σ_d) and volumetric variation (ε_v) versus axial strain (ε_a) are presented, which correspond to the triaxial (CID) tests performed in the clayey soil and in the mixture C90P10 with confining stress of 50, 150 and 300kPa.

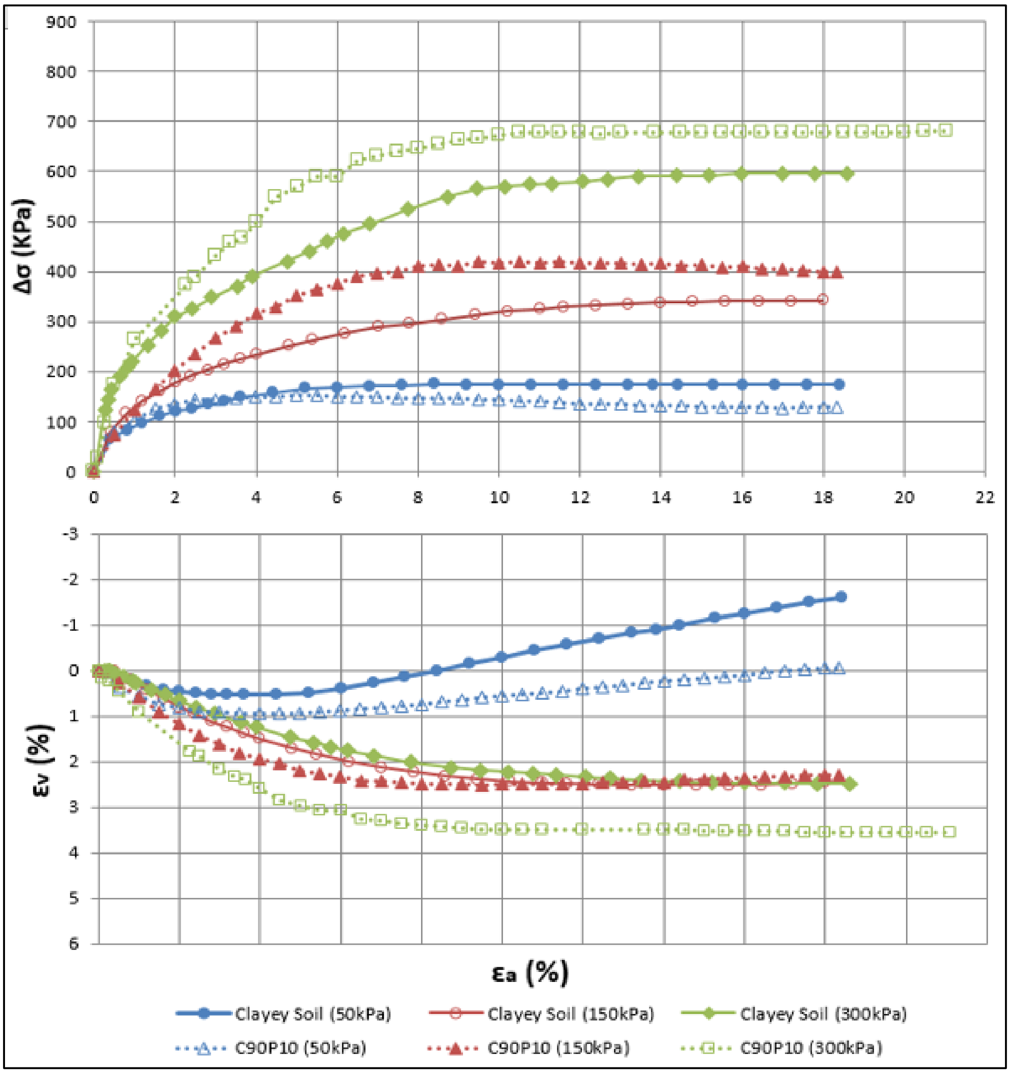

Figure 4.14 - Curves of deviator stress (σd) and volumetric variation (εv) versus axial strain (εa) for the clayey soil and C90P10 in triaxial tests.

In Figure 4.15, the curves of deviator stress (σ_d) and volumetric variation (ε_v) versus axial strain (ε_a) are presented, which correspond to the triaxial (CID) tests performed in the clayey soil and in the mixture C80P20 with confining stress of 50, 150 and 300kPa.

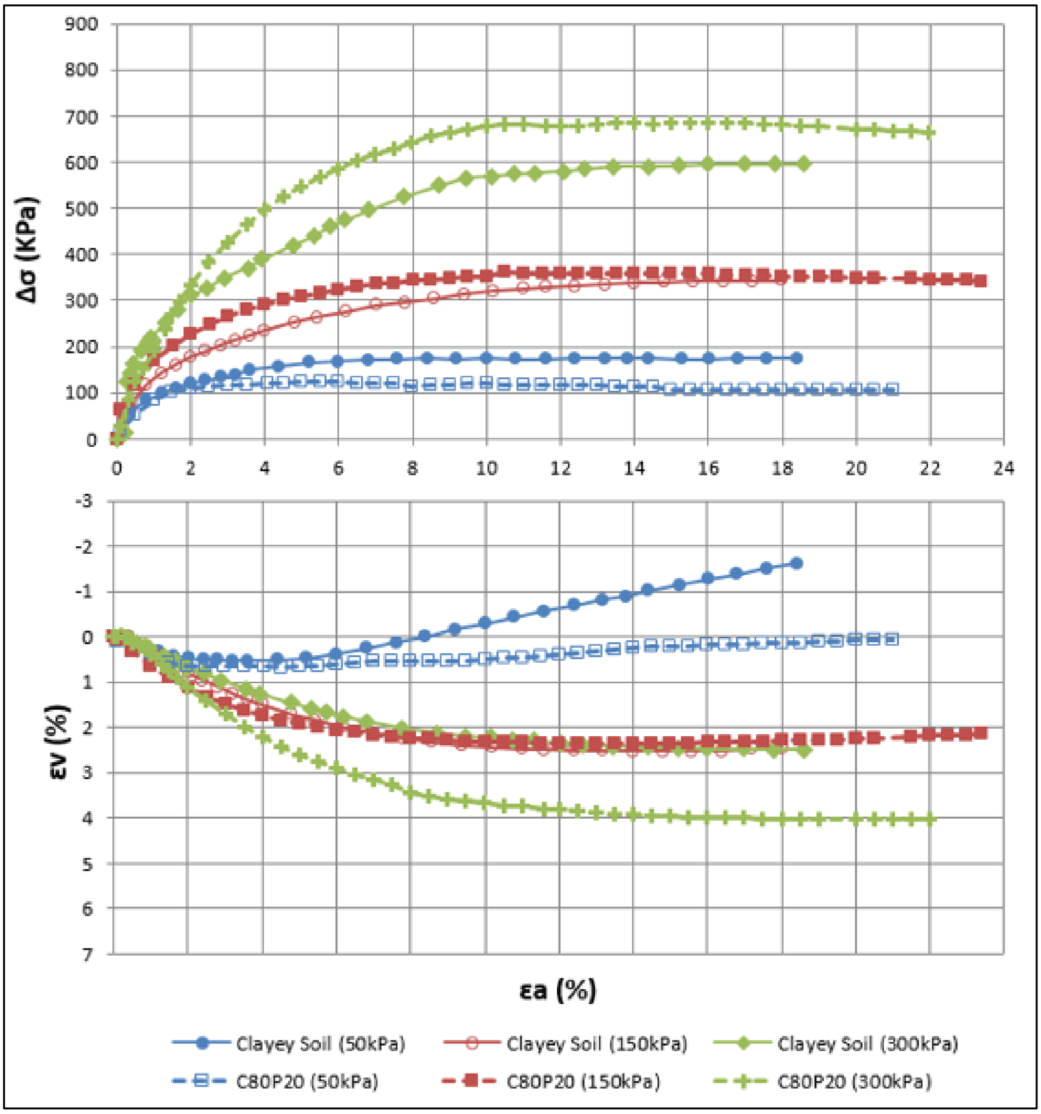

Figure 4.15 - Curves of deviator stress (σd) and volumetric variation (εv) versus axial strain (εa) for the clayey soil and C80P20 in triaxial tests.

In Figure 4.16, the curves of deviator stress (σ_d) and volumetric variation (ε_v) versus axial strain (ε_a) are presented, which correspond to the triaxial (CID) tests performed in the clayey soil and in the mixture S70P30 with confining stress of 50, 150 and 300kPa.

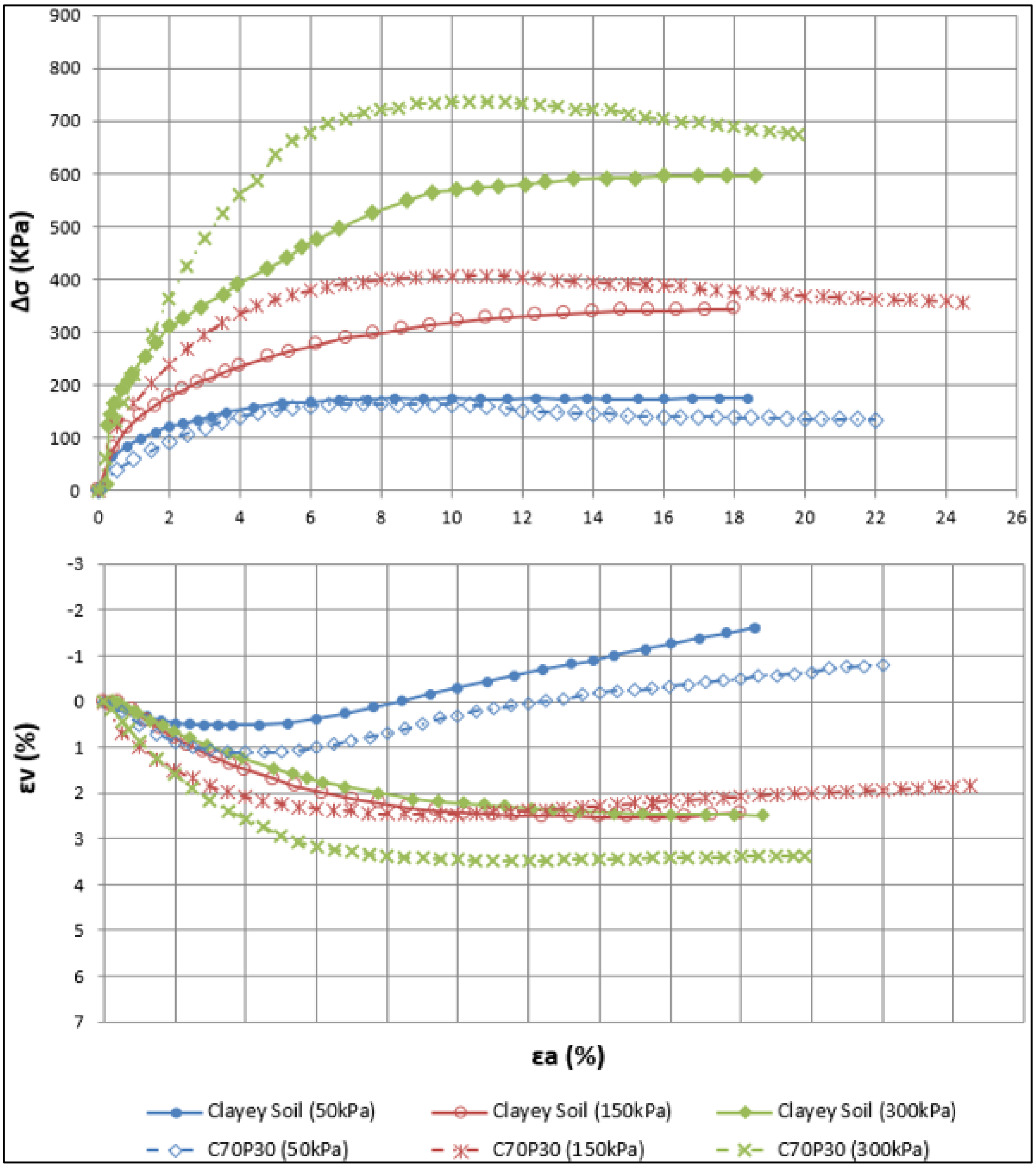

Figure 4.16 - Curves of deviator stress (σd) and volumetric variation (εv) versus axial strain (εa) for the clayey soil and C70P30 in triaxial tests.

ii. Influence of the Amount of Fine Crushed PET in the Clayey Soil

The behavior of deviator stress (σ_d) and volumetric variation (ε_v) versus axial strain (ε_a), which correspond to the triaxial (CID) tests performed in the clayey soil and in the mixtures, are presented in the Figure 4.17.

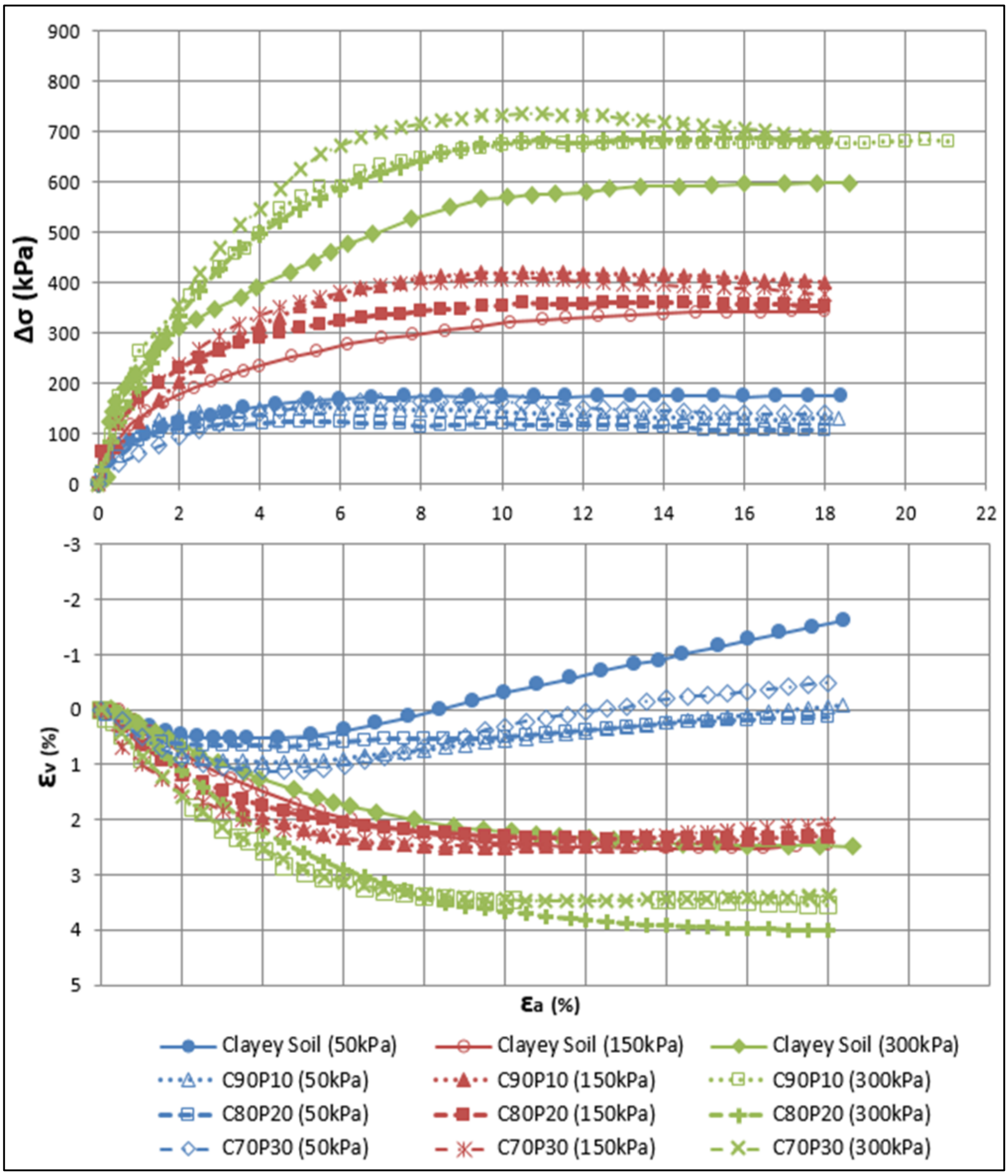

Figure 4.17 - Curves of deviator stress (σd) and volumetric variation (εv) versus axial strain (εa) for the clayey soil and the mixtures in triaxial tests.

It is observed that for higher confining stress (300kPa) the addition of fine crushed PET improved the behavior of the soil from the beginning of the axial strain. All mixtures overcame the load capacity of the pure soil, but C90P10 and C80P20 supported the same levels of stress and both reached a very similar residual stress. However, the mixture C70P30 had a load capacity bigger than the pure soil and the previous mixtures and also presented a small peak around 10% of axial strain, with residual stress remained similar to the other mixtures. Through the curve of volumetric strain versus axial strain can be noticed that, the mixtures suffered a decreasing in the volume, comparing with the pure soil.

At a confining stress of 150kPa, the clayey soil and the mixtures had no well-defined peak strength. At this level of confinement all mixtures presented a better behavior than the pure soil, supporting higher loads at smaller and bigger strains, having almost the same residual strength. The behavior of the mixtures C90P10 and C70P30 remained the same through practically the entire test, while the mixture C80P20 had a smaller load capacity than the other mixtures. About the volumetric strain, the pure soil and the mixtures remained with almost the same changes in the volume shrinking throughout the triaxial test.

For a confining stress of 50kPa the clayey soil had a better behavior than the mixtures. All the samples of soil-PET did not overpass the bearing capacity of the pure soil, they had the same initial behavior but after 3% of axial strain the mixture started to reduce their load capacity reaching just about the same value of residual strength. In the curves of volumetric strain versus axial strain all the mixtures behaved as the pure soil, they first suffered a shrinkage and then they started to swell until the end of the test.

It is noticed that in all mixtures, when material is submitted to a low confining stress the insertion of fine crushed PET does not improve the load capacity of the soil, possibly because in a lower confining stress the grains are not totally in contact with each other, leaving gaps between the particles, making the load capacity of the mixtures weaker, comparing to the pure soil. However, at higher confining stresses the improvements of the behavior of the soil are evident. This behavior can be explained because, possibly the fine crushed PET does not react with the soil particles creating a cementation process, as it happened with lime or ashes of municipal solid waste (Szeliga, 2014 and Quispe, 2013). The fine crushed PET works more as a grain size improvement, and in higher confining stress, when the consolidation step is applied, the fine crushed PET fills the remaining voids in the soil, leaving less gaps between the soil particles. So at the same axial strain, the mixture withstand a higher deviator stress comparing with the clayey soil. The tests were performed in a clayey soil, and it could be observed through a microscopy that the grains of the clayey soil are very edged, like the fine crushed PET grains. In a lower confining stress, the grains are not totally in contact with each other, leaving gaps between the particles, making the load capacity of the mixtures weaker, comparing to the pure soil. On the other hand, in higher confining stresses the interactions among the grains are greater, and there are less voids remaining, resulting in a better bearing capacity of the mixtures in relation with the pure soil.

iii. Envelopes and Shear Strength Parameters

The Figure 4.18, 4.19, 4.20 and 4.21 show the shear strength parameters of Mohr-Coulomb criterion and the strength envelopes, plotted in the p':q space, of the clayey soil and the mixtures. For the same reason as the sandy soil, all the envelopes were plotted at 18% of axial strain, and also it was able to reach this level of strain in all tests.

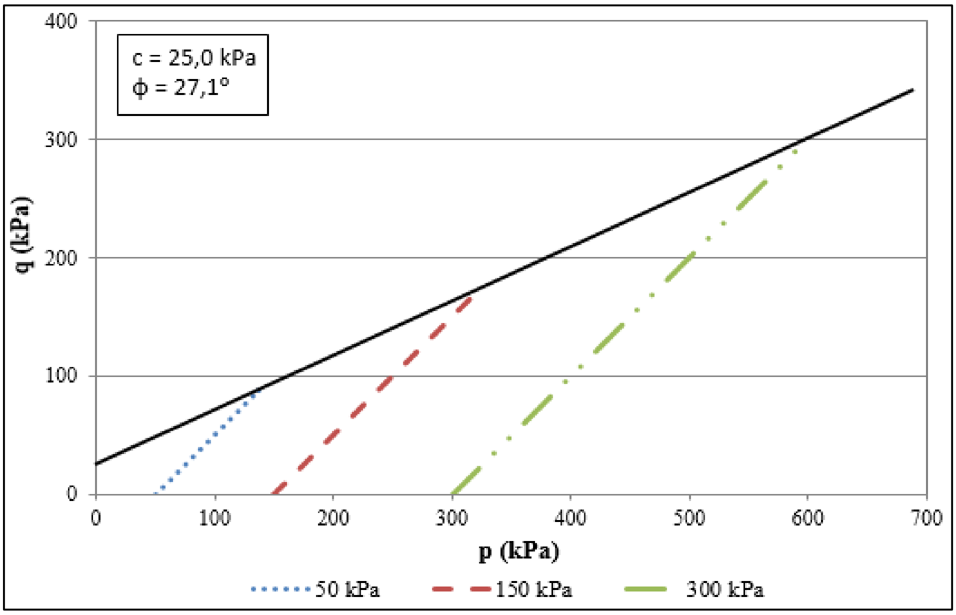

Figure 4.18 - The shear strength parameter and the strength envelope of the clayey soil.

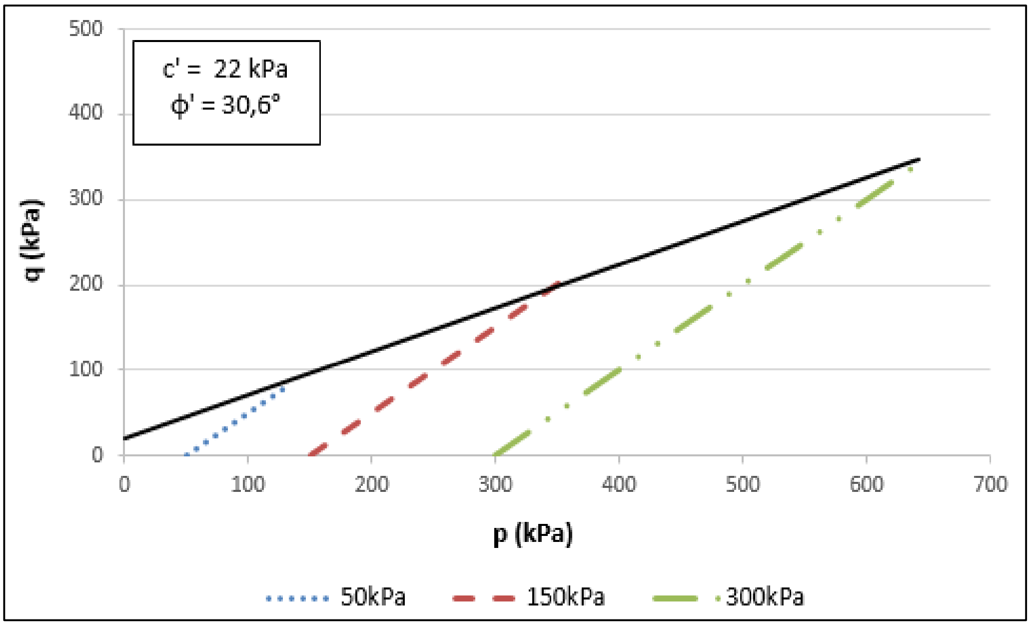

Figure 4.19 - The shear strength parameter and the strength envelope of the mixture C90P10.

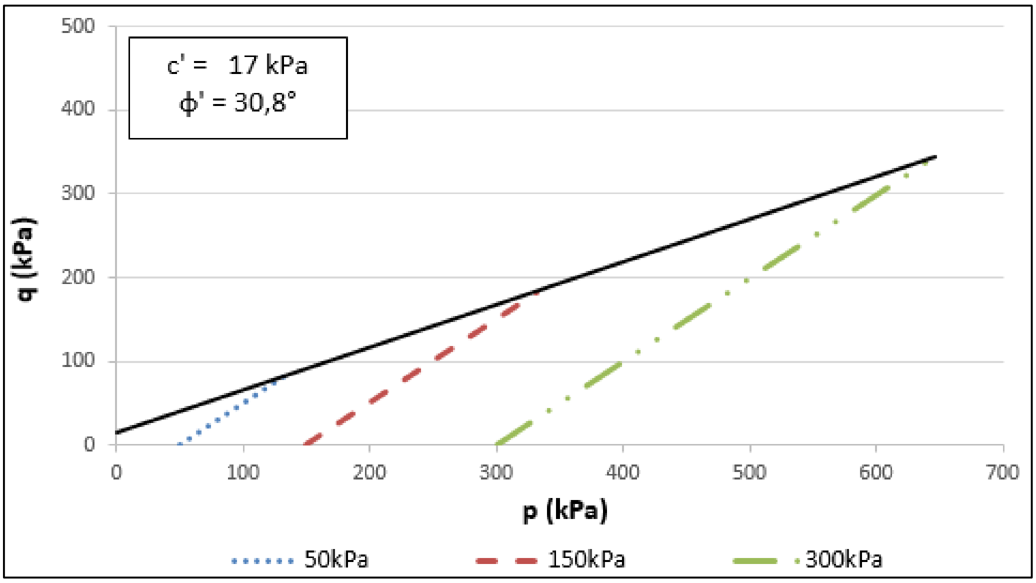

Figure 4.20 - The shear strength parameter and the strength envelope of the mixture C80P20.

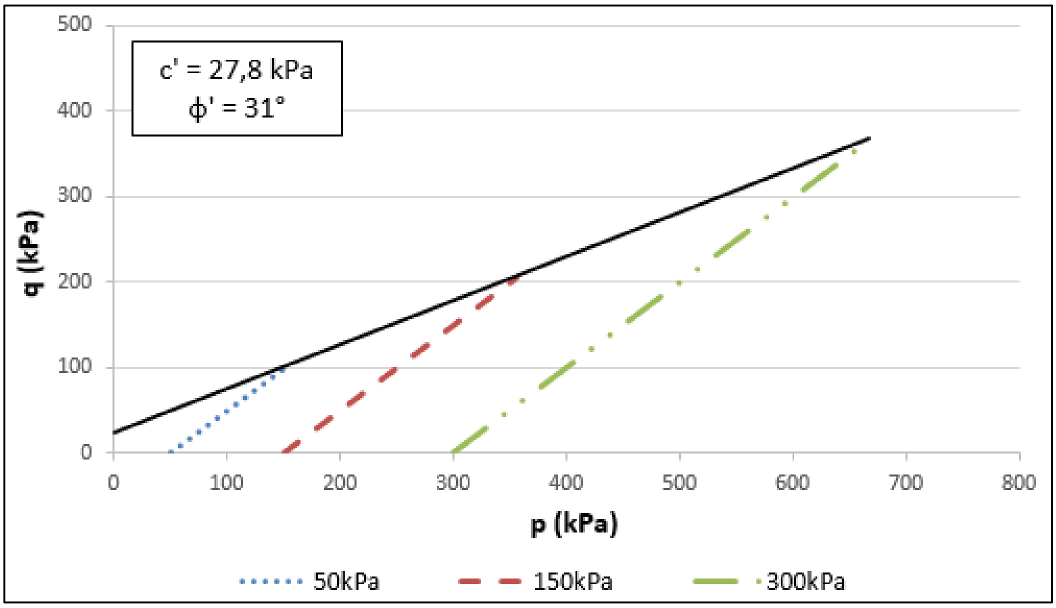

Figure 4.21 - The shear strength parameter and the strength envelope of the mixture C70P30.

The Table 4.9 summarizes the values of cohesion and friction angle of the pure soil and the mixtures at 18% of strain.

Table 4.9 - Results of shear strength parameters for the clayey soil and mixtures.

Material/Mixture	Cohesion (kPa)	Friction Angle (°)
C100	25,0	27,1
C90P10	22,0	30,6
C80P20	17,0	30,8
C70P30	27,8	31,0

It can be inferred from the graphics that, as much as the amount of PET is raised, an improvement in the friction angle is observed, and consequently the values of cohesion decrease for the mixtures C90P10 and C80P20, but with the mixture C70P30 both parameters had an important upraise.

Because the results of deviator stress vs axial strain, at a lower confining stress, were slightly below the ones found for the pure clayey soil, the strength envelopes provided values for cohesion smaller than the pure clayey soil, and higher for the friction angle. As said previously, the fine crushed PET works as grain size improvement, do not causing any cementation process with the soil particle. So, cohesion parameter does not suffer any improvement with the addition of this material, however the friction angle does get higher, because this parameter is affected in a grain size improvement.

For the mixture C70P30 the amount of fine crushed PET in the soil was able to fill better the voids, improving the interaction between the particles of PET and soil, causing an enrichment of the cohesion and also the friction angle. Through the results of deviator stress vs axial strain, it can be noticed that, among all mixtures at lower confining stress, the C70P30 has practically the same behavior as the pure soil, and better at higher confining stresses, what explains the improvement in both parameters. Because the mixture C70P30 better improved the mechanical parameters and the bearing capacity of the soil, this was considered the best mixture, in which the cohesion raised 11% and the friction angle raised 14,4% compared with the pure soil.

4.3.2.3
Clayey Soil and PET Flakes

i. Deviator Stress and Volumetric Variation vs Axial Strain Behavior

In Figure 4.22, the curves of deviator stress (σ_d) and volumetric variation (ε_v) versus axial strain (ε_a) are presented, which correspond to the triaxial (CID) tests performed in the clayey soil and in the mixture C97F03 with confining stress of 50, 150 and 300kPa.

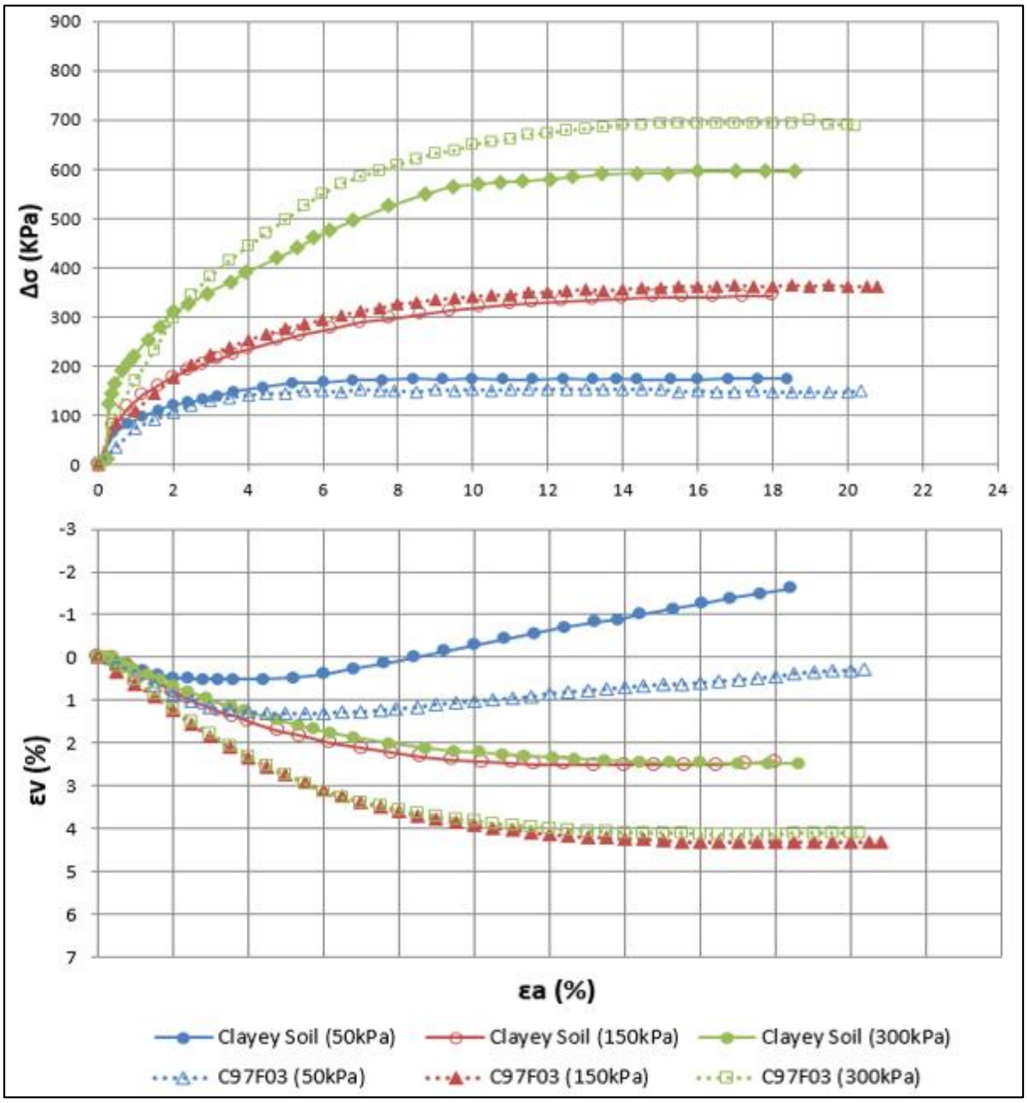

Figure 4.22 - Curves of deviator stress (σd) and volumetric variation (εv) versus axial strain (εa) for the clayey soil and C97F03 in triaxial tests.

In Figure 4.23, the curves of deviator stress (σ_d) and volumetric variation (ε_v) versus axial strain (ε_a) are presented, which correspond to the triaxial (CID) tests performed in the clayey soil and in the mixture C95F05 with confining stress of 50, 150 and 300kPa.

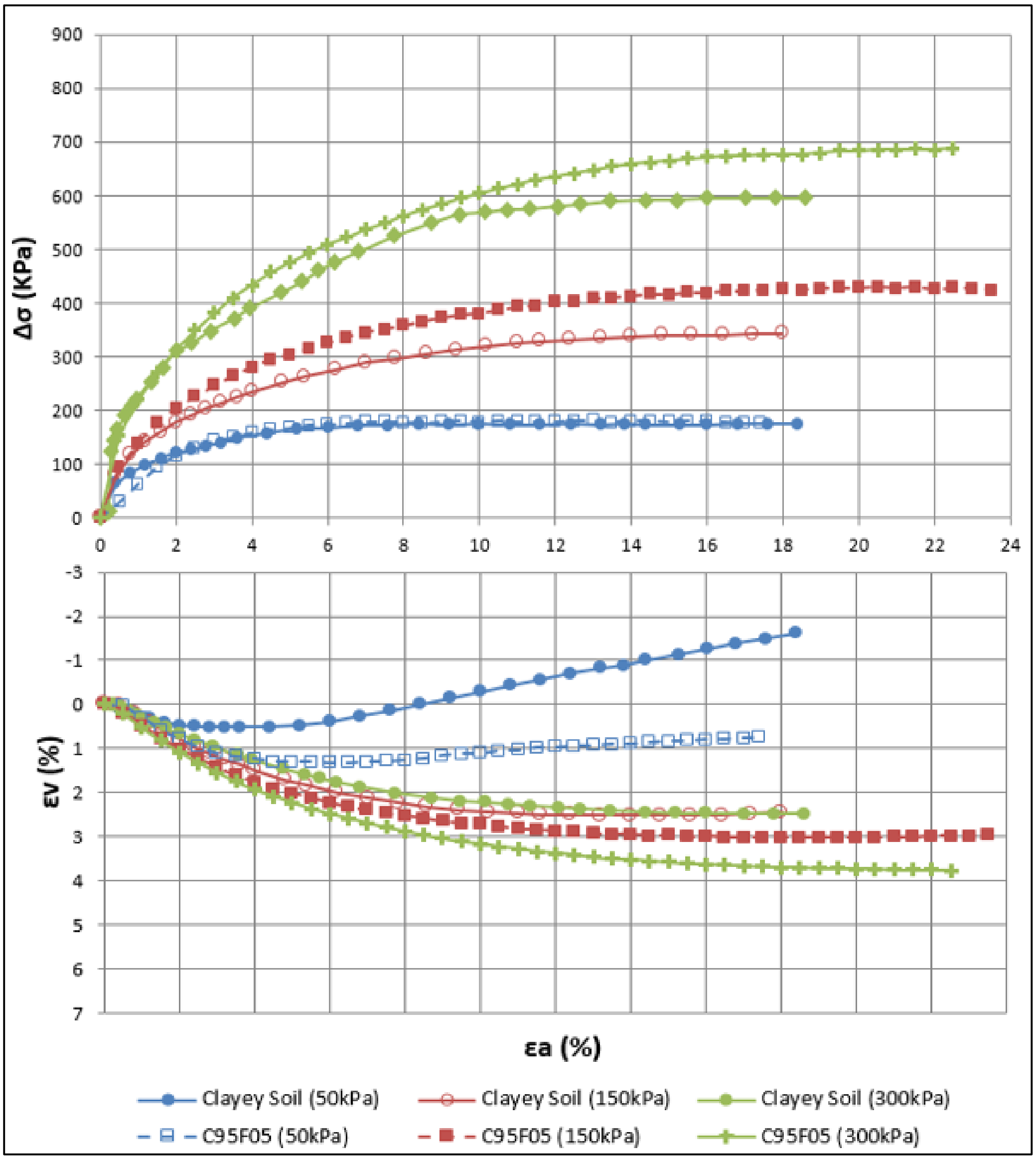

Figure 4.23 - Curves of deviator stress (σd) and volumetric variation (εv) versus axial strain (εa) for the clayey soil and C95F05 in triaxial tests.

ii. Influence of the Amount of PET flakes in the Clayey Soil.

The behavior of deviator stress (σ_d) and volumetric variation (ε_v) versus axial strain (ε_a), which correspond to the triaxial (CID) tests performed in the clayey soil and in the mixtures, are presented in the Figure 4.24.

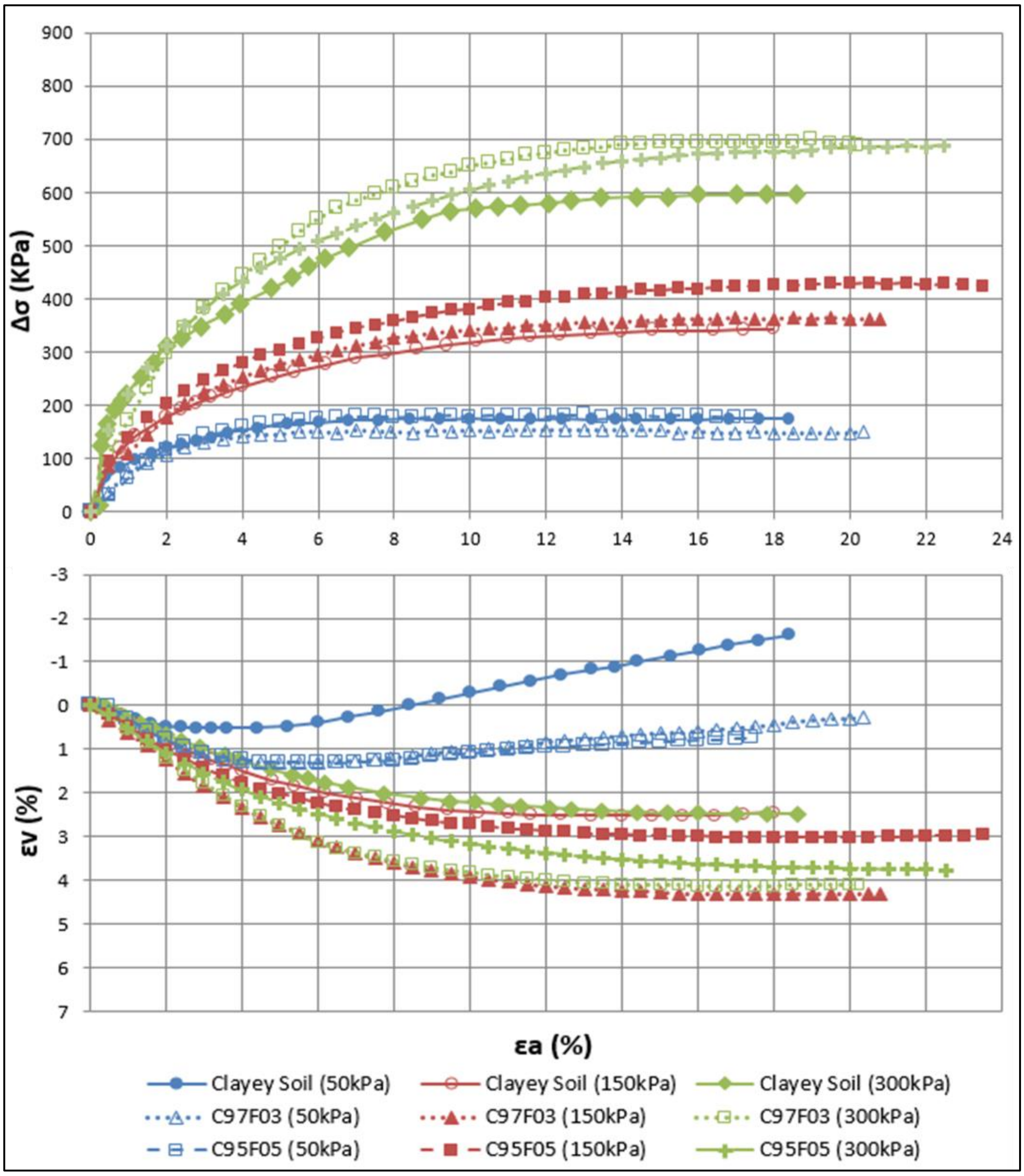

Figure 4.24 - Curves of deviator stress (σd) and volumetric variation (εv) versus axial strain (εa) for the clayey soil and the mixtures in triaxial tests.

It is observed that for higher confining stress (300kPa) the addition of fine crushed PET improved the behavior of the soil from the beginning of the axial strain. All mixtures overcame the load capacity of the pure soil, C97F03 and C95F05 supported almost the same levels of stress and both reached a very similar residual stress. Through the curve of volumetric strain versus axial strain can be noticed that, the mixtures suffered a decreasing in the volume, comparing with the pure soil.

At a confining stress of 150kPa, the clayey soil and the mixtures had no well-defined peak strength. At this level of confinement all mixtures presented a better behavior than the pure soil, supporting higher loads at smaller and bigger strains, having different residual strength than the pure soil. The behavior of the mixtures C97F03 and C95P05 remained the same through practically the entire test, but the mixture C95F05 supporting higher loads. About the volumetric strain, the pure soil and the mixtures remained with almost the same changes in the volume, shrinking throughout the triaxial test, the mixture C97F03 suffered a bigger shrinkage than the C95F05.

For a confining stress of 50kPa the clayey soil had a better behavior than the mixtures. The C97F03 sample did not overpass the bearing capacity of the pure soil, it had the same initial behavior but after 5% of axial strain the mixture started to reduce it load capacity reaching a lower residual strength than the pure soil. Instead, the mixture C95F05 remained with the same behavior as the pure soil through the entire test. In the curves of volumetric strain versus axial strain all the mixtures behaved as the pure soil, they first suffered a shrinkage and then they started to swell until the end of the test.

It is observed that in all mixtures, as it happened with the mixtures of fine crushed PET and clayey soil, when material is submitted to a low confining stress the insertion of fine crushed PET does not improve the load capacity of the soil. However, at higher confining stresses the improvements of the load capacity can be easily noticed. The same explanation for the fine crushed PET and clayey soil is applied, the PET flakes work as a grain size improvement, and in higher confining stress, when the consolidation step is applied, the PET flakes fill the remaining voids in the soil, leaving less gaps between the soil particles. So at the same axial strain, the mixtures withstand a higher deviator stress comparing with the clayey soil.

At a lower confining stress, the grains are not totally in contact with each other, leaving gaps between the particles, making the load capacity of the mixtures weaker, comparing to the pure soil. On the other hand, in higher confining stresses the interactions among the grains are greater, and there are few voids remaining, resulting in a better bearing capacity of the mixtures in relation with the pure soil. Another possible explanation for this behavior is related with an anisotropy induced by the stresses, causing an alignment of the PET flakes resulting from the increasing of the confining stress.

Figure 4.25 from the scanning electron microscope (SEM) highlights the behavior of the PET as grain size improvement, and the interaction among particles of soil and PET, as well as the amount of voids in the soil according to the level of confining stress applied, as previously explained.

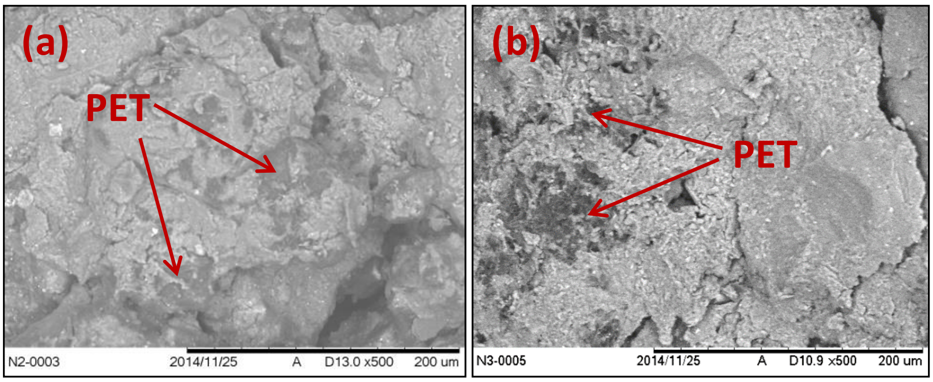

Figure 4.25 - SEM pictures of the mixtures (a) C80P20-50kPa and (b) C80P20-300kPa.

iii. Envelopes and Shear Strength Parameters

The Figure 4.26, 4.27 and 4.28 show the shear strength parameters of Mohr-Coulomb criterion and the strength envelopes, plotted in the p':q space, of the clayey soil and the mixtures. For the same reasons previously highlighted, all the envelopes were plotted at 17% of axial strain, and also it was able to reach this level of strain in all tests.

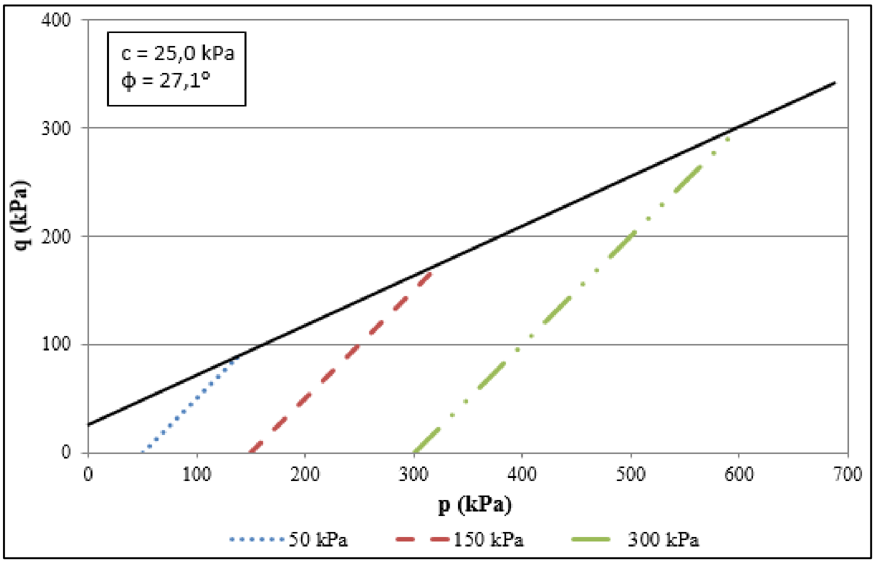

Figure 4.26 - The shear strength parameter and the strength envelope of the clayey soil.

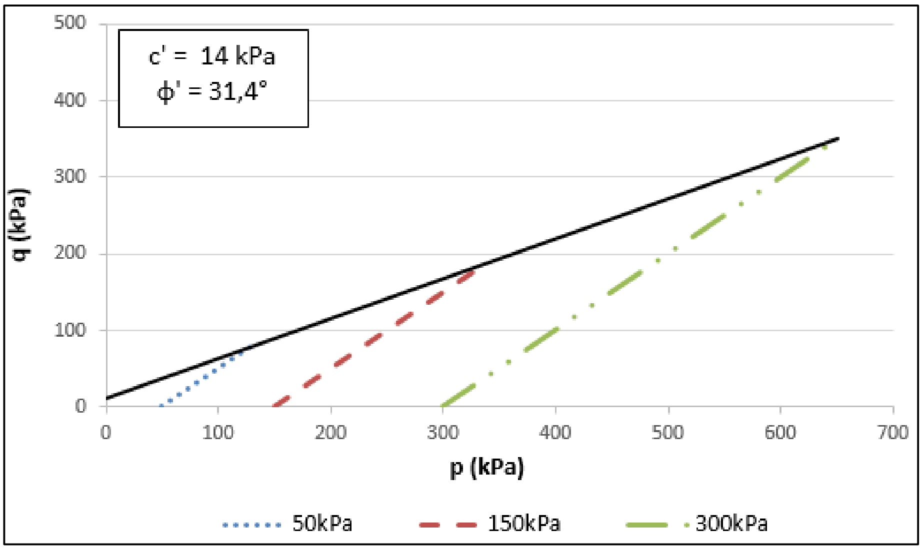

Figure 4.27 - The shear strength parameter and the strength envelope of the mixture C97F03.

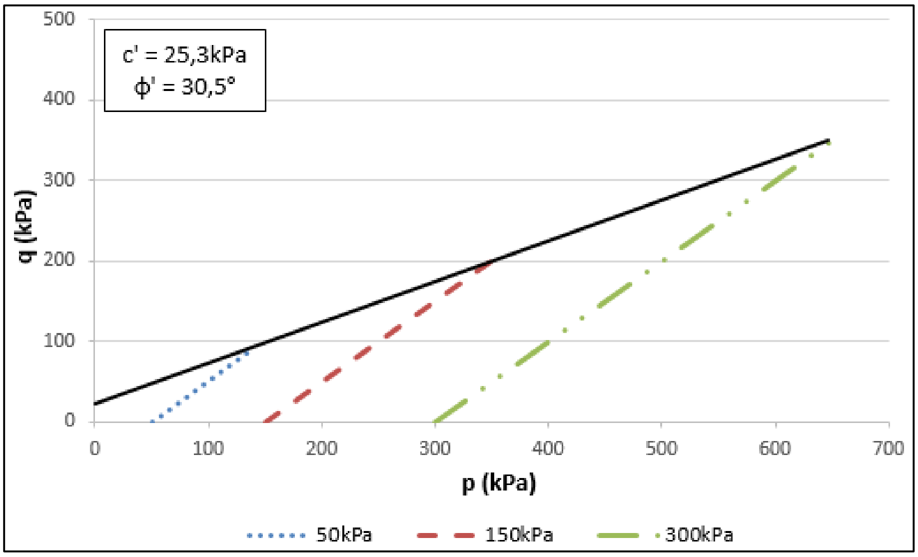

Figure 4.28 - The shear strength parameter and the strength envelope of the mixture C95F05.

The Table 4.10 summarizes the values of cohesion and friction angle of the pure soil and the mixtures at 17% of strain.

Table 4.10 - Results of shear strength parameters for the clayey soil and mixtures with PET flakes.

Material/Mixture	Cohesion (kPa)	Friction Angle (°)
C100	25,0	27,1
C97F03	14,0	31,4
C95F05	25,3	30,5

It can be inferred from the graphics that, as much as the amount of PET is raised, an improvement in the friction angle is observed in all mixtures. For the mixture C97F03 the value of cohesion decreases and for the mixture C95F05 it remained the same.

As well as happened with other samples, the results of deviator stress vs axial strain for the mixture C97F03, at a lower confining stress, were slightly below the one found for the pure clayey soil, so the strength envelopes provided values for cohesion smaller than the pure clayey soil, and higher for the friction angle. As said previously, the PET flakes work like the fine crushed PET, as grain size improvement. Thus, cohesion parameter does not suffer any improvement with the addition of this material, however the friction angle does get higher, because this parameter is affected in a grain size improvement.

For the mixture C95F05 the amount of fine crushed PET in the soil was able to fill better the voids, improving the interaction between the particles of PET and soil, causing an enrichment of the cohesion and also the friction angle. Through the results of deviator stress vs axial strain, it can be noticed that, at lower confining stress, the C95F05 has the same behavior as the pure soil, and better at higher confining stresses, leading the envelope to a greater slope, what explains the improvement in both parameters. The mixture C70P30 was the one that better improved the mechanical parameters and the bearing capacity of the soil, in which the cohesion raised 1,0% and the friction angle raised 12,5% compared with the pure soil.

4.3.3
Direct Shear Test

The direct shear tests were performed of the pure bentonite and the mixtures, applying vertical stress of 50 and 100kPa. These tests were carried out in order to determinate the shear strength parameters from the soil and mixtures.

4.3.3.1
Bentonite and fine crushed PET

i. Shear Stress and Vertical Displacement vs Axial Displacement Behavior

In Figure 4.29, the curves of deviator stress and vertical displacement versus axial displacement are presented, which correspond to the direct shear tests performed in the bentonite and in the mixture B70P30 with confining stress of 50 and 100kPa.

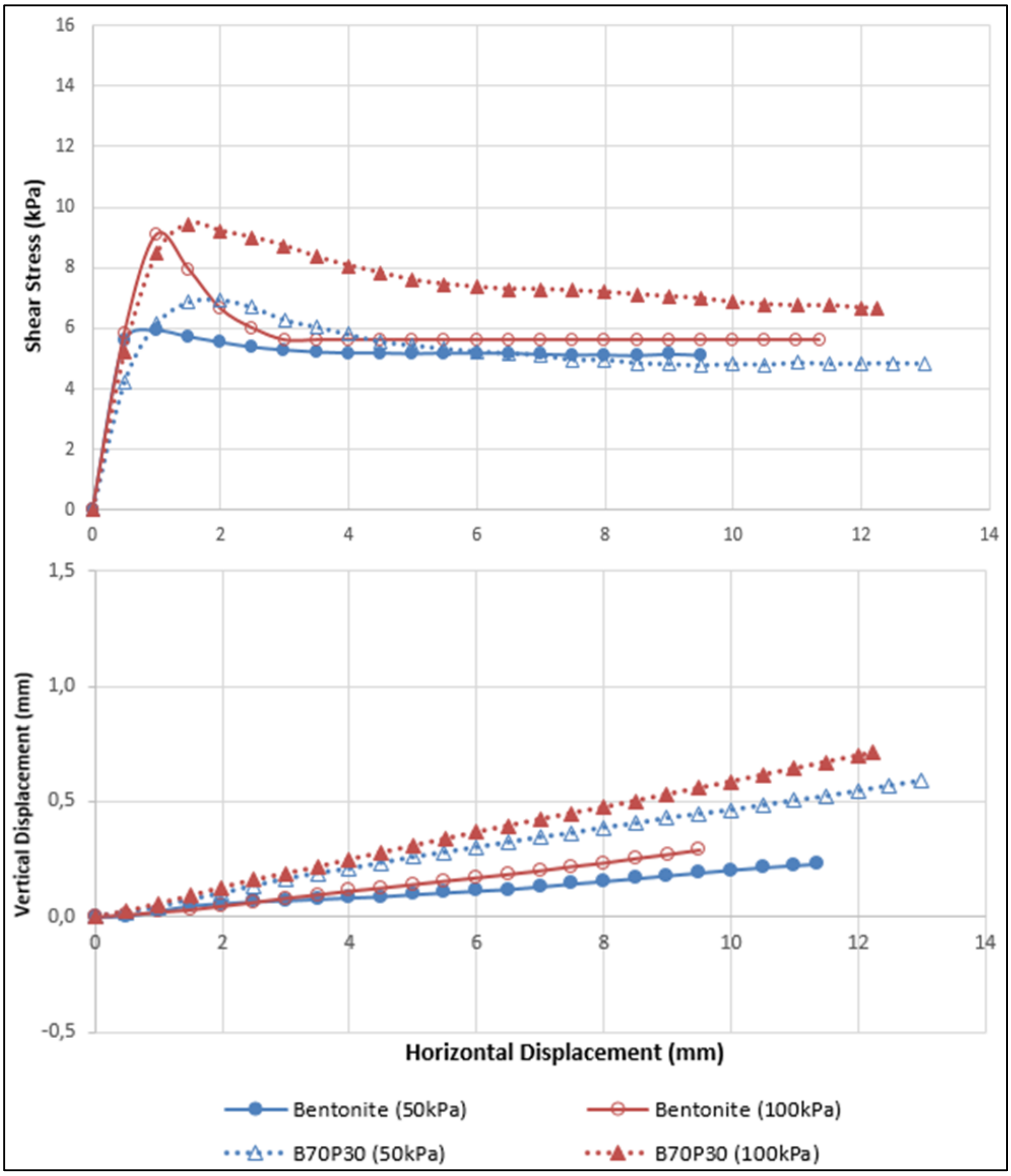

Figure 4.29 - Curves of shear strength and vertical displacement versus axial displacement for the bentonite and the mixture B70P30 in the direct shear test.

In the vertical stress of 50 kPa, the pure soil presents a smaller peak strength than the mixture B70S30, and the peak occurs earlier either. After the peak value both materials reach the same value at about 6 mm of displacement, and then the residual strength of the mixture B70F30 started to become smaller than the pure bentonite. In the vertical stress of 100 kPa, the peak strength of the mixture was slightly bigger than the pure bentonite. The residual strength of the mixture remained higher through the entire test, but for bigger displacement the tendency of the mixture residual strength is to approach the value of the pure bentonite.

The graphic vertical displacement versus horizontal displacement of the mixture, in both vertical stress, were higher than the values found for the bentonite, the fine crushed PET insertion in the bentonite led to bigger swelling of the specimens.

ii. Envelopes and Shear Strength Parameters

The Figure 4.30 and 4.31 show the shear strength parameters of maximum and residual strength and also the strength envelopes, of the bentonite and the mixture B70F30.

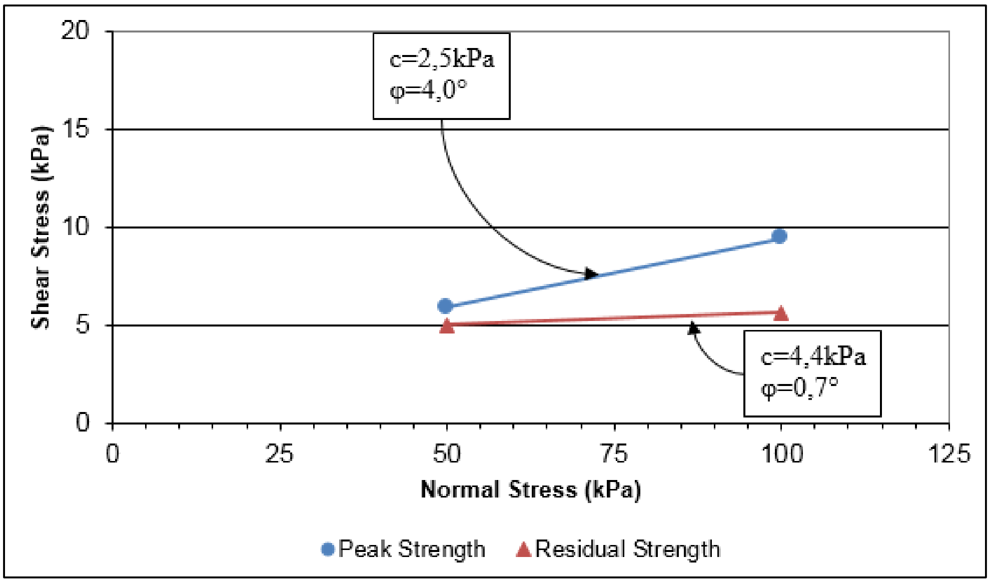

Figure 4.30 - The shear strength parameter and the strength envelope of the bentonite.

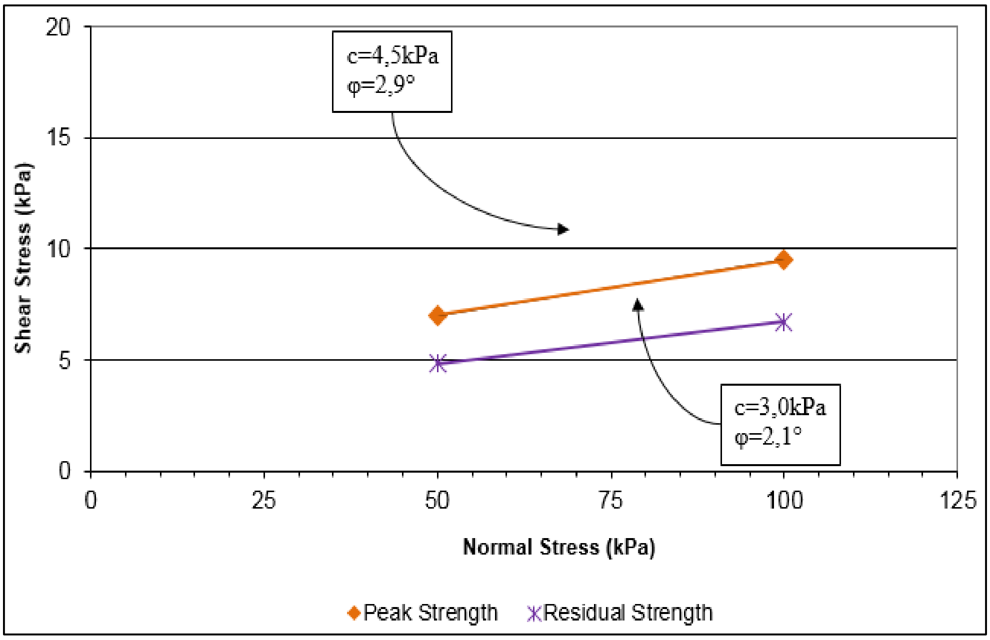

Figure 4.31 - The shear strength parameter and the strength envelope of the mixture B70P30.

The Table 4.11 summarizes the values of cohesion and friction angle of the pure soil and the mixtures for peak and residual strength.

Table 4.11 - Results of shear strength parameters for the bentonite and mixture C70P30.

Material/Mixture	Peak Strength		Residual Strength	
	Cohesion (kPa)	Friction Angle (°)	Cohesion (kPa)	Friction Angle (°)
B100	2,5	4,0	4,4	0,7
B70P30	4,5	2,9	3,0	2,1

It can be inferred from the graphics that, as much as the amount of fine crushed PET is raised, an improvement in the cohesion related with the peak strength is observed in the mixture, however, the friction angle suffers a small decrease. This behavior can be explained because the interaction between the particles of bentonite and fine crushed PET are higher than the interaction of the particle of the pure bentonite, so the cohesion increases. On the other hand, the friction angle decrease because the difference among the peak strength of 50 and 100 kPa are smaller than the difference found in the pure bentonite.

In the case of the residual strength the opposite happens, where, the cohesion decrease and the friction angle increase with the addition of the fine crushed PET. This phenomenon highlights that the fine crushed PET changes the mechanical behavior of the material in relation with the peak and residual strength. This can be explained because the size of the bentonite grains are smaller the size of the fine crushed PET, and when the bentonite is mixture with the fine crushed PET, this material possibly reduces the expansion of bentonite when it is mixture with water.

4.3.3.2
Bentonite and PET Flakes

i. Shear Stress and Vertical Displacement vs Axial Displacement Behavior

In Figure 4.32, the curves of deviator stress and vertical displacement versus axial displacement are presented, which correspond to the direct shear tests performed in the bentonite and in the mixture B97F03 with confining stress of 50, 70 and 100kPa.

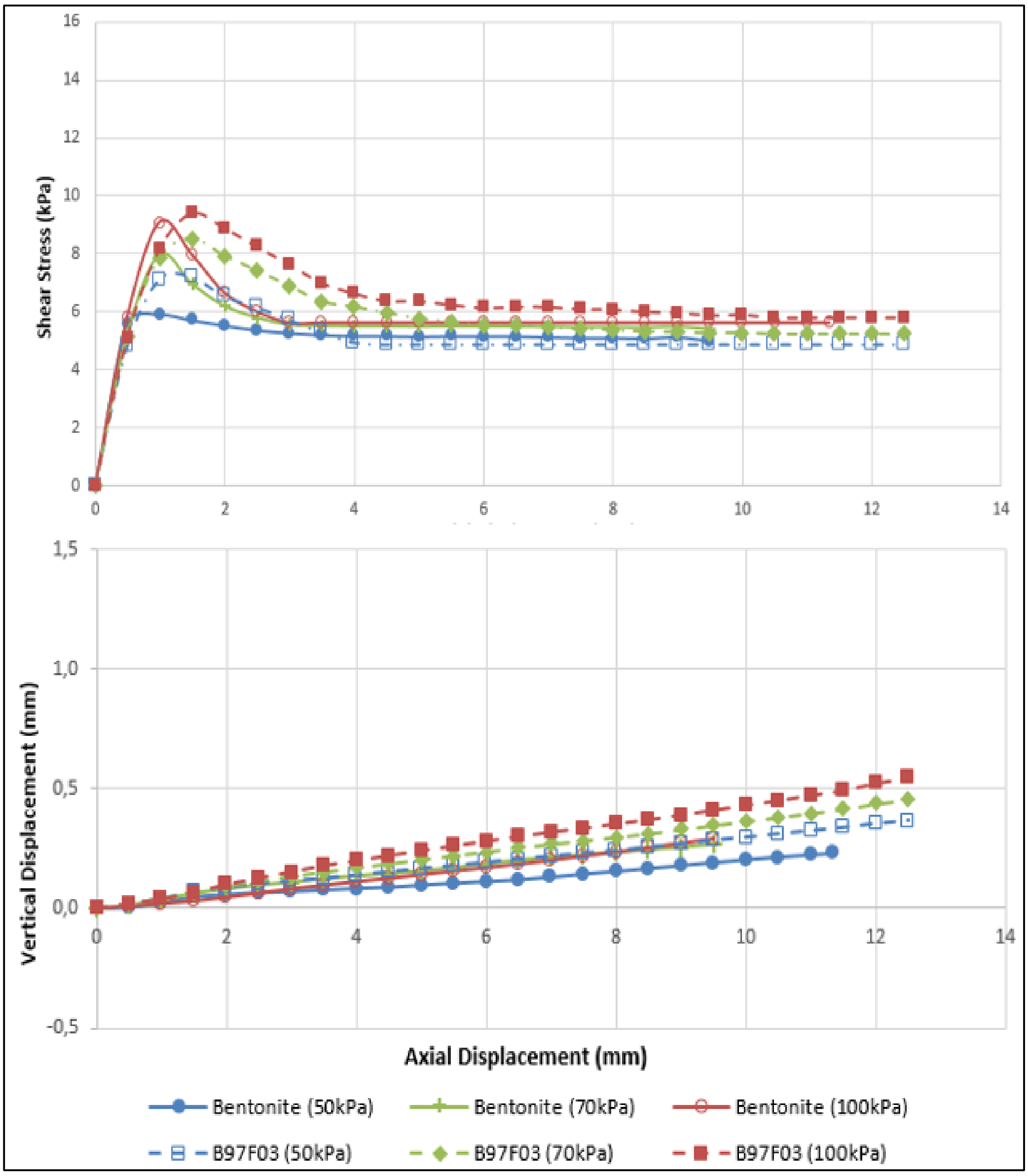

Figure 4.32 - Curves of shear strength and vertical displacement versus axial displacement for the bentonite and the mixture B97F03 in the direct shear test.

In Figure 4.33, the curves of deviator stress and vertical displacement versus axial displacement are presented, which correspond to the direct shear tests performed in the bentonite and in the mixture B95F05 with confining stress of 50, 70 and 100kPa.

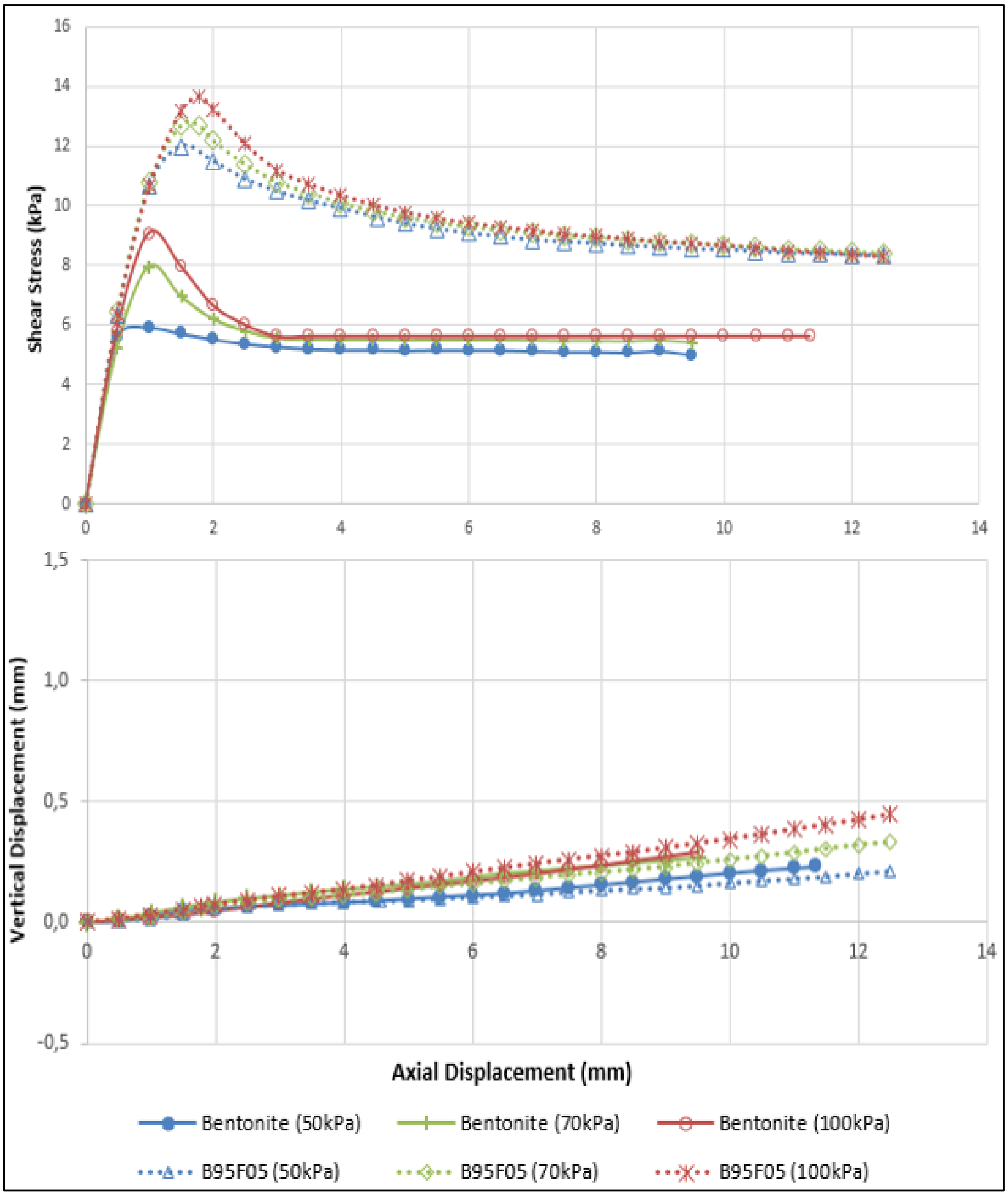

Figure 4.33 - Curves of shear strength and vertical displacement versus axial displacement for the bentonite and the mixture B95F05 in the direct shear test.

ii. Influence of the Amount of PET flakes in the Bentonite.

The behavior of deviator stress and vertical displacement versus axial displacement, which correspond to the direct shear tests performed in the bentonite and in the mixtures, are presented in the Figure 4.34.

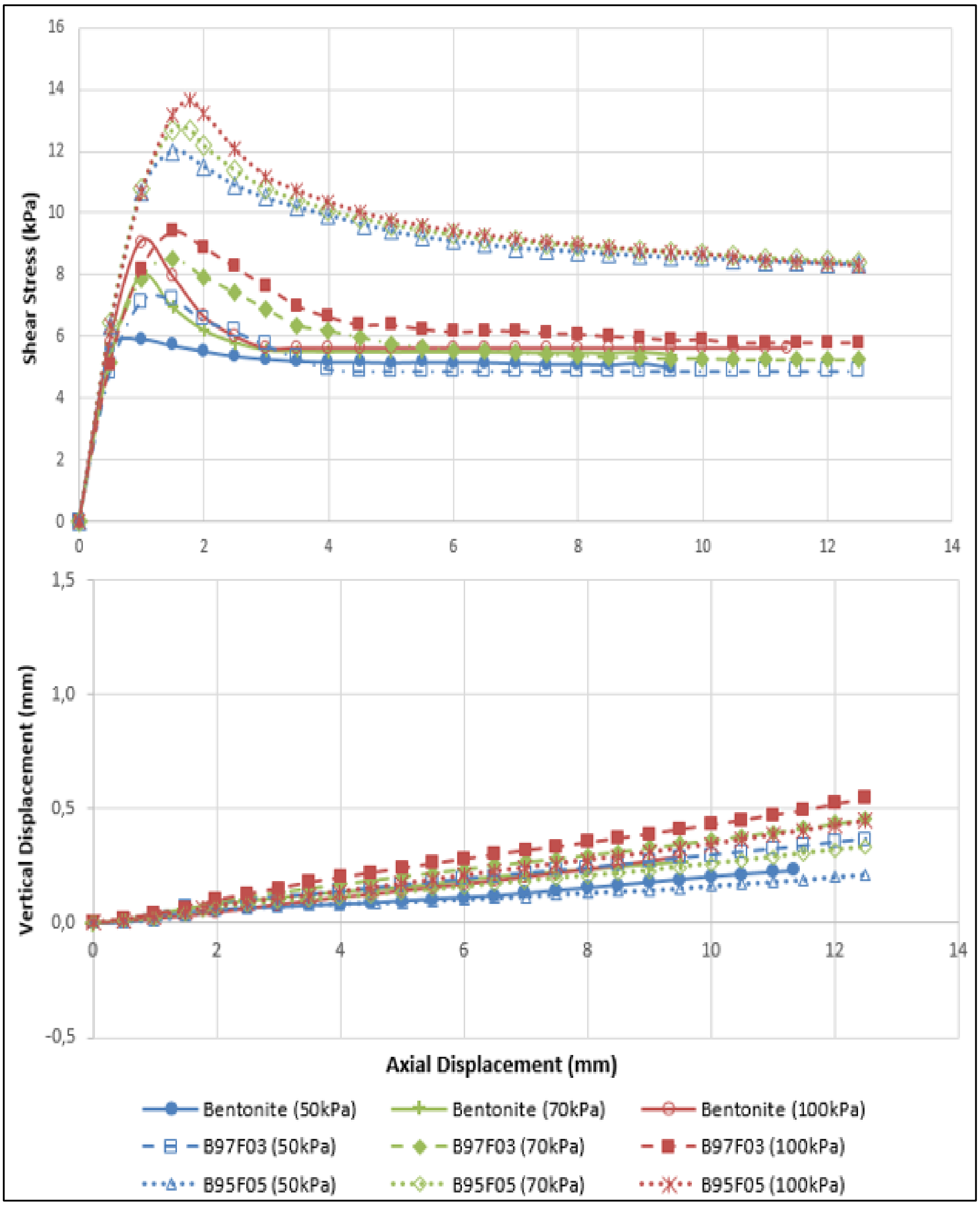

Figure 4.34 - Curves of shear strength and vertical displacement versus axial displacement for the bentonite and the mixtures in the direct shear test.

In the vertical stress of 50 kPa, the pure soil presents smaller peak strength than the mixtures, and the peak occurs slightly earlier. The mixture B95F05 presents, for both vertical stresses, a major improvement in the bearing capacity of the soil, reaching values of shear stress higher than the pure bentonite and the mixture B97F03. After the peak value the mixture B97F03 reached the same value as the bentonite of residual strength at about 4 mm of displacement, and then the residual strength of the mixture B97F03 started to become smaller than the pure bentonite. The mixture B95F05 reached values of peak and residual strength higher than the pure bentonite through the entire test, highlighting the great improvement in the soil parameter for this mixture. In the vertical stress of 70 and 100 kPa, the peak strength was slightly bigger than the pure bentonite for the mixture B97F03 and significantly higher for the mixture B95F05. The residual strength of the mixtures remained higher through the entire test.

The graphic vertical displacement versus horizontal displacement of the mixture B97F03, for 50, 70 and 100 kPa of vertical stress, were higher than the values found for the bentonite. For the mixture B95F05 the insertion of fine crushed PET, caused a swelling in the specimen just at a vertical stress of 100kPa.

iii. Envelopes and Shear Strength Parameters

The Figure 4.35, 4.36 and 4.37show the shear strength parameters of maximum and residual strength and also the strength envelopes, of the bentonite and the mixtures with PET flakes.

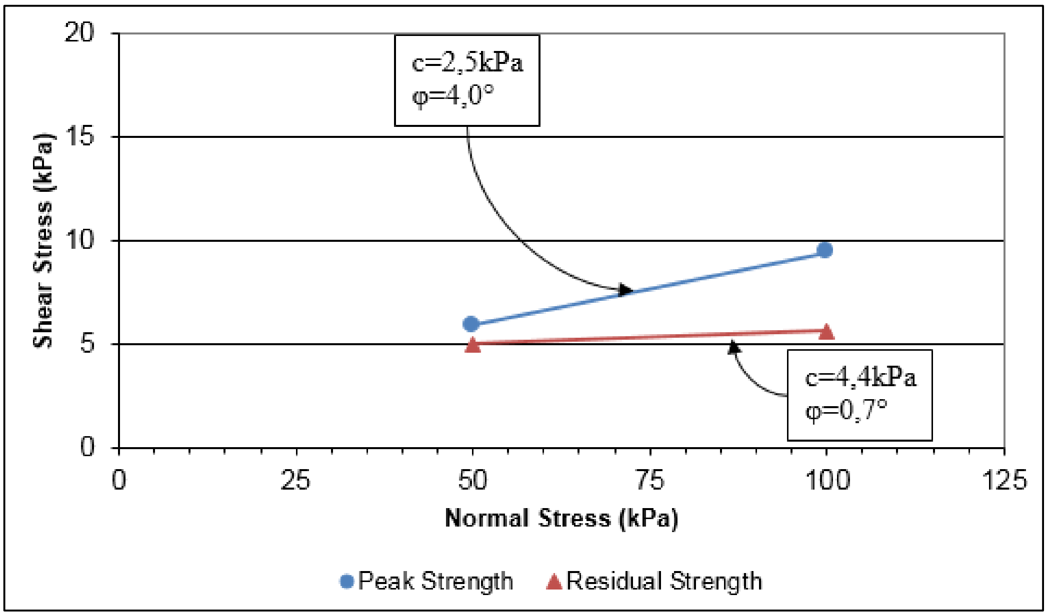

Figure 4.35 - The shear strength parameter and the strength envelope of the bentonite.

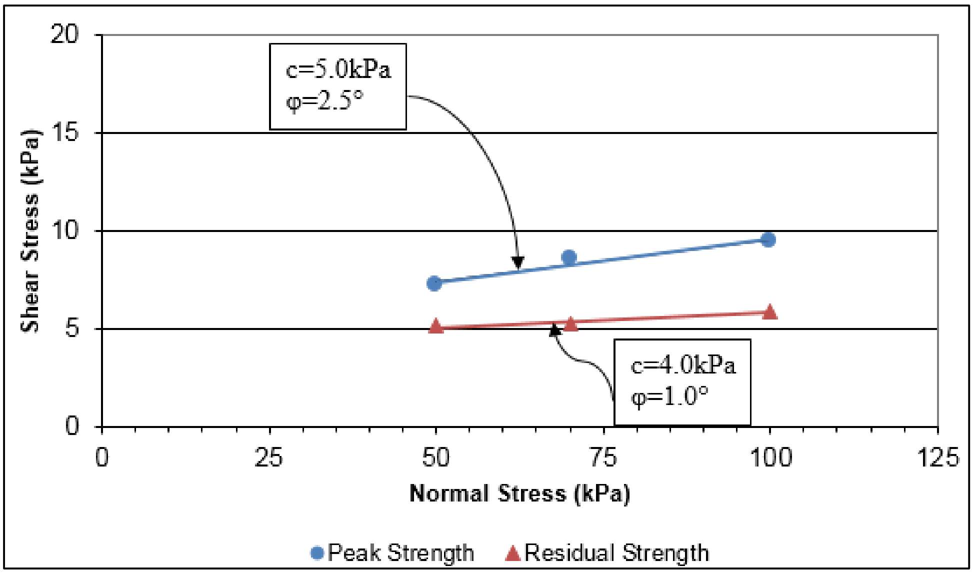

Figure 4.36 - The shear strength parameter and the strength envelope of the mixture B97F03.

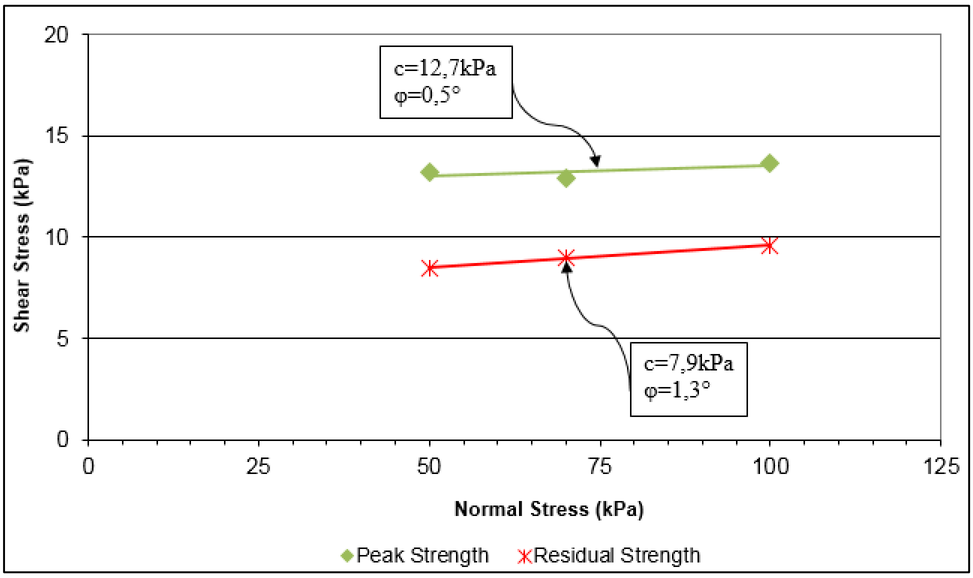

Figure 4.37 - The shear strength parameter and the strength envelope of the mixture B95F05.

The Table 4.12 summarizes the values of cohesion and friction angle of the pure soil and the mixtures for peak and residual strength.

Table 4.12 - Results of shear strength parameters for the bentonite and the mixtures.

Material/Mixture	**Peak Strength**		**Residual Strength**	
	Cohesion (kPa)	**Friction Angle (°)**	**Cohesion (kPa)**	**Friction Angle (°)**
B100	2,5	4,0	4,4	0,7
B97F03	5,0	2,5	4,0	1,0
B95F05	12,7	0,5	7,9	1,3

It can be inferred from the graphics that, as much as the amount of PET flakes is raised, the same behavior as the mixture B70F30 happens. An improvement in the cohesion related with the peak strength is observed in both mixtures, however, the friction angles get smaller. This phenomenon can be explained as said previously, the interaction between the particles of bentonite and PET flakes are higher than the interaction of the particle of the pure bentonite, so the cohesion increases. In contrast, the friction angle reduces because the difference among the peak strength of 50, 70 and 100 kPa remains smaller than the difference found in the pure bentonite.

In the case of the residual strength for the mixture B97F03, the cohesion decreases, whereas with the mixture B95F05 it has a better improvement. For both mixtures the friction angle increase with the addition of the fine crushed PET. This phenomenon also highlights that PET flakes change the mechanical behavior of the material in relation with the peak and residual strength.

The mixture B95F05 caused a major improvement in the strength parameter, where, for peak strength the cohesion became five times higher than the pure soil and for the residual strength the friction angle raised 70% and the cohesion raised 79%, compared with the pure bentonite. The PET flakes worked as particle size improvement, the increasing of bigger particles among the bentonite, caused the development of the strength parameters.

4.4 Final Considerations

In this section will be presented all the results founded for the soils, as well as a comparison between the influence of the PET residue and other residue previously studied.

The Table 4.13 summarizes the results founded for the strength parameters of the sand and the clayey soil, while the Table 4.14 shows the results founded for the bentonite.

Table 4.13 – Strength parameters of the sand, clayey soil and mixtures.

Material/Mixture	Cohesion (kPa)	Friction Angle (°)
S100	0	34,2
S90P10	7,0	33,1
S80P20	11,0	30,7
C100	25,0	27,1
C90P10	22,0	30,6
C80P20	17,0	30,8
C70P30	27,8	31,0
C97F03	14,0	31,4
C95F05	25,3	30,5

Table 4.14 – Strength parameters of the bentonite and mixtures.

Material/Mixture	Peak Strength		Residual Strength	
	Cohesion (kPa)	Friction Angle (°)	Cohesion (kPa)	Friction Angle (°)
B100	2,5	4,0	4,4	0,7
B70P30	4,5	2,9	3,0	2,1
B97F03	5,0	2,5	4,0	1,0
B95F05	12,7	0,5	7,9	1,3

Through the tables, it can be inferred that among the mixture using clayey soil and fine crushed PET the mixture that stood out was the S90P10, since it raised the cohesion and caused a slightly decrease in the friction angle compared with the pure soil. For the mixtures of clayey soil/PET flakes the C95F05 was the considered the best, whereas this mixture raised both strength parameters. Between the bentonite and PET flakes mixtures, the B95F05 was the most outstanding, raising the bearing capacity of the soil and the strength parameters.

The behavior observed for the mixture clayey soil/PET flakes can be compared with the results founded by Calheiros (2013), where the EPS behaved as the PET flakes. The results of clayey soil and PET flakes also can be compared with the ones founded by Ramírez (2012), the mixtures clayey soil and granular rubber had the same behavior in all confining stresses as the mixtures using PET flakes. Both results from Calheiros (2013) and Ramírez (2013) used the same clayey soil as the one used in the present research, and either the EPS or granular rubber worked as worked as a grain size improvement, filling up the remaining voids in the soil sample. The results founded for the bentonite, where the PET residue raised the peak, post-peak and residual strength, can be compared with the ones reached by Casagrande (2006), since the fibers had the same behavior of the PET flakes.