3
Experimental Program

The experimental program here established had as mainly objective to evaluate the effect of an addition of Polyethylene Terephthalate (PET) residue in the mechanicals properties of a clayey colluvial soil, a sandy soil and a bentonite. For that were made mixtures of soils and different contents of fine crushed PET and PET flakes. In order to obtain the physical index of both, pure soils and mixtures involved in this research, were initially performed the physical characterization tests. Thus, it was possible to highlight the parameters that could be correlated with the real mechanical performance of the materials used. Further, using Triaxial Consolidated Isotropically Drained Test and also the Direct Shear Test it was possible to study and evaluate the mechanical behavior of the materials involved.

The stages proposed for this experimental program, as well as the materials used, the tests methods and the equipment involved, are all described in this chapter.

All the tests performed for this research were executed at the Laboratory of Geotechnical and Environmental of Pontifical Catholic University of Rio de Janeiro (PUC-Rio).

3.1
Materials Used

For this research five distinguishes materials were used: Clayey Soil (C), Sand (S), Bentonite (B), Fine Crushed PET (P) and PET Flakes (F). It was worked with these materials in a pure form and on different mixtures.

3.1.1
Sandy Soil

The sand used in this study comes from a beach located in Barra da Tijuca in the west side of Rio de Janeiro city (Szeliga, 2013). The sand was collected in an area between Gastão Formenti and Jornalista Pierre Plancher streets, approximately 60 m from the sea water and 50 cm depth, in order to prevent collecting any kind of dust or undesirable particles. All the material gathered was characterized and the results will be shown in the present chapter. The Figure 3.1 gives an idea of the gathering place and surrounding area and Figure 3.2 shows a sample of the sand collected.

Figure 3.1 - Sand's collecting point at Barra da Tijuca, Rio de Janeiro.

Figure 3.2 - Sand sample used on this research.

3.1.2
Clayey Soil

According to Moreira (1998) *apud* Soares (2005), this is a colluvial ripe soil, clay-sandy; possibly it has the origin associated with erosive processes in past times. The soil was collected between 0,0 to 2,0 m depth from the surface in the Experimental Field II located in the PUC-Rio Campus, as shown in Figure 3.3. This soil has been studied by other authors in previous research such as: Marinho (1986), Lins (1991), Daylac (1994), Beneveli (2002), Soares (2005), Szeliga (2011), Ramirez (2012), Quispe (2013), Calheiros (2013) and Bolaños (2013) leaving an enormous knowledge about it.

Figure 3.3 - PUC-Rio Experimental Field.

The soil studied (Figure 3.4) has characteristics of yellowish red color, micro-granular texture and homogeneous appearance, consisting basically of quartz, altered garnet, clay minerals (essentially kaolinite) and oxides of iron and aluminum, as a result of weathering of primary minerals of biotite gneiss (Moreira, 1998 *apud* Soares, 2005).

The physics geotechnical characteristics of the present soil such as grain size, liquid and plastic limits and the specific weight (Gs) are presented and analyzed in section 4.1.

The material was manually gathered and stored in plastic buckets, latter it was taken to the laboratory and left in the drying oven at 60°C. After reaching constant water content the soil was placed in sealed plastic bags and kept in a wet chamber.

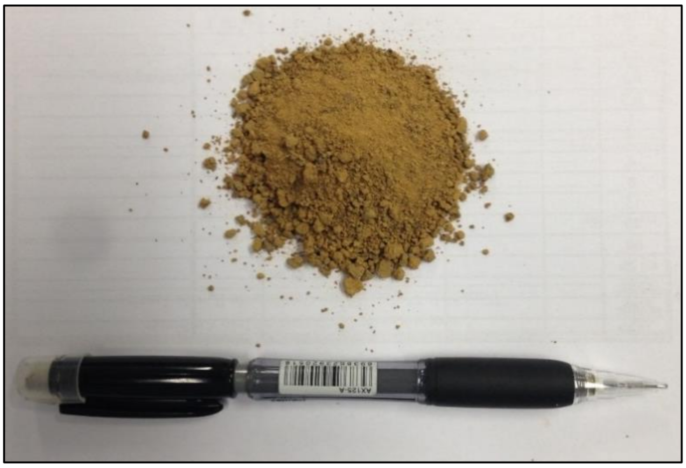
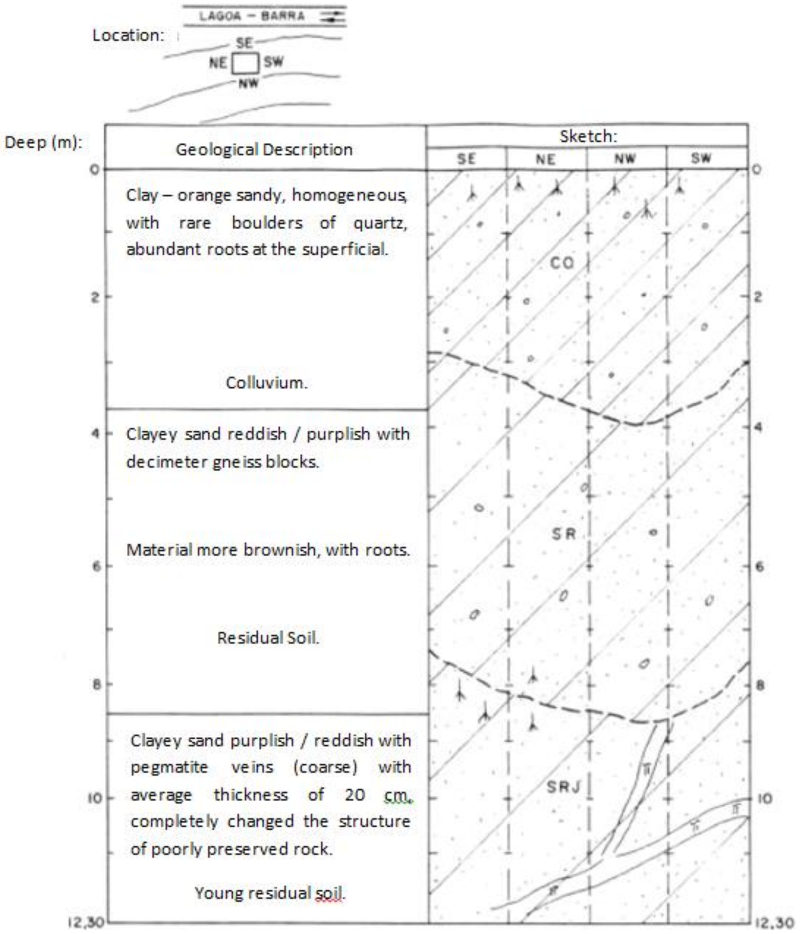


Figure 3.4 - Clayey soil sample used in this research.

Daylac (1994) did a representative morphologic description of the Experimental Field II soil profile at PUC-Rio from a well 13,5 m depth, shown at Figure 3.5. In the place where the soil was gathered, some fragments of quartz were observed. At the moment of the soil's preparation (powdering) for the tests the roots and remain rocks pieces were taken out.



Clay – orange sandy, homogeneous, with rare boulders of quartz, abundant roots at the superficial.

Colluvium.

Clayey sand reddish / purplish with decimeter gneiss blocks.

Material more brownish, with roots.

Residual Soil.

Clayey sand purplish / reddish with pegmatite veins (coarse) with average thickness of 20 cm, completely changed the structure of poorly preserved rock.

Young residual soil.

Figure 3.5 - Morphologic description of the PUC-Rio Experimental Field profile (Daylac, 1994).

Elaborate by Daylac (1994), the Table 3.1 summaries the results obtained by Sertã (1986) of a mineralogical analysis of the soil in the Experimental Field II for samples taken between 3,0 – 3,5 m depth. The major presence of some minerals such as kaolinite, gibbsite and goethite, together with the morphological profile previously shown suggest that the soil studied has a high degree of weathering.

Table 3.1 - Mineralogical Analysis (Sertã, 1996).

Portion of Soil	Mineral	Quantity/Observations
Gravel	Quartz Altered Garnet	Grains with arris colored between transparent and milky
Sand	Quartz Very Altered Garnet Ferruginous aggregates Magnetite	Grains with arris Correspond approximately 5% of the total sample Small proportions
Silt	Quartz Kaolinite Geothite	Presence Presence Presence
Clay	Kaolinite Geothite	Presence Some proportions

3.1.3
Bentonite

The sodic bentonite used in this studied (Figure 3.6) was commercially purchased in Rio de Janeiro, and according to the ABNT NRB 6502:1995, this bentonite can be classified as clay. The results of physics index and particle size distribution curve are presented in the section 4.1.3.

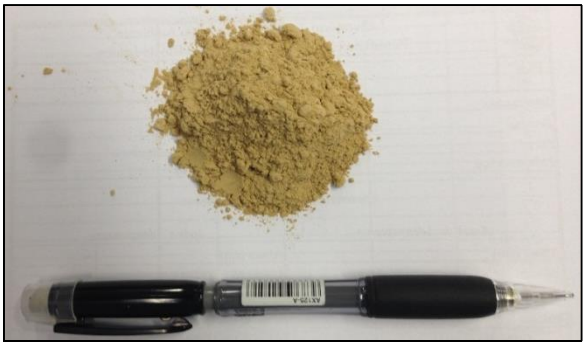


Figure 3.6 - Bentonite Sample used in this research.

3.1.4
Polyethylene Terephthalate (PET)

3.1.4.1
Fine Crushed PET

The fine crushed PET (Figure 3.7) used in this research was purchased in Campina Grande, Paraíba. The product is a result of a specific method of crushing normally done in six steps, and the PET comes out with a particle size up to 50 mesh (Melo, 2004).

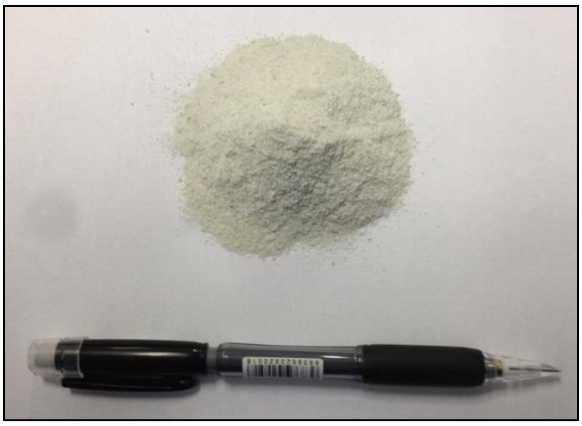


Figure 3.7 - Fine crushed PET used in this research.

According to Melo (2004) in the production of fine crushed PET, virgin or post-consumer, to obtain particles with a size up to 50 mesh, it is necessary six different steps described below:

- The first step consists in gathering the PET bottles, which the label and the caps are removed, and the remaining parts of the bottles are submitted to a washing process with water;
- The second step is grinding, where the bottles are crushed in a mill and the results are the PET flakes;
- The third step is the agglomeration, in which because the low density of the flakes, they receive a thermic treatment with heat in order to decrease the volume and consequently increase the density, making the material more suitable for the rotomolding process;
- The forth step is rotomolding, where the material is prepared for the milling stage;
- The fifth step is the milling process, where the material is cut, ending in a pellets shape.

The sixth and final step consist in the micronization, reducing the material in a powder with particle size passing 0,42 mm mesh.

As an example of the micronization process, the German company called Pallmann crushes the material into a powder size, using the PKM machine (Figure 3.8).

Figure 3.8 - PKM machine from Pallmann.

Operation method of the Pallmann PKM machine (Figure 3.9): via a storage bin (1), by means of a dosing unit (2), the material to be ground is fed into the mill (3). The pulverized material is conveyed out of the mill by means of a fan (4) and is transported via a cyclone separator (5) with downstream rotary airlock (6) onto a special screening unit (7). Coarse material from the screen is reintroduced into the mill for further size reduction.

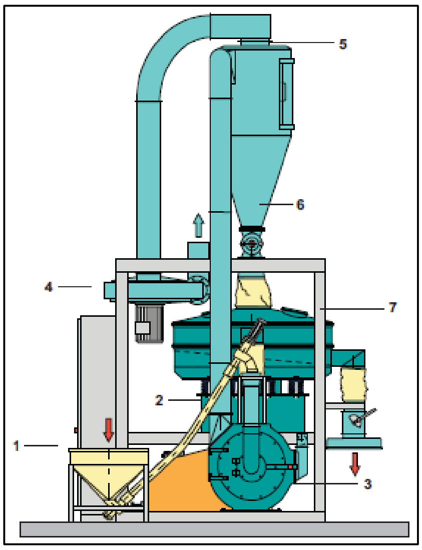


Figure 3.9 - PKM machine layout from Pallmann.

3.1.4.2
PET Flakes

The PET flakes came from the crushing process made in the material crusher at the Laboratory of Structures and Materials of PUC-Rio. The hole crushing process can be divided in four steps described below.

1st step: the PET bottles were cleaned and the top and bottom parts and the label were removed (Figure 3.10).

Figure 3.10 - PET bottles cleaned and without the label and the top and bottom parts.

The high speed crusher from Radial LaFrance model SG-500F (Figure 3.11), crushes the material using five very sharp blades. The PET bottles are introduced on the top of the machine (1), the blades cut them until they pass through the sieve (2), and finally the crushed material is collected in a box (3). This crushing process is repeated for each sieve and until the material achieve the wanted size.

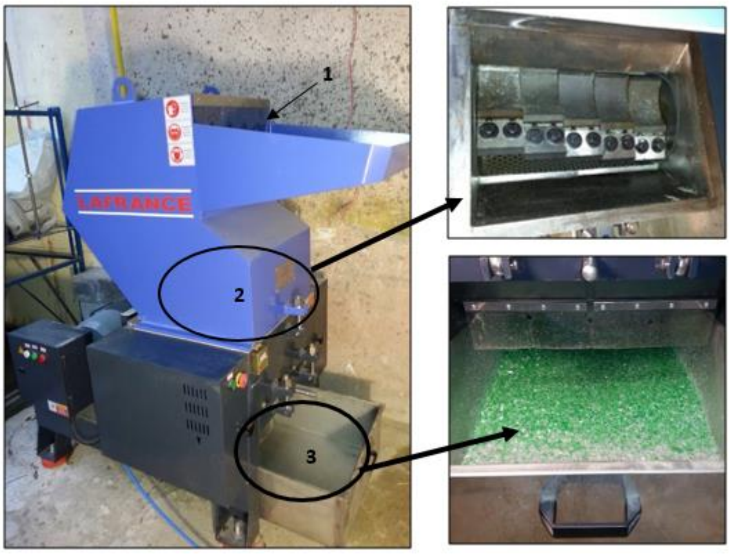


Figure 3.11 - High speed crusher used.

2nd step: the remaining portions of the bottles were crushed in a high speed crusher. They were initially crushed until they could pass through 10mm sieve, it was necessary to pass the material three times in the machine, in order to get it more homogeneous (Figure 3.12).

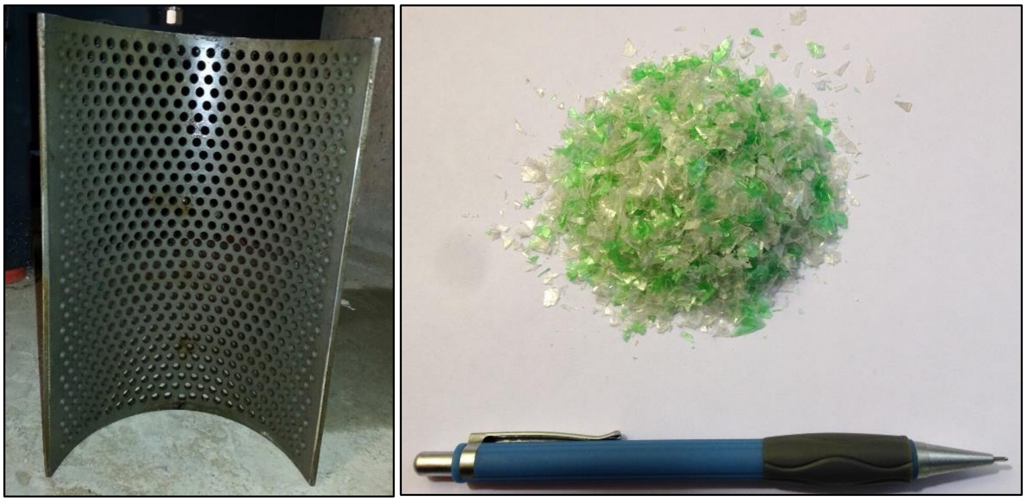

(a) (b)

Figure 3.12 - (a) 10mm sieve and (b) the PET flakes with 10mm size.

3rd step: the 10 mm sieve is changed and a 2 mm sieve is placed, and the crushed material passes through it at least five times (Figure 3.13).


(a) (b)

Figure 3.13 - (a) 2mm sieve and (b) the PET flakes with 2mm size.

4th step: the 1mm sieve is placed and all the material is crushed until it passes through this last sieve, the material passed in the machine approximately eight times to homogenize it (Figure 3.14).

(a) (b)

Figure 3.14 - (a) 1mm sieve and (b) the PET flakes with 1mm size.

3.1.5
Water

The water used in the specimens preparations for the compactions tests, triaxial shear tests and direct shear test came from the public water supply of the city of Rio de Janeiro. In the physical characterization test, it was used distilled water, as specified in standards.

3.1.6
Soil-PET Mixture

For each soil studied, it was prepared mixtures with different contents of fine crushed PET and PET flakes in order to determinate the optimal level for the insertion of this material as a soil improvement. The mixtures using the sand were prepared with 10 and 20% of fine crushed PET. With the clayey soil the mixtures were 10%, 20% and 30% of fine crushed PET and 3% and 5% of PET flakes. For the bentonite, the mixtures were made with 30% of fine crushed PET and 3% and 5% of PET flakes. For all mixtures the content of fine crushed PET and PET flakes were calculated relative to the dry weight of the pure soils, and they were adjusted according to the results obtained.

The choice of these contents was made with the aim of examining the development or reverse of the strength parameters in each type of soil and mixtures, to establish a maximum improvement with the highest volume of PET waste, since one of the objectives of using this material as reinforcement, is to give an environmentally friendly destination for the largest possible amount. This choice was also based in previous researches that used residue as soil improvement.

The water in the clayey soil was added related to the optimum water content obtained in the Standard Compaction test. For the sand and the bentonite, the mixtures were prepared with humidity of 10% and 170%, respectively. These contents were determinate from directed shear test in the pure soil, where theses contents showed better results in terms of strength. These values were similar to the ones found by Casagrande, 2005.

The Table 3.2 presents the abbreviations used to identify each type of soil and mixtures. It was performed 29 triaxial and 8 direct shear tests.

Table 3.2 - Abbreviations used for soils and mixtures.

Material / Mixture	Soil (%)	Fine Crushed PET (%)	PET Flakes (%)	Abbreviation
Sand	100	0	0	S100
Mixture 1	95	05	-	S95P05
Mixture 2	90	10	-	S90P10
Mixture 3	85	15	-	S85P15
Mixture 4	80	20	-	S80P20
Clayey Soil	100	0	0	C100
Mixture 5	90	10	-	C90P10
Mixture 6	80	20	-	C80P20
Mixture 7	70	30	-	C70P30
Mixture 8	97	-	3	C97F03
Mixture 9	95	-	5	C95F05
Bentonite	100	0	0	B100
Mixture 10	70	30	-	B70P30
Mixture 11	97	-	3	B97F03
Mixture 12	95	-	5	B95F05

3.2
Methods and Tests Procedures

The main purpose of performing this experimental program was to obtain the physical, chemical and mechanical characterization of the soils used. Evaluating their behavior through the results of the Triaxial Consolidated

Isotropically Drained (sand and clayey soil) and the Direct Shear (bentonite) tests, in order to know their strength parameters and get an idea in how the PET (fine crushed and flakes) can work as improvement in the soil.

Hereafter all the steps of the tests performed in this study will be presented, as well as the detailed description of the procedures and all the technical standards used.

3.2.1
Physical Characterization Tests

With the aim to determinate the index properties of the samples of sand, bentonite and clayey soil, physical characterization tests were carried at the Laboratory of Geotechnical and Environmental at PUC-Rio. The three different soils used were prepared following the Brazilian standards procedure (Brazilian Association of Technical Standards – ABNT). For the clayey soil and the bentonite the tests were performed as it is specified by the following standards:

- NBR 6457/1986 – Soil Sample – Preparation for compaction test and characterization;
- NBR 7181/1984 – Soil – Particle Size Analysis;
- NBR 6508/1984 – Soil –Determination of the specific gravity of the soil solids;
- NBR 6459/1984 – Soil – Determination of the liquid limit;
- NBR 7180/1984 – Soil – Determination of the plastic limit.

For the sand and the fine crushed PET, the tests were carried out as indicated by the following standards:

- NBR 6457/1986 – Soil Sample – Preparation for compaction test and characterization;
- NBR 7181/1984 – Soil – Screen Analysis;
- NBR 6508/1984 – Soil –Determination of the real grains density;
- NBR 12004/1990 – Soil – Determination of the maximum void index of non-cohesive soils;
- NBR 12051/1001 – Soil – Determination of the minimum void index of non-cohesive soils;

In the PET flakes, the characterizations tests were not done, because it was considered an inert material.

3.2.1.1
Real Density of the Grains

To determinate the real density of the grains for the sand, the clayey soil and their mixtures, it was used the material that passed through the mesh #40 (0,425 mm), adopting the procedures as described in the ABNT standard NBR 6508/1984.

The passing material was dried out at 105°C in the drying oven, and approximately 100 grams were used. Subsequently, 25 grams of each material were set into three pycnometers of 250 ml each, and then distilled water was added so the soil could be completely submerged. Later the remaining air, which might have been stayed in the soil voids, was removed with the aid of a vacuum pump. This step took 15 minutes to be completed; this is the time that takes to extract all air inside the pycnometers. After taking out all the left air, the total volume of pycnometers was completed with water and they were left in water bath to equalize the temperature that lowered down during the vacuum process. Next, each set (pycnometer+ water+soil) was weighed and the results were deducted from the weight of another set (pycnometer+water).

To determinate the real density of grains to the bentonite using the same procedure as the previous soils was not able, since the material showed a very fine grain size. Thus, the water added to the pycnometers could not penetrate and wet the same 25 g as it happened in the other soils. The main problem was that because the sodium bentonite has a very fine grain size material and it is also highly expansive, many problems happened while performing the test such as: the material stuck on the wall of the pycnometers and formed many lumps. Calheiros (2013) developed an alternative method which made possible to perform this test in the bentonite and it is described below.

- The use of a soil mass of 10g;
- In order to avoid forming a layer of soil stuck at the bottom of the pycnometer and to wet all the material, the soil was added to the pycnometer with water already inside it; note that the set water and

pycnometer were previously weighed, so the weight was only the weight of the material;

- The material inside the pycnometers was mixed for about 30 minutes with the aid of an ultrasound device, to obtain a more effective mixture;
- Again, the air was removed by applying vacuum.

All the results achieved for the soils and mixtures will be shown in Chapter 4.

3.2.1.2
Atterberg Limits

The plastic and liquid limits, were determined using the material which pass through the #40 mesh (0,425 mm), according to NBR 6459/1984 and NBR 7189/1984 from ABNT.

3.2.1.3
Sieve Analysis

In order to determinate the particle size distribution of the sand and the clayey soil, 1000 g of each material were sieved on the #40 mesh, according to the NBR 7181/1984 from ABNT.

The material retained on the sieve was washed and dried for 24 hours at 105°C, performing the coarse sieving after this period.

From the material that passes through the #40 mesh, approximately 70 g for the sand and 50,39 g for the clayey soil were used to the sedimentation process. These samples were mixed with 125 ml of sodium hexametaphosphate solution and they were left to rest for 24 hours.

After the sedimentation process finished, all the materials were washed on the #200 mesh, and the retained materials were taken to the drying oven. After dried, the fine sieving was proceeded.

To determinate the particle size distribution of the bentonite through the sedimentation process, the same problems mentioned before were noticed. Firstly, the test was carried on following the description of NBR 7181/1984 from ABNT, however a large quantity of material got stuck to the walls causing material loss. Another problem found during the sedimentation test was that, the sodium hexametaphosphate was supposed to act as a deflocculant but it did not happen.

In order to avoid this problem, 125 ml of sodium hexametaphosphate were mixtured with 200 ml of water and 50 g of bentonite, this mixture was left to rest for 24 hour and then the sedimentation test was performed. After this procedure finished, all the material was washed and nothing was retained on #200 mesh.

3.2.1.4
Maximum and Minimum Void Index

To determinate the maximum and minimum void index of the soil and mixture was used the procedures described in the NBR 12004/1990 and NBR 12051/1991, respectively. Firstly, the samples were homogenized and it was measured the height and the internal diameter of the cylindrical mold, in order to obtain the internal volume.

To determine the maximum void index, with the aid of a funnel the soil was placed inside the mold as soft as it is possible, leaving it to arrange in a constant flux on a vertical position. The height of the funnel was constantly rearranged in order to maintain the same height (1 cm), keeping a continuous flux of the soil's particles through the entire test, with no contact between the funnel and the soil. The funnel was moved around according to a spiral path, from the edge to the center of the mold, resulting in layers with uniform thicknesses. The mold was filled up to 1-2 cm above the top, the excess of soil was removed with the aim of a straight edge ruler, and then the set (soil+mold) was weighed.

For the minimum void ratio the same process using the funnel to place the soil inside the mold was followed. However initially was filled up just 1/3 of the cylinder volume, placing next, a disc and a weight inside to apply an overload in the material, leaving the set in a vibrating base for 1 min. This procedure was repeated for 3 layers up to 1-2 cm above the top of the cylinder. Later the excess material was removed and the set was weighed.

To both void index the same process was repeated 3 times, in order to obtain a more precise result. The value calculated for the indexes were the average of the three repetitions.

3.2.2
Chemical Characterization Tests

It was carried out the Energy Dispersive X-Ray Fluorescence Spectrometer Test (EDXRF), at the chemical laboratory of PUC-Rio, in the fine crushed PET and in the mixture, in order to determinate the chemical components and also to verify the existence of any hazard materials.

These tests are extremely important, since the classification of the waste as hazardous or non-hazardous and inert or not inert defines the choice of final disposal that it should have and their applications in the future. The results of the chemical tests were compared with the ones stablish by the Brazilian standard NBR 10004:2004 and are shown in section 4.2.

In order to determine the concentrations of the chemical elements of the fine crushed PET, and any possible results of reactions between them and the soil, it was performed Energy Dispersive X-Ray Fluorescence Spectrometer Test (EDXRF), using the equipment model EDX-700, in the fine crushed PET and in the mixture, this test allow to define the total chemical composition.

The fluorescent X-Ray spectrometer is an instrument, which determines qualitatively and semi-quantitatively the elements present in a certain sample by applying X-rays on the sample surface and later analysis of the fluorescent X-rays emitted back. This is a non-destructive technique for all types of sample such as solids, liquids or post.

3.2.3
Mechanical Characterization Tests

3.2.3.1
Standard Compaction Test

The compaction tests were performed for the clayey soil and the mixtures PET-soil, with the aim to determinate the optimum water content (w_{otm}) and the maximum dry density (γ_{dmax}) of the materials. These tests were carried out following the prescriptions of NBR 7182/1986 from ABNT, using the standard compaction energy and with material reuse.

After the material had been dried in the oven at 60°C, it was crushed and then passed through #4 mesh as it described at NBR 6457/1986 from ABNT –

preparation with previous drying process at hygroscopic humidity. Next a certain quantity of water was added, so the material could remain with 5% of humidity below the optimum moisture content. This value can be estimated trough the plastic limits, which the value may approach to the optimum humidity. After the soil (pure and the PET-soil) had been mixtured with the water volume calculated, it was well homogenized.

Later with the mixture prepared, the material was placed into the cylindrical mold with dimensions 10 cm x 12,7 cm (diameter x height). Then 26 blows were applied with a 2,5 kg tamper from a height of 30,5 cm approximately. The compacted portions of soil should occupy 1/3 of the cylinder height, the compaction was done in three layers. In order to have a good adhesion between the compacted layers, every layer was slotted before the next one was applied. Normally after complete the three layer compaction, it is reached a higher height than the cylinder mold, what happen because an extra mold is used, ensuring the total height needed. This extra mold is taken out at the end of the test, and the excess soil is removed.

Finishing the compaction process, the set (cylinder+soil) is weighed. With the total weigh of the sample and the cylinder volume it is possible to calculate the water unit weight. Through the removal of three sample from inside the specimen, the average humidity is calculated after the drying process in an oven. Finally the specific dry weight of the material is calculated.

After all the procedure finished, a new specimen is prepared with a higher quantity of water, raising the humidity of the mixture in approximately 2%. After this a new compaction process is performed obtaining a new pair of values of water content (w) and dry unit weight (γ_d).

With all values, a graphic of dry unit weight versus water content is potted, so the compaction curve is achieved. The values of w_{otm} and γ_{dmax} accomplished correspond to the peak of the curves, and they were used to mold the specimens for the triaxial CID test. The complete procedure was repeated 5 times for each mixture, in order to obtain five pairs of values, where at least two are at the dry branch and two are in the wet branch of the compaction curve.

The results of the compaction test are shown in section 4.3.1.1.

3.2.3.2
Triaxial CID Tests

The triaxial is one of the most trustful tests to determinate the strength parameters of the soil. According to Bishop & Henkel (1964), the type of triaxial test most commonly used in research work and in routine testing is the cylindrical compression test.

The Figure 3.15, by Bishop & Henkel (1964), illustrates a triaxial chamber with a cylindrical specimen inside. It consists essentially of a cylindrical specimen sealed in a watertight rubber membrane that is enclosed in a chamber in which it can be subjected to a fluid pressure, normally water. An axial load is applied on the top of the specimen and the test ends when the sample breaks by shear.

Tests are therefore classified according to the conditions of consolidation and drainage, which are: consolidated drained (CD); consolidated undrained (CU) and unconsolidated undrained (UU) tests (Bishop & Henkel, 1964).

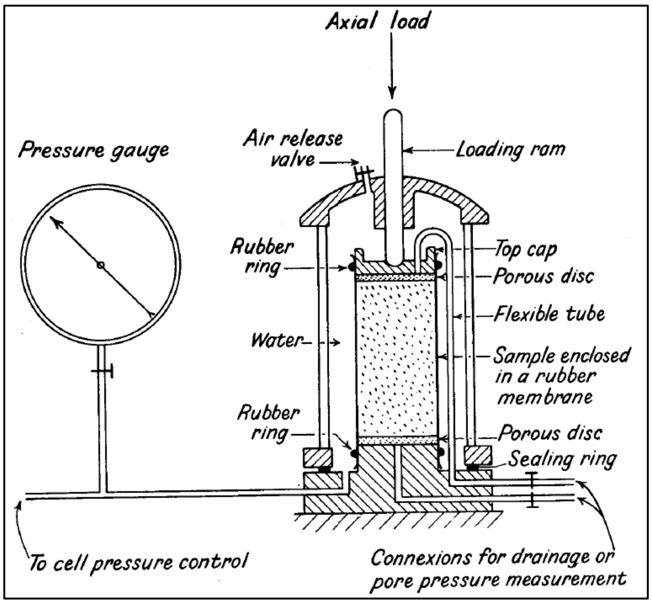


Figure 3.15 - Diagrammatic layout of the triaxial test (Bishop & Henkel, 1964).

With the aim of studying the mechanical properties of materials and mixtures, it was carried out Triaxial Consolidated Isotropically Drained tests. The tests were executed at Laboratory of Geotechnical and Environmental Engineering of PUC-Rio. Next will be shown the procedures applied on the specimen preparation, the saturation and shear process.

i. Equipment Used

The triaxial equipment used is from *Wykeham-Ferrance* with controlled displacement velocity, and capacity of 10 tons. The displacement velocity adjustments of the piston is determined by the proper selection of cog's pairs and the respective gear. The triaxial chamber used is suitable for specimens with a diameter of 1,5" and has an acrylic body that supports a maximum confining pressure of 1000 kPa.

The load cell used is from ELE International Ltd., with maximum capacity of 5000 kN and accuracy of 0,1 kN. To obtain the displacement it was used LVDT from *Wykeham-Ferrance* with 25 mm of course and accuracy if 0,01 mm. The transducer applied to measure the pressure in the chamber, the volume gauge and the pore pressure is from Schaevitz, with range of ± 2,0 kPa and maximum capacity of 1700 kPa.

The volume change is obtained through the volumetric variation measurer (VVM), manufactured in PUC-Rio, following the Imperial College model.

The recording of the measured data made through the transducer was done using the data acquisition system composed by the hardware Quantum X with eight channels from a Germany company called HBM, and also by the CatmanEasy software. With this system was possible to execute and monitor, in real time, all phases of the tests, Figure 3.16 resumes all the equipments that composes the triaxial test.

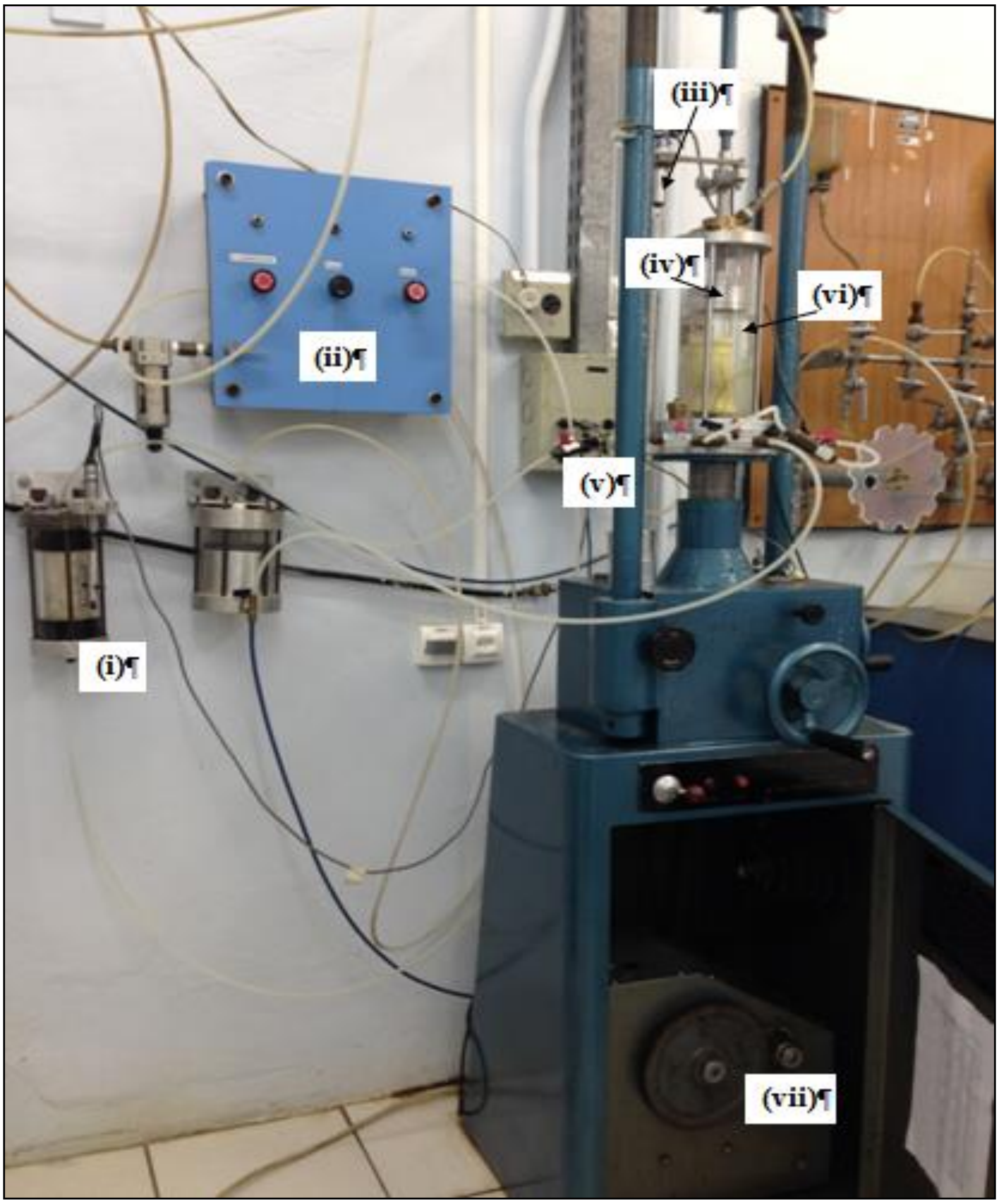


Figure 3.16 - (i) volumetric variation measurer; (ii) Pressures control dashboard; (iii) LVDT; (iv) Load cell; (v) Pressure transducer; (vi) Acrylic chamber; (vii) Set of cogs to apply the shear velocity.

ii. Specimen preparation of the clayey soil

To prepare the specimens of pure clay soil and the soil-PET mixtures, initially, a cylinder of soil was compacted at the standard Proctor energy, using the optimum moisture content and the dry specific weight reached for the soil and each kind of mixture (Figure 3.17).

With the compacted cylinder a specimen was shaped using an equipment manufactured by the laboratory of PUC-Rio (Figure 3.17). From each compacted cylinder, three smaller specimen can be obtained, making sure that the same condition is being used for all tests. The specimens dimension were 7,8 cm of height and 3,8 cm of diameter.

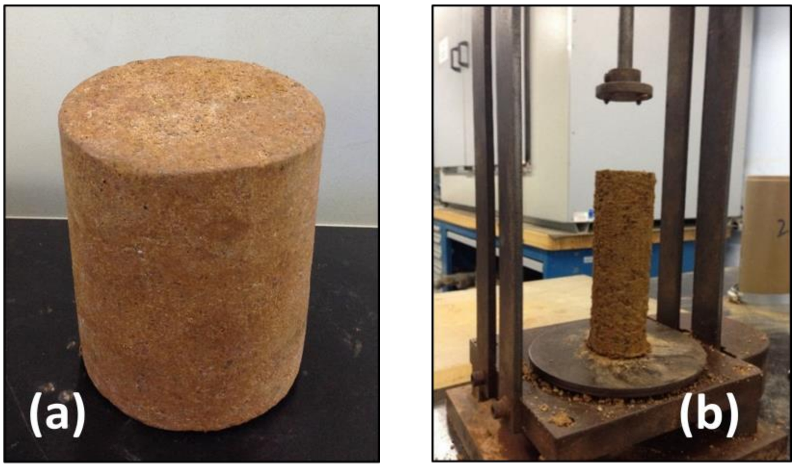


Figure 3.17 - Specimen preparation: (a) Compacted cylinder and (b) clayey soil after the shaping.

iii. Specimen preparation of the sandy soil

The preparation of the specimen of the sand and the soil-PET was done direct into the tripartite mold (Figure 3.18). This compaction was performed manually in six layers. For both, pure soil and mixture, the values of water content and relative density adopted were 10% and 50%, respectively.

Figure 3.18 - Tripartite mold.

Before assembling each specimen, the quantity needed to feel all the tripartite mold was calculated in order to maintain the compaction parameter indicated before. The Figure 3.19 illustrates the steps of specimen assembling.

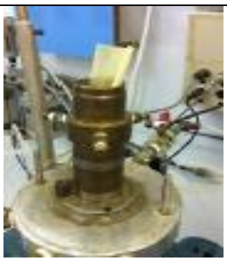
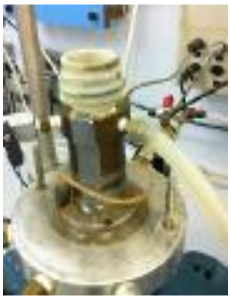
Assembling steps of the sandy specimen	
	1- The membrane and the o-rings are placed in the base of de cell;
	2- The tripartite mold is placed and the three parts are assembled together using a metallic clamp;
	3- All the gaps are sealed by a tape and the tripartite holes are closed with the aid of valves. The o-rings and the membrane are ajusted. Finally, the mold is connected to the vacum machine that maintains the membrane sticked to the mold’s walls;
	4- The material is compacted inside the mold in six layers, than the filter paper and the porous stone are placed followed by the top cap. Later the membrane and o-rings are adjusted;
	5- All the elements that help the specimen assembling are removed. The acrylic chamber is placed and the test are ready to start.

Figure 3.19 - Assembling steps of the sandy specimen for triaxial test.

iv. Specimen saturation process

The saturation process used for the specimen of pure soil and mixtures, was the saturation by seepage and by back pressure. In the seepage case, the pressure difference between the base and the top were 5 kPa, the seepage path was from the bottom to the top. In the saturation by back pressure, the confining pressure applied in the sample exceeded the back pressure in 10 kPa, minimizing the effects of the consolidation process, the flux in this process was allowed by the top and the base.

In order to verify the degree of saturation, the Skempton's parameter B was constantly calculated, and it is given by the following equation (2.1):

$$\boldsymbol{B} = \frac{\Delta \boldsymbol{u}}{\Delta \boldsymbol{\sigma_c}} \tag{2.1}$$

Where:

Δu: pore pressure excess created;
$\Delta \sigma_c$: increase of confining pressure applied.

For both clayey soil and sand samples, was considered acceptable values of B equal or superior than 0,95. Besides measuring the B parameter, it was also monitored the quantity of water that passed through the sample, considering it saturated when the volume percolated was two times the volume of voids of the specimen.

v. Calculation of shear velocity

After the saturation of the specimen, the isotropic consolidation phase was initiated. The consolidation process had an average duration of 24 hours. At this time, the data from the volume change were collected.

With these data, the graphic volume change (ml) x square root of time ($\text{min}^{0,5}$) was plotted. According to Head (1986), it should be made the extension of the initial straight path until it finds the horizontal extension of the final path. This final path corresponds to the stabilization of the volume changes. The intersection point of these two extended lines gives the square root of t_{100} ($\text{min}^{0,5}$) in the x axis. Then, with the value of t_{100}, the shear velocity is calculated.

For the drainage triaxial tests, the expression used (Head, 1986) was the following (Equation 2.2):

$$\boldsymbol{v = \frac{\varepsilon_f . L}{100 . t_f}} \tag{2.2}$$

Where:

v: maximum shear velocity in mm/min,

L: specimen height in mm,

ε_f: estimated axial strain at the failure in %,

t_f: minimum failure time in minutes.

The value of t_f for this kind of triaxial test is given by 8,5 times the value of t_{100}. However, if the time is smaller than 120 min Head (1986) proposes to use a minimum value for t_f of 120 min.

The objective to define a very slow velocity for the axial load is to allow the total drainage of the water inside the specimen without creating any pore pressure excess.

All values obtained for the specimen of pure soil and mixtures were smaller than 120 minutes. Thus, it was adopted t_f=120 minutes. So, the maximum velocity (v) calculated was the same for all tests (0,033 mm/min), and the adopted velocity was equal to 0,030 mm/min.

vi. Shearing

With the shear velocity, the next step was to adjust the pair of cogs that define the desired velocity in the triaxial equipment. For the calculations, was adopted 18% of maximum strain.

For the triaxial tests, the variants of stress q (deviator stress) and p' (effective stress) were calculated using the formulation of Lambe. For the soil strength parameters, it was used values of the strength envelope (α') and cohesion (c') obtained in the space p':q to calculate the strength parameters in the Mohr Coulomb space (ϕ' – c'). The formulations of Lambe and the parameters that are presented in the results graphics are defined as:

$$\boldsymbol{q} = \frac{(\sigma_1' - \sigma_3')}{2} \tag{2.3}$$

$$\boldsymbol{p}' = \frac{(\sigma_1' + \sigma_3')}{2} \tag{2.4}$$

$$\mathbf{tan}(\alpha') = \mathbf{sin}(\varphi') \tag{2.5}$$

$$\boldsymbol{a}' = \boldsymbol{c}'.\mathbf{cos}(\boldsymbol{\varphi}') \tag{2.6}$$

Where:

α': slope of the strength envelope in the p’:q space;

a’: intercept with the q axis of the strength envelope in the p’:q space;

φ’: slope of the strength envelope in the σ:τ space (Mohr – Coulomb);

c': intercept of the strength envelope in the σ:τ space (Mohr – Coulomb).

3.2.3.3 Direct Shear Test

i. Specimen preparation of the bentonite

For the preparation of specimens of pure bentonite and bentonite-PET mixture, the material compaction was made directly into the direct shear test (inside the shear box) manually.

The bentonite samples were prepared with 170% of humidity, which correspond a void ratio of 4,93. To make sure that the material stayed with the right properties, it was calculated the right amount of dry material that should be placed into the shear box, then performing the mixture with the quantity of water and later with the PET contents. With the aid of a metallic template, it was possible to adjust the proper height of the material inside the equipment.

ii. Procedure of the test

The direct shear tests were carried on with the bentonite and the mixtures, with the aim to determinate the shear strength of the soil. This strength is obtained through the parameters of cohesion (c) and friction angle (ϕ). These tests were performed following the methods described by the standard ASTM D 3080/2004.

To perform this test, the specimen was placed inside the metallic shear box. The box is divided horizontally in two and the normal force is applied on the top of the specimen in the shear box. The shear force is applied by moving one half of the box relative to the other in order to cause failure. The upper and lower boxes are separated in 1,0 mm before initiates the shear test, so it is possible to have the relative displacement between them. Above and below the specimen are placed plates with grooves, which provide friction to the soil preventing it to slide when a horizontal force is applied. Filter papers to prevent the particles from being carried, and porous stones so the drainage can occur freely, even if the specimen was partially or totally saturated, are placed in the right position.

The shear test was performed with strain control, where a constant rate of shear displacement is applied to the upper half of the box by an engine, which operates with cogs with a velocity that is determinate by a factor, according to the load applied vertically. This velocity is calculated through the data that comes from the initial phase of the test called the consolidation phase, where the specimen is submitted to vertical stress and it is measured the variation of the specimen height with the time, until this height stabilize. Through the graphic of vertical displacement versus square root of time (t), is obtained the value of t_{100}, that corresponds to 100% of consolidation, and the velocity to be used in the shear phase is calculated. The consolidation time was estimated in 24 hours.

In the shearing phase, the failure of the specimen occur along the division plane of the box. The horizontal displacement of the upper half of the box was measured by a horizontal LVDT (Linear Variable Differential Transformer), which works as a sensor to measure the linear displacement. The variation of the specimen height, in other words, the variation of the volume of the specimen throughout the test are obtained by the vertical LVDT readings. The load ring measures the horizontal force applied on the specimen.

The tests were carried out in similar specimen, for the bentonite and the mixtures. It was planned to perform the tests in three different, 50, 100 and 200kPa. However, during the separation of the shear box the material escaped through the gap left between them, making difficult to continue the test. Thus, the mixtures were tested in two different values of normal stress (50 and 100kPa). It was also expected to perform more direct shear test in other mixtures with the fine crushed pet but, as much as the bentonite content decreased, more plastic the mixture became. This happened because the fine crushed PET is an inert material, and all the water added in the mixture was absolved by the bentonite. Through the graphic of Maximum Shear Stress versus the Normal Stress, the failure envelopes and the shear strength parameters of the soil are determinate. The Figure 3.20 illustrates the direct shear equipment used in this research.

Figure 3.20 - Direct shear equipment.

3.2.3.4 Scanning Electron Microscope (SEM)

In order to evaluate the interaction among the particle, it was performed a scanning electron microscope test with a magnification of up to 30.000 times (model TM-3000 from Hitachi), in the department of material engineering of PUC-Rio. The SEM test consists in a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that can be detected and that contain information about the sample's surface topography and composition.