2
Literature Review

In this section will be highlighted the main researches using alternatives materials for soil improvement, such as natural (coconut, sisal and areca nut) and synthetic (PET, polystyrene) fibers, granular rubber, expanded polystyrene (EPS) and ashes of solid municipal waste (SMW). It also will be presented a national/international recycling scenario, as well as the PET characteristic and brief history.

2.1
Polyethylene Terephthalate (PET)

2.1.1
General Aspects of the PET

The Polyethylene Terephthalate, or simply PET, is a thermoplastic polymer, from the family of the polyester. What distinguish the thermoplastic is that they soften when heated and become more fluid as additional heat is applied. The curing process is completely reversible as no chemical bonding takes place (Figure 2.1). This characteristic allows thermoplastics to be remolded and recycled without negatively affecting the material's physical properties. However, there is another kind of polymer, the thermoset, which contains polymers that cross-link together during the curing process to form an irreversible chemical bond. The cross-linking process eliminates the risk of the product remelting when heat is applied, making thermosets ideal for high-heat applications such as electronics and appliances.

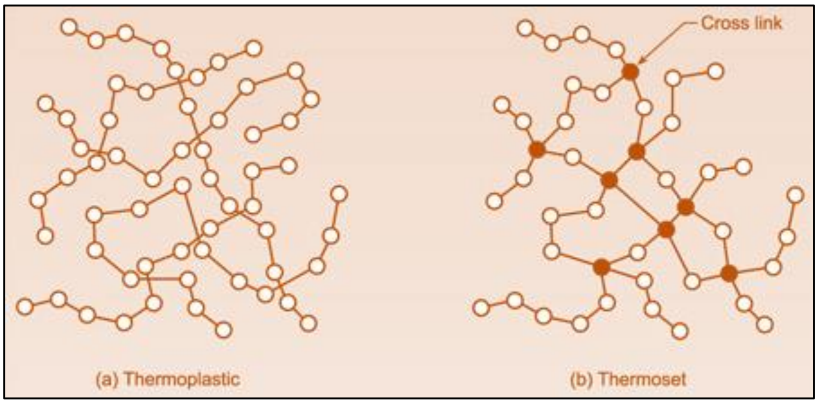

Figure 2.1 – Thermoplastic (a) and Thermoset (b) chemical bonding.

The PET was firstly synthetized by two British chemical Whinfield and Dickson, in 1941, composed by the reaction between two monomers, the terephthalic acid and the ethylene glycol. The first monomer is a solid whose melting point is around 140 °C, and the second is an alcohol, liquid at room temperature and with the boiling point of 197ºC (Mano and Mendes, 2001).

After the Second World War, the textile industry of the time, based basically on cotton fibers, linen and wool was affected, and the researches were focused on the study of polyester to textile applications, driven mainly by the company *DuPont*. After that, the use of PET increased drastically due to technological advances and this polymer was vastly applied. In the early sixties, it was developed the bioriented film of PET, which consistss in a fine pellicle of the polymer bioriented in two steps and in different direction, was largely used as material for food packing (Barry and Pellereau, 1993). In the 70s, the first PET bottles were created in the United States and Europe, after careful review of the safety and environmental aspects. In 1988, PET arrived in Brazil and was also first used in the textile industry. Only, in the 90s, PET occupied an important place in the packaging market, revolutionizing it, especially the market of carbonate drinks.

The PET bottle solved the transportation problem that the glass bottles produced, because the PET bottle is a packaging with excellent mechanical strength properties (impact), transparency, waterproofness and lightness. Otherwise than some kinds of polymers, the PET resists the damaging attack of the acids, water and bases. This phenomenon can be explained due to the fact that the PET presents aromatic rings and also packaging of their polymeric chain, making difficult the access of the degrading materials (Barboza, 2003).

The industrial production of PET can be done in two or three steps, depending on your application: (I) pre-polymerization; (II) polycondensation and (III)polymerizing in the solid state. The prepolymerization and polycondensation are used generally for producing textile fibers which do not require high mechanical stresses. For PET bottles the polymer needs a high molecular weight (> 30,000 gmol^{-1}) and this can be achieved only by applying the polymerization step in the solid state. The Table 2.1 shows the data of the virgin resin of PET (Mano and Mendes, 2001).

Table 2.1 - Data of the virgin resin of PET (Mano and Mendes, 2001)

Monomers	Dimethyl terephthalate (solid) Ethylene glycol (liquid).
Melting point	140°C - 284°F
Boiling Point	197° C – 386,6°F
Polymer	-(OOC-C_6H_4-COO-CH_2CH_2)n – Poly (ethylene terephthalate).
Preparation	Mass polycondensation. Monomers: calcium acetate, antimony trioxide, 280°C (536ºF).
Properties	- Molecular Weight: 40000u.ma; - Density: 1,33-1,45 g/cm^3; - Crystallinity: variable; - Glass Transition: 70-74ºC (158-165ºF); - Melting temperature: 250-270ºC (482-518ºF); - Thermoplastic material, high mechanical, chemical and thermal strength; - Low gases permeability.
Applications	- As fiber, textile industry, in general. Blankets for industrial filters and slope stability. - As device: components in the automotive and electronics industry. - Food packaging, cosmetics and pharmaceuticals products.

	- Bottles for carbonated beverages. - As film: magnetic tapes, in X-Ray and photography reproduction.
Commercial Names	Dacron, Mylar, Techster, Terphane, Bidim.
In Brazil	Rhodia-Ster (MG), Fibra (SP), Hoechst (SP) e Dupont (SP).

Because of the excellent relationship between mechanical and thermal properties and production cost, PET is the most produced thermoplastics in the world, reaching world production of around 2,4 x 1010 kg in the end of nineties (Romão *et al*, 2009). Figure 2.2 represents the polycondensation reaction that results on the PET.

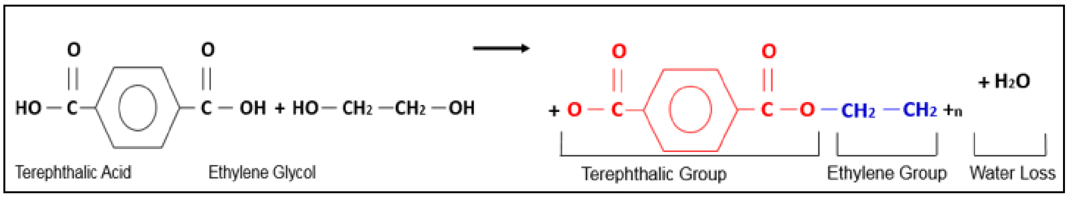

Figure 2.2 - PET polycondensation reaction (Romão *et al*, 2009).

According Romão (2009), in Brazil, the main application of PET is in the packaging industry (71%). As stated by CEMPRE (2014), Brazil consumed 514.000 tons of PET resin in the manufacturing of packaging in 2011.

2.1.2 Environmental impact and PET recycling

Currently, the polymers are a significant part in the composition of solid municipal waste (SUW). According to Romão *et al* (2009), in 2005 they were about 20% (percentage by weight) of SUW collected in Brazil. Figure 2.3 shows the main polymers produced in Brazil in 2005. It is observed that the production of PET is 9% of the total polymer production in Brazil; however, the PET fraction of SUW that corresponds to the polymers is on average of 20% (Figure 2.4).This is because the polypropylene (PP) and polyvinyl chloride (PVC) are used in the manufacture of long-life products, whereas PET is used in short life products such as packages.

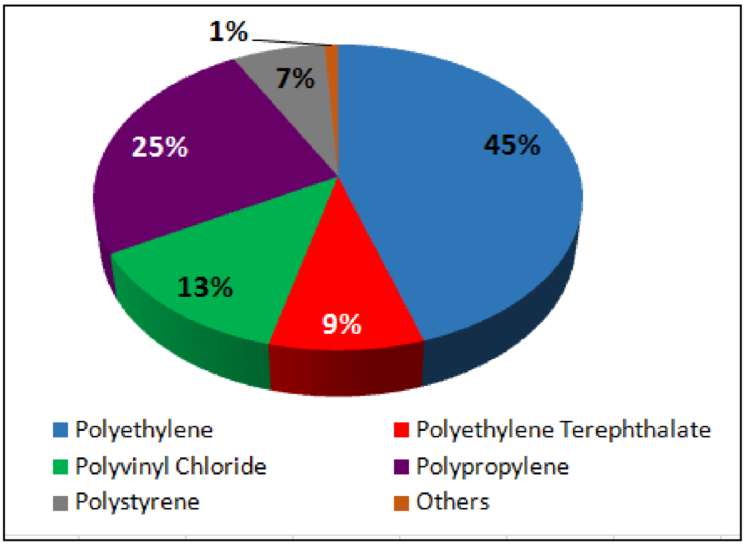

Figure 2.3 - Domestic production of thermo-plastic polymers in 2005 (Romão *et al*, 2009).

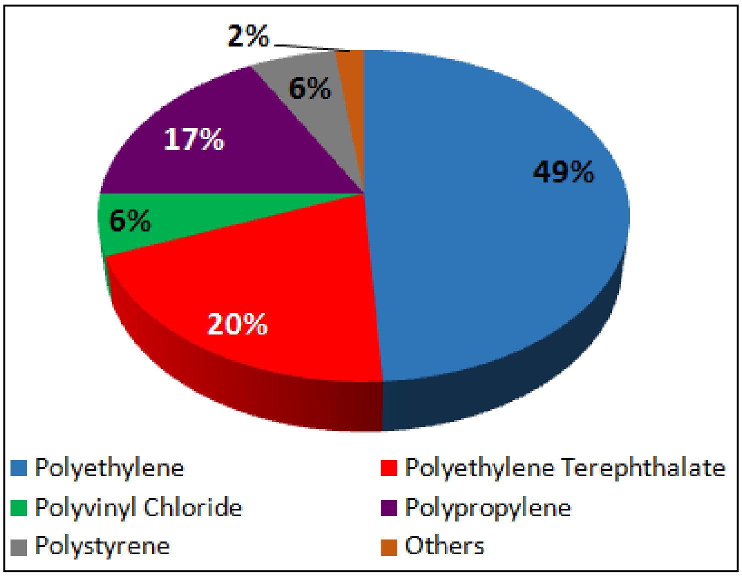

Figure 2.4 - Percentages of the contribution, by weight, of the thermoplastic polymers in SUW (Romão et al, 2009).

Romão *et al* (2009), Spinacé and De Paoli (2005) stated that, the polymers recycling can be divided in four different category: primary, secondary, tertiary and quaternary. The main difference between the primary and secondary is that, in the primary it is used polymers pre-use and in the secondary it is used polymers post-use, but both use the mechanical recycling process. The tertiary and quaternary processes are called chemical and energetic recycling, respectively. In chemical recycling PET components are separated to provide raw material for resins and solvents, among other products. The energetic recycling is carried out with PET burning, taking advantage of the heat generated to produce electricity (power plant), to power boilers and blast furnaces. The PET has a high calorific value and exhale, when burned, substances such as carbon monoxide, carbon dioxide, acetaldehyde, vinyl benzoate and benzoic acid (Melo, 2004).

The mechanical recycling is the most used in Brazil due to various factors like: cost of labor, low investment for installing a recycling plant and large volume of post-consumer polymer, unlike the countries from Europe and Japan, which use the chemical and energy recycling, mostly (Spinacé and De Paoli, 2004).

As reported by ABIPET, in 2009 Brazil ranks second after Japan in the PET recovery rate (recycling rate), placing itself ahead of some European countries and the United States which have more advanced recycling techniques (Figure 2.5).

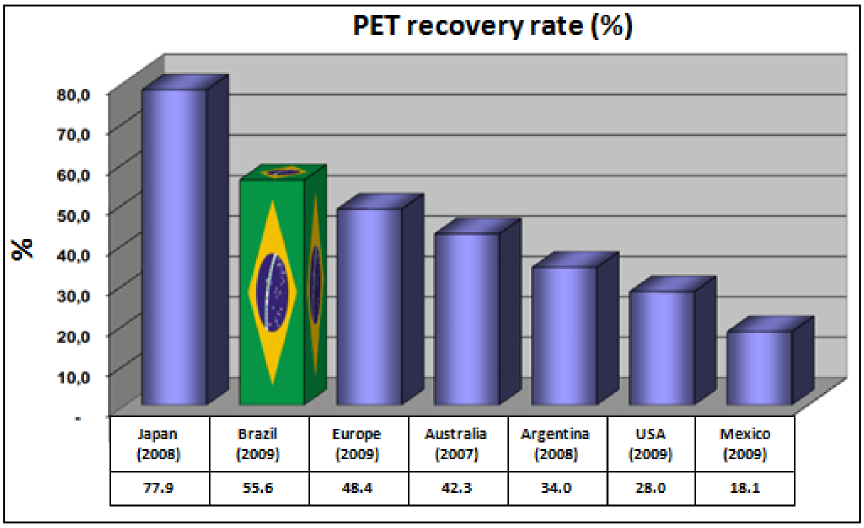

Figure 2.5 - PET recovery rate (ABIPET, 2009).

ABIPET also reported that, the volume of recycled PET in 2012 was 331.000 tons with what Brazil achieved a recycling rate of 58,9% (Figure 2.6). However, this figure also shows that, there is a large portion of PET whose final disposal remains in the landfills. The PET is nowadays considered the second most recycled product in Brazil, losing just for the aluminum.

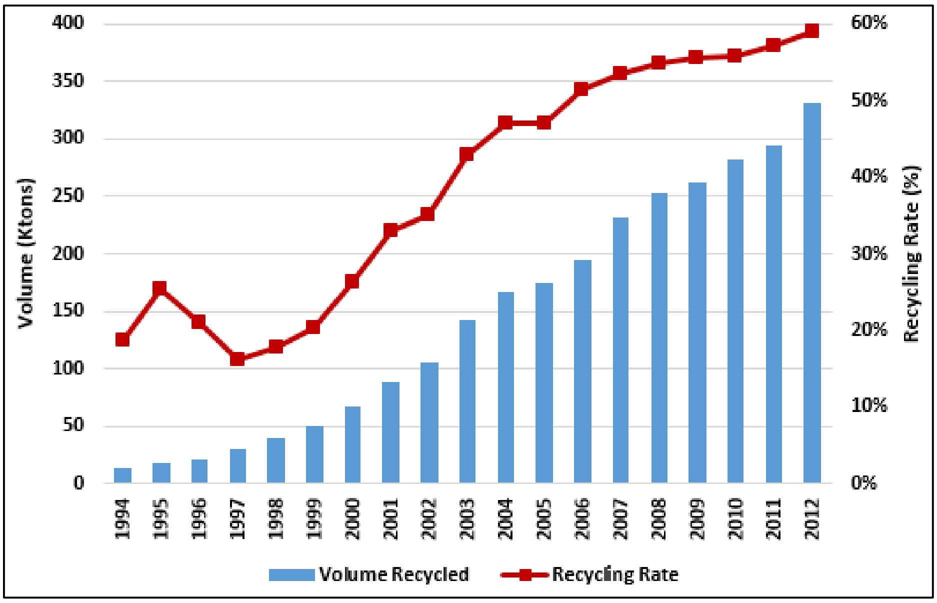

Figure 2.6 - PET recycling in Brazil (ABIPET, 2013).

2.1.3 Brazilian legislation regarding of the use of PET

In Brazil, the post-consumer packing of PET are considered solid waste, and its disposal/recycling are governed by the Brazilian legislation 13.305, from August, 2010.

In accordance with the decree No. 987 of 1998 of the Health Surveillance Secretariat of the Ministry of Health, it is only possible the use, for recycling, the post-consumer PET with multilayer packages from the packaging of non-alcoholic carbonated beverages.

Therefore, the objects made from recycled polymers have limited application, on other words, it can not be used in contact with beverages, medicines, food, toys and hospital material, because depending on the previous use, it can be contaminated. (Spinacé and De Paoli, 2005).

The PET is chemically classified as a thermoplastic polyester and, according to the norm of the Brazilian Agency of Technical Standards - ABNT NBR 13.230 from 1994, has the coding represented in Figure 2.7.

Figure 2.7 - PET recycling symbol.

2.1.4 Soil Improvement

Soil reinforcement is defined as a technique to improve the geotechnical characteristics of the soil (Ling *et al*, 2003). Reinforcement consists of inserting certain material in another, in order to increase its properties. So, many different kinds of materials have been studied with the aim of improving the strength properties of some soils.

Casagrande (2005) highlighted that, soil reinforcement it is known as a method that uses physics and/or chemical process in order to improve the mechanical properties of the soil. The main proposes of this method is to raise the soil strength while it compressibility and permeability decrease. The term soil improvement is associated with chemical treatment, and the term soil reinforcement is linked with the addition of some material in landfills and embankment.

The notion of soil reinforcement is an ancient technic and is it largely demonstrated by the nature such as, animals, birds and the action of the roots. This technics are known to be used since the fifth and fourth century before Crist (Jones, 1985). The idea of soil reinforcement has as main propose, the improvement of the soil parameters. This concept was firstly developed by a French engineer called Henri Vidal in the sixties, in which he proved that, introducing a reinforcement element in a soil mass it will improve the soil shear resistance.

Nowadays the soil improvement techniques are very well developed, and in order to find alternative materials, many researches have been carried out with large amount of different materials like natural fibers (coconut, arecanut and sisal), synthetic fibers (PET, polypropylene and glass), expanded polystyrene (EPS), granular rubber waste and ashes of solid municipal waste (SUW) are being used in order to improve the bearing capacity of the soil.

Gray and Ohashi (1983) developed a theoretical model to study the behavior of a sand reinforced with different fiber such as naturals, synthetics and metallic. The authors performed direct shear test in the sand in a soft and dense state, reinforced with the fibers. Gray and Ohashi (1983) concluded that the insertion of the fibers raise the peak strength and reduce the post peak drop. They also noticed that there is a confining stress, where under this, the fibers are ripped and over that the fibers are elongated.

According to Rowell *et al.* (2000), the reject of the coconut fruit is the outer covering, which is a fibrous material of a matured fruit and it is called coconut husk. The fibers consist mainly in tannin, lignin, cellulose, pectin and other soluble substances. However, because the high amount of lignin, the degradation of the fiber happens more slowly than order natural fiber. Therefore, this kind of fiber has a long lasting life of 4 to 10 years. This fiber has been largely studied, Ravishankar and Raghavan (2004) reported the maximum dry density of a lateritic soil stabilized with coconut fibers, decrease with the addition of the fibers, in the other hand, the optimum moisture content of the soil increases with the increment in the percentage of the coconut fibers added to the soil. The California bearing ratio increases almost 10% of coconut content, and further raise in the fiber amount results in the reduction of the value. The authors also noticed the percentage of water absorption growths with an increase in the coconut percentage. The tensile strength of the soil reinforced with coconut (oven dry samples) increase with as the percentage of coconut raises. The tensile strength also increases when the quantity of coconut raises in a coir-reinforced soil at the optimum moisture content. It is observed that for both, pure soil and coir-reinforced soil, the tensile strength at the optimum water content were considerably lower than the one obtained for oven dry samples.

Bolanõs (2013) studied the mechanical behavior of a clayey soil reinforced with coconut fiber, where a local clayey soil was mixtured with milled coconut fibers in two different contents (0,5 and 1,0%) and with cut fibers in contents of 0,5%, 0,75%, 1,0%, 1,25% and 1,5% in relation with the dry weight of the soil. The author observed increase in the shear strength of the soil-fiber mixtures, since it was observed a small increase in friction angle and a significant increase in the cohesion of the reinforced mixtures, compared with the results obtained for the pure soil.

Singh and Arif (2014) conduced an experimental study on a local silty sand soil mixed with variable percentage of coal ash and coconut fiber. For the experiment, Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) tests were conducted on the soil mixed with coal ash, coconut fiber and/or both. The percentage of coal ash by dry weight of soil was taken as 20%, 30%, 40% and 50%. They noticed a significant increase in UCS and CBR value was observed for addition of 20% of coal ash in the soil. UCS value is maximum (1,81 kg/cm^2) for 20% coal ash mixed with soil. The unsoaked and soaked CBR values as 10,5% and 5,6% increase to 27,7% and 14,6%, respectively. It was also observed that the rate of increase in CBR values decreased after further addition of coal ash beyond 20%. Randomly mixed coconut fiber was included in optimum soil-coal ash mix (i.e. 80% soil and 20% coal ash) and varied as 0,25, 0,50, 0,75 and 1,0%. As result, the value of UCS increased considerably with inclusion of coconut fiber in soil-coal ash mix. The addition of these waste materials (coal ash + coconut fiber) resulted in an increase in the strength of soil and less thickness of pavement.

Lekha *et al.* (2014) used the areca nut coir and cement as soil reinforcement, the main focus of the work was to study the durability test and physical evaluation of the mixture. The areca nut content was varied from 0,2% to 1% with an increment of 0,2%. For further improvement, a uniform dosage of 3% cement was added to soil. Laboratory tests performed included the Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), durability and fatigue behavior. The test results indicated that the improvement in characteristics of the soil cement areca nut mixtures were functions of coir dosage, soil type and curing days. As the percentage of areca nut increased, the UCS value also increased up to a certain limit and beyond that it slightly decreased. Then, the optimum strength was obtained at 0,6% coir and 3% cement content, and further increase in areca nut leads to decrease in strength.

Sotomayor (2014) studied the influence of the inclusion of coconut fiber as reinforcement of soil. The authors compared the sandy soil reinforced and unreinforced evaluating load-settlement behavior through real-scale plate load testing. It was observed through the results that, the load-settlement curves showed a better stress distribution using fiber rug but a greater degree of surface fissuring was noted. Instead using randomization distribution, stress distribution was lower but was inhibited surface fissuring propagation; both results were compared with soil without addition of fibers increased resistance to settlement.

Another natural fiber that has been largely studied is the sisal fiber. Sisal is a plant originally from Mexico, and it is one of the four most widely used natural fibers and it is almost half of the total production of the textile fibers (Mishra *et al*, 2004).

Leocádio (2005) evaluated through laboratory tests the effect of the addition of sisal fibers in a lateritic soil, in order to establish the mechanical behavior of the material. The tests performed were Normal Proctor, CBR and direct shear test. The sisal fibers were randomly included in soil in different contents 0,25% and 1% by weight and also in different lengths between 10 and 25 mm. The author noticed that the addition of sisal fibers improved the mechanical properties of the lateritic soil, mainly the peak strength, which compared with the pure soil, had great improvement in all levels of normal stress.

Prabakar and Sridhar (2002) use sisal fiber under four different percentages of fiber content, i.e. 0,25%, 0,5%, 0,75% and 1% by dried weight, and four diverse lengths 10, 15, 20 and 25 mm. The authors studied the strength behavior of the soil reinforced with randomly included sisal fiber. The reinforced soil samples were subjected to compaction and triaxial compression tests. The results of these tests have shown a significant improvement in the failure deviator stress, shear strength parameters (c and ϕ) of the studied soil. Prabakar and Sridhar concluded that sisal fiber can be considered as a good earth reinforcement material.

Manjunath *et al* (2013) investigated the effect of sisal fiber and lime on the compaction characteristics, California Bearing Ratio and Unconfined Compressive Strength of soil. The fibers were cut into pieces of 10mm length and were randomly mixed with soil in varying percentages (0,25%, 0,5%, 0,75% and 1%) by dry weight of soil. The addition of various percentages of lime to black cotton soil increased value in the unconfined compressive strength up to 3% and addition of lime with sisal fiber also raised the compressive strength up to 0,75%.The curing period with addition of lime and sisal fiber gave higher strength values. Hence, the authors concluded that 3% of lime content and 0,75% of sisal fiber was considered as optimum percentages for black cotton soil.

Besides the natural fibers, recently, soil reinforcement using synthetic fibers have being largely studied. Casagrande et al. (2005) observed the isotropic compression behavior of a sandy soil reinforced with polypropylene fibers. The fibers were randomly distributed and, the content of fiber mixed with soil was 0,5% with the length of 24 mm and 0,023 mm of thickness. The authors observed two distinct and parallel normal compression lines for the fiber-reinforced and nonreinforced sand. The fibers were exhumed after testing and it was found that fibers had both extended and broken, indicating that the fibers tend to suffer large plastic tensile deformations before breaking and that the fibers act under tension even in isotropic compression. Consoli *et al.* (2007), Casagrande *et al.* (2007) and Casagrande *et al.* (2009) used a sand reinforced with the same fibers and performed a series of tests to evaluate the influence of the inclusion of the fiber in the behavior of the soil.

Casagrande *et al.* (2006) studied the behavior of a polypropylene fiber-reinforced bentonite evaluated at large shear displacements by a series of ring shear tests carried out at normal stresses varying between 20 and 400 kPa. Bentonite/polypropylene fiber mixtures were molded at an initial moisture content of 170%, with fiber lengths of 12 or 24 mm. The fiber thickness was 0.023 mm and the fiber content was either 1,5 or 3% by dry weight. The authors concluded that, inclusion of randomly distributed fibers increased the peak shear strength of the bentonite, but the increase in strength deteriorated at large displacements and the residual strengths of both the non reinforced and fiber-reinforced bentonite were similar. The peak shear strength was found to increase both with increasing fiber length and content. The fibers were exhumed after testing and it was found that the fibers had both extended and broken, with a predominance of broken fibers.

Tang et al (2006) investigated the effects of discrete short polypropylene fiber (PP-fiber) on the strength and mechanical behavior of uncemented and cemented clayey soil. For the investigation, the authors prepared 12 groups of soil samples at three different percentages of PP-fiber content (i.e. 0,05%, 0,15% and 0,25% by weight of soil) and two different percentages of cement content (i.e. 5% and 8% by weight of soil), unconfined compression and direct shear tests were carried out after 7, 14 and 28 day of curing periods. The test results indicated that the inclusion of fiber reinforcement within uncemented and cemented soil caused an increase in the unconfined compressive strength, shear strength and axial strain at failure, decreased the stiffness and the loss of post-peak strength, and changed the cemented soil's brittle behavior to a more ductile one.

Correia *et al* (2014) researched the effect of binder and fiber quantity on the mechanical behavior of "Baixo Mondego" soft soil, chemically stabilized with binders and reinforced/non-reinforced with short polypropylene fibers. The experimental program covered four types of tests, unconfined compressive strength test, direct tensile strength test, split tensile strength test and flexural strength test. The results indicated that an increasing in the binder content caused an increment in the stiffness, the compressive and tensile strength, but had a lower impact on the specimens reinforced with fibers. The authors also noticed that in general, the addition of a low quantity of fibers to the stabilized soft soil originates a decrease in the stiffness, compressive and direct tensile strength, a reduction of the loss of strength after peak and a change in behavior, from brittle to more ductile. In flexural strength tests the impact of the fibers was significant, while in the direct tensile strength tests the inclusion of fibers has a negligible effect.

Yi Cai *et al* (2006) studied the influence of the mixture of polypropylene fiber and lime on the engineering properties of a clayey soil, for that the authors separated the mixtures in nine groups of treated soil specimens and tested them at three different percentages of fiber content 0,05%, 0,15%, 0,25% by dried weight and also three different percentages of lime 2%, 5% and8% by dried weight. The mixtures were subjected to unconfined compression, direct shear, swelling and shrinkage tests. It was founded by the researcher that fiber content, lime content and curing duration had significant influence on the engineering properties of the fiber–lime treated soil. An increase in lime content resulted in an initial increase followed by a slight decrease in unconfined compressive strength, cohesion and internal friction angle of the clayey soil. On the other hand, an increase in lime content led to a reduction of swelling and shrinkage potential. However, an increase in fiber content caused an increase in strength hand shrinkage potential but brought on the reduction of swelling potential. An increase in curing duration improved the unconfined compressive strength and shear strength parameters of the stabilized soil significantly.

In order to find other alternative materials apart from the fibers, Abdelrahman *et al* (2009) studied the influence of the EPS mixture with soil to substitute the expansive soil, hence reducing swelling pressures on the structure foundation. The laboratory tests were presented on the formation of expansive clay using bentonite. The authors also used a laboratory model using a replacement material made of a mixture of sand and EPS beads to measure the decrease of the swelling. The results showed that the effect of different compositions and different ratios between EPS-beads, and sand as a replacement soil on the expansive soil, had free of swell equal to 96,7% were observed. The results also showed that he EPS beads mixed with sand significantly reduces the volumetric change of the expansive soils

Calheiros (2013) studied the behavior of soils reinforced with EPS (Expanded Polystyrene) beads through experimental study. The soils used were a coluvionar soil, a clean and barely graduated sand and bentonite. The author performed physical characterization, Standard Proctor, consolidated drained triaxial and direct shear tests in order to establish patterns of behavior that may explain the influence of the addition of expanded polystyrene beads in shear strength parameters. The results found by Calheiros showed that the kind of soil, the EPS content and level of confining stress influence positively on the final mechanical behavior of the mixtures, but there is no well-defined pattern of behavior to examine each factor independently.

Another residue that has been largely studied is rubber from tires, Ghazavi (2004) studied the mixture of sandy soil and rubber, using 0, 10, 15, 20, 50, 70 and 100% of rubber with an average size of 4,0mm. Although the increase in the shear strength were not significant, the peak strength of the mixtures happened for higher axial strain, comparing with the pure soil, but the curves of shear strength x horizontal displacement did not show a well-defined peak as the pure sandy soil. On the strength envelopes, it can be noticed that for the mixtures with 10 and 20% of rubber the friction angle reached the greatest values.

Ramírez (2012) and Ramírez *et al* (2014) performed triaxial test on mixtures of clayey soil/rubber and sandy soil/rubber with different content of rubber. Through showed that the rubber content and level of confining pressure influence on the final mechanical behavior of the mixture and it was not observed a define behavior when the mixtures were analyzed separately. Ramírez concluded that for the clayey mixtures the ground rubber is more effective for confinement stresses up to 200 kPa, for higher confining stresses, the presence of rubber is harmful and the optimum rubber content was between 10 and 20%. For the sandy mixtures, the rubber inclusions were more effective at confining stresses between 100 and 200 kPa and the optimum rubber content stayed between 0% and 5%.

Nakhaei *et al* (2012) studied the dynamic properties of granular soils mixed with different percentages of granulated tire rubber using a large-scale consolidated undrained cyclic triaxial tests. The samples diameters and heights were 15 and 30 cm, respectively. The results showed that, for all confining pressures, with an increase in rubber percentage, shear modulus decreases while for any percentage of rubber inclusion, shear modulus increased as the confining pressure increased. It was observed by the authors that, with an increase in rubber percentage, damping ratio decreased for the confining pressures of 50 and100 kPa while this contribution was the reverse for the confining pressures of 200 and 300 kPa. Nakhaei *et al* also observed that, with a decrease in confining pressure, damping ratio increased for the soil with no rubber inclusion and it was the reverse for the soil with rubber inclusion.

The use of residue in different construction sectors has been the object of study around the world recently, making it a potential solution to the disposal of materials that formerly had no usefulness and that in most cases are arranged incorrectly on the environment, such as the municipal solid waste. Thus, Vizcarra *et al.* (2013) studied the addition of municipal solid waste (MSW) incineration ash (obtained from an electric energy generation plant) in a non-lateritic regional clay soil for base of road pavements layers. Chemical, physical, mechanical tests and the mechanistic-empirical design for a typical pavement structure were carried out on the pure soil and in the soil mixture with the different ash content (20 and 40%). The author concluded that the fly ash reduced the expansion of the material, showing an increase in the california bearing ratio and resilient modulus value. The results were satisfactory, depending on the content and type of ash used, highlighting the positive work of MSW fly ash for the use in base road pavement layers.

Using the same residue as Vizcarra *et al.* (2013), Quispe (2013) studied the behavior of a colluvial clayey soil stabilized with ashes from MSW under static load, using isotropically consolidated-drained triaxial test. The tests were performed in the pure soil and soil-ash mixtures with percentages of 20%, 30% and 40% of fly ash and bottom ash, also was evaluated the curing time (30 and 60 days). The results showed that all mixtures soil-ash had better shear strength compared to the pure soil, where the soil- fly ash mixtures showed better results compared to mixtures of soil- bottom ash. The author concluded thar the mixtures with 40% fly ash and 30% bottom ash, showed the best characteristics of strength and could be used as stabilizer in the studied soil.

Szeliga (2014) researched the behavior of a sandy soil stabilized with municipal solid waste ash and lime, performing isotropically consolidated-drained triaxial test. The author studied the influence of ash content (30 and 40%), type of ash (fly ash and bottom ash) and curing time (0, 60 and 90 days) for mixtures containing fly ash and lime. It was concluded that mixtures with both kinds of ashes present a satisfactory behavior, increasing or maintaining the shear strength parameters similar to the pure material. It was also observed that for both kinds of ashes the variation of the content did not provided significant changes in the strength parameters, but, 40% was considered the best content, once it provides a bigger destination of the residue. It was compared the fly and bottom ash, and the last presented better results than fly ash. For mixtures with lime and cure process, it was observed better results for 60 days of cure, with major gain of strength.

2.1.5
Experimental study using PET residue

Soncim *et al* (2004) proposed that the recycling of the PET waste could be used as an alternative material in the construction of reinforcing highway sub-base. The addition of 30% of the material by weight, in a soil considered inappropriate for base and sub-base of highways, raised its classification to an appropriate soil, according to the HRB, an institute that rules and classified the soils recommended for roadwork.

Consoli *et al* (2000) conducted a study on the mechanical behavior of cemented sand reinforced with plastic waste, evaluating the effects of inclusion of PET fibers randomly distributed, the strengthening of artificially cemented soils, forming a composite soil-cement-fiber. It was evaluated the effects of the fiber percentage, fiber behavior, the percentage of cement and confining pressure on the properties of the mixtures. It was found that the inclusion of PET fibers increases the peak and the ultimate strength of the cemented and non-cemented matrix, and decreases the fragile character of the cemented matrix and also did not appear to change the rigidity of the studied mixtures.

Da Silva (2007) studied the behavior of silty soils reinforced with fibers and observed that at CBR test using PET fiber showed an improvement in the material support determined by the California bearing ratio. In addition, it was observed that the apparent dry weight of the compacted soil can vary for more or less, depending on the amount and type of fiber used. In the shear strength envelopes, The authors noticed a tendency, with addition of the fibers, to reduce the maximum shear stress obtained for low levels of normal stress. However, as the confinement of the material was increased with increments of normal stress, the resistance of soil-fiber mixtures tends to increase.

Modro *et al* (2009) conducted an evaluation in a Portland cement concrete containing PET residue. The authors observed that for all traces in all ages, the mechanical strength decreased with increasing in the volume fraction of PET. The authors stated that this decrease of compression strength of the traces obtained with the substitution of mineral aggregates by PET residue, compared with the pure material, is associated with less chemical interaction between the polymer and the cement matrix, and the residual porosity generated, but mainly due to lower intrinsic mechanical strength of polymers with respect to mineral aggregates. Considering the results of this study, the replacement of mineral aggregates for PET residue could only be made for the manufacture of non-structural artifacts, such as: internal closing brick work, covering for ribbed slabs, covers for precast slabs, etc. Later Pelisser *et al* (2012) also investigated the addition of PET fibers in the concrete and concluded that with this addition, the flexural strength and impact resistance improved although the reduction of the compression strength.

Meneses (2011) used recycled PET fibers embedded in concrete with 15mm of length and 2mm of width, fck = 30MPa and water/cement ratio of 0,46, made in order to verify the mechanical strength of the mixtures submitted to high temperature. The specimens of concrete with addition of PET fibers were tested after exposure to temperatures: room (30ºC), 100°C, 200°C, 300°C, 400°C, 600°C and 900°C. It was found that the concrete loses significant strength when exposed to temperatures above 300°C, however the use of fiber PET may delay the risk of collapse of structures because the formation of a network of channels that facilitate the escape of water steam, reducing the pore pressure inside the structural element.

Silva *et al* (2013) presented a study about the use of PET in the composition of asphalt mixtures. The mechanical tests were carried out varying the percentage of fine crushed PET as fine aggregate (sand) in the range of 2,5%, 5,0%, 7,5%, 10% and 12,5%. The authors observed that, adding the PET and fine aggregate with percentage above 10% provided asphalt mixtures with a high void content and low mechanical strength (Table 2.2 and 2.3). They concluded that the use of PET as an aggregate in asphalt mixtures should be limited to maximum addition of 5% in order to attend the volumetric and mechanical parameters recommended by current standards. Meanwhile, based on the results of resilience module, the increase of PET in asphalt mixtures tends to makes lining less susceptible to permanent deformation and consequently increases the fatigue life.

Table 2.2 - Volumetric properties of asphalt mixtures compound with PET as fine aggregate (Silva *et al*, 2013).

TESTS	%Vvp	%Vma	%RBV
2,5% of PET as Aggregate	4,25	13,93	69,39
5,0% of PET as Aggregate	5,19	14,49	64,16
7,5% of PET as Aggregate	6,42	15,39	58,28
10,5% of PET as Aggregate	8,26	16,90	51,12
12,5% of PET as Aggregate	12,69	20,77	38,90
Criteria	**4,00**	**13,00**	**65% up to 75%**

Where: RBV- Relationship Voids Bitumen; Vvp-Volume of voids; Vma-Voids in the mineral aggregates.

Table 2.3 - Mechanical properties of asphalt mixtures compound with PET as fine aggregate (Silva et al, 2013).

TESTS	TR (MPa)	Lottman (MPA)	RM (MPa)
2,5% of PET as Aggregate	1,109	81,8	4.382,50
5,0% of PET as Aggregate	0,942	79,9	4.265,50
7,5% of PET as Aggregate	0,740	71,3	2.932.00
10,5% of PET as Aggregate	0,627	68,2	2.139,00
12,5% of PET as Aggregate	0,507	66,9	1.590,50
Criteria	**4,00**	**13,00**	**(2.000-8.000)**

Where: RT- Tensile Strength; Lottman-Lottman Test; RM- Resilient Modulus.

2.2 Final Considerations

The use of PET residue as soil improvement is relatively new and there a just few researches about it. So, the present literature review focused on showing the main alternatives materials that may work as the PET residue in the soil (fibers, EPS, granular rubber), and thus be able to make a correlation between soil behavior with these residues and with PET.