Improvement of the Mechanical Characteristics of Soil Contaminated with Lubricant Oil – Cal Mix

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Abstract. The demographic and technological evolutions are confronted by geo-environmental problems. When chemicals or contaminants are introduced into the soil, they affect the soil properties such as the grain size curves, the structure, compressibility and stress-strain behaviour. However, the classical soil mechanics models and methods to incorporate the effects of contaminants have not yet been developed. In this study the proposed analysis of geotechnical structure involving effect of chemicals contaminants such as a wasted lubricate oil with lime on the main factors affecting the behaviour of a compacted soil mass and the analysis of a granite residual soil involving effect of the moisture on the compressibility and shear stress behaviour. These concepts can improve the use of these kinds of soils in geotechnical engineering works.

1. Introduction
The high urbane-industrial occupation, the use of soils in various engineering works and contamination increase lead to the soils availability decrease. To re-use contaminated soils on building construction leads to the need of its physical, chemical and mechanical improvement [1]. There is a trend to improve the use of contaminated soil or else to re-use it on embankments or on coping coats in embankments or in foundations or sub-foundations of roads. The improvement of these features will depend on the properties and the quantities of stabilizing chemical agents used, the contaminative agents, the kind of clayey fraction and the restoration time, in general. The chemical stabilization associated with this process consists of increasing stiffness by developing potential links between particles.

The soil is a chemical system which can be described by the interactions that occur inside it and by the results that contamination through advection; dispersion and diffusion have on its chemical composition and on its own phases. The lime put into the soil produces ionic exchanges mechanisms in which the Ca$^{2+}$ cation replaces the less valence cations that brings to the flocculation of the thin particles, so decreasing plasticity and increasing resistance. Consequently, the soil properties become better. The lime supplement in clayey soils of high plasticity is very common but less reported in soils where the clay is kaolinite. This kind of soil is not included in the granitic residual soils of Covilhã [2]. The reactive ability of the soil used changes when wasted lubricating oil is mixed with lime.

When the soils are contaminated with no-polar organic liquids, due to the lubricating action there is an improvement in compaction characteristics. This increasing trend is not continued when oil content increases beyond the value where all the soil particles are coated. Properties of this oil are similar to the properties of heating oil. Results of chemical analysis of the soil did not indicate the presence of any metals or organic chemicals with concentrations exceeding the minimum allowable concentration levels for hazardous waste classification [3]. The concentration of heavy metals after the stabilization process with lime is made and described on table 1.
Table 1. Analysis of the heavy metal concentration: limit values (mg / kg) of the concentration of heavy metals to natural soil (NS), stabilized after contamination (M5 to M20) and limit values according to the Directive 86/278/EEC

| Element             | Natural Soil | M5 to M20 | European Directive (EEC, 86) |
|---------------------|--------------|-----------|------------------------------|
| Aluminium (Al) % (mass) | 6.34 – 3.31  | 2.57      | -                            |
| Arsine (As) mg/kg    | 0.44 -1.89   | 8.15      | -                            |
| Cadmium (Cd) mg/kg   | 0.65 – 1.80  | 0.13      | 1 - 3                        |
| Chrome (Cr) mg/kg    | 8.0 – 17.0   | 9         | -                            |
| Lead (Cu) mg/kg      | 3.4 -5.6     | 9.3       | 50 - 300                     |
| Iron (Fe) % (mass)   | 0.56 – 1.96  | 0.73      | -                            |
| Manganese (Mn) mg/kg | 77.0 – 82.0  | 58        | -                            |
| Nickel (Ni) mg/kg    | 6.0 -18.0    | 17.3      | 30 - 75                      |
| Copper (Pb) mg/kg    | 3.6 – 37.7   | 38.4      | 50 – 140                     |
| Zinc (Zn) mg/kg      | 70 - 98      | 98.0      | 150 - 300                    |

1 - Atomic absorption; 2 - Graffite chamber; 3 - Hydrides.

The results including those of the artificial soil (M15) comply with the European Directive 86/278 / EEC [3], emphasizing that the results point to the lime’s potential to stabilize the heavy metals present in the lubricating oil, as previously advocated.

2. Natural and artificial soils classification

The soil that in the present work serves as matrix to the mixture of wasted lubricating oil and lime is a granitic saprolitic soil, which results from the alteration of feldspar through kaolinization. The granite belongs to chalco alkaline group and in the mineralogical point of view; it contains two micas where biotite is predominant. The rock texture is porphyritic with mega crystals of potassium-sodic feldspar [2].

The waste material to be mixed with soil is composed of lime (L) and lubricating oil (O). The concentration of components was chosen so it occurs an exothermic reaction in order to correct pH and neutralize heavy metals contained in the lubricating oil. The artificial soils were produced using a 5% to 20% mixture of waste material with natural soil. Three groups of samples were obtained: i) Granitic natural residual soil - NS; ii) Granitic natural residual soil with various proportions of mixture, artificial soil - M5 to M20 and iii) Granitic natural residual soil with 5% of waste lubricant oil – OS5. The content of 5% of oil was chosen to be added to the soil because its lubricating effect goes to higher values of relative density. Grain size and physical characteristics are presented at table 2 and figure 1.

Table 2. Grain size and physical characteristics of tested soils

| Sample | Coefficient of uniformity - $C_U$ | Coefficient of curvature - $C_C$ | Effective size $D_{10}$ (mm) | Liquid limit $-w_L$ (%) | Plasticity index $IP$ (%) | Clay activity -At |
|--------|-----------------------------------|----------------------------------|------------------------------|------------------------|-------------------------|------------------|
| NS     | 33-200                            | 0.3-5.9                          | 0.006-0.13                   | 40.4-42.5              | 1.7-5.6                 | very low         |
| OS5    | 30                                | 3.3                              | 0.1                          | 30.5                   | 11.5                    | -                |
| CS5    | 7.7                               | 1.0                              | 0.2                          | 43.0                   | 4.6                     | -                |
| CS10   | 7.9                               | 0.8                              | 0.2                          | 44.0                   | 11.6                    | -                |
| CS15   | 7.5                               | 0.8                              | 0.2                          | 44.1                   | 10.8                    | -                |
| CS20   | 0.3                               | 0.4                              | 0.2                          | 46.5                   | 12.7                    | -                |

*a The deflocculant used in the test is hexametaphosphate.
The classified granite residual soil belongs to group SW-SM with gravel, and clay activity is normal to low, revealing the presence of Kaolinite, a low expansion clay. Liquid limit and low plasticity index, reflecting the presence of mica minerals, retaining water in internal cleavage. The classified granitic soil moisture belongs to group SW-SP with gravel [4]. The plasticity index is low in the natural soil for being connected to the low capacity of ionic exchange 1.53 and 1.90 mE/mg of the existing fines. The plasticity index on the artificial soils increases due to the plasticity index decreasing ($w_p$), as oil replaces the fines’ capacity of retaining water and increases the particles lubrication.

The comparative granulometric curves of natural and artificial soils shows that the addition of the mixture changes the particles original dimension a great deal. The thin particles of soil agglutinate themselves due to the lime and the oil effect making flakes of bigger dimensions, lime hydrate nucleus, as the images obtained through retro diffused electrons can show and the diffraction spectres of X-rays, figure 2.

The chemical tests show that on the NS soil elements can mainly be found silica (62%), aluminium (24%), and iron oxide (4.61%), which are typical components of granitic residual soils. The M5 to 20 artificial soils are also composed of calcium oxide (12-30%) and carbon (signs), important to develop the “cement” which can be responsible for the stiffness increase.
3. Compaction properties

The “ordinary” and heavy compaction test according [5] was used on NS soils, M5 to 20 soils and on OS5 soil in order to establish the content of the mixture to be added to the soil to guarantee the biggest dry unit weight (γ_d) and the lowest plasticity index, so that improvement could be excellent.

The curves for the artificial soils have the typical shape of sandy soils, according to its virtual classification, figure 3a). For these soils, the dry unit weight decreases as according to the increase of the mixture proportion but the optimum water content almost the same as the natural soil one. However, the OS5 soil shows up the same value of dry unit weight as the NS soil does but the optimum water content is lower because oil replaces water in the particles lubrication function, figure 3a).

The addition of waste material has generated a reduction on the compaction value when compared to the natural soil, figure 3b). The reduction of a dry unit weight, with increasing waste percentage is due to the effect of dispersion and lime expansion overlapping, the increased viscosity due to the lubricating oil. With a dispersed soil structure, it is difficult to produce a dense matrix with compactive action.

![Figure 3](image)

**Figure 3.** Compaction tests results: a) natural soil (NS) and contaminated (M 5-20; OS 5); b) evolution of maximum dry unit weight and optimum water content of tested soils

4. Compressibility behaviour

Oedometric or uniaxial compressibility tests were made under an axis symmetrical condition with no radial strain and saturated elements firstly by using a 100 mm diameter and 40 mm height link and afterwards with a 63 mm diameter and 20 mm height link [5].

Initially consecutive samples of M15 soil were studied. These samples were obtained from the dry and wet branch of the compaction curve (M15-0 to M15-5) in figure 4a), in order to estimate the compressibility. The following trend was confirmed: In the dry branch the compressibility is lower, due to the suction forces, figure 4b).
In a second phase specimens of NS, M5 to 20 and OS5 soils were obtained from the compaction curves with maximum dry unit weight and optimum water content. These samples were tested at uniaxial compressibility. Their physical features and the virtual preconsolidation stress are summarized on Table 3.

**Table 3. Characteristics of samples and uniaxial compressibility test results of soil**

| Sample | Initial void ratio, e₀ (-) | Dry unit weight, γᵣ (kN/m³) | Virtual preconsolidation stress, σ_p* (kPa) |
|--------|----------------------------|-----------------------------|------------------------------------------|
| NS     | 0.471                      | 18.3                        | 140                                      |
| OS5    | 0.434                      | 18.2                        | 120                                      |
| M5     | 0.567                      | 17.3                        | 190                                      |
| M10    | 0.468                      | 17.2                        | 200                                      |
| M15    | 0.521                      | 16.8                        | 210                                      |
| M20    | 0.530                      | 16.1                        | 200                                      |

From the uniaxial compressibility test it is noticeable an increase of virtual preconsolidation stress (σ_p*) as the percentage of mixture is increased, Table 3 and figure 5a). The comparative compression index (C_c), exhibits increased difficulty on stabilization for artificial soils, as it happens in natural soil during normal behaviour, that is for stress levels higher than virtual preconsolidation stress (σ_p*), figure 5b). The artificial soils for stress levels lower than σ_p* presents higher C_c values than the NS and OS5 soils, which means a slight improvement on stiffness. The OS5 soil presents an increase of compressibility and a decrease of σ_p* due to the pure lubrication of oil effect. On M5 to 20 soils, the stress increase of virtual pre-consolidation has nothing to do with the used mixture proportion.
Figure 5. Uniaxial compressibility test results of natural (NS) and artificial soil (M): a) evolution of normalized void ratio; b) evolution of compression index

The lime addition changes the soil behaviour in which most of the laying occurs immediately after loading being connected to the fact that the soil becomes more granular which apparently is not affected by the addition of oil into the lime.

The behaviour of these granitic residual soils with lime and oil addition is closer to soil with cement connections with an area of metastable behaviour. For remoulded natural soils and the same vertical effective tension the structured material can coexist with void indices as high as possible beyond the border of the stable space [6] and [7]. It is therefore convenient to define two different spaces on the index field of effective tension-voids: the space defined by the line that determines a possible loose state of casing for a remoulded soil and the space beyond that line where the soil can only exist due to its original or raised structure.

5. Shear stress behaviour
Some trials of direct shear box were made, which were drained and consolidated according to the following increments to each sample with the vertical effective stress of: $\sigma'_v = 26; 44; 82 e 157$ kPa. The used shear box has circular sections with 100 mm diameter and the sample height of 40 mm [5]. The samples tested at resistance were obtained from the maximum dry unit weight and optimum water content of all soils with no restoration time.

The change of the shear strain behaviour on artificial soils (M10 to 20) is especially a result of the flocculation and probably also a result of the incipient development of psolanic connections between clay and lime, i.e., the inverse reaction from lime building through the silica and alumina solution. Such induces to a simulation of increased cemented connections between particles that provides increased stiffness, also observed on the behaviour of shear strength curves ($\tau$) and normalized shear strength curves versus horizontal displacement ($\delta_h$), figure 6a) and 6b) and increase of the angle of internal friction in terms of effective stress ($\phi'$), figure 6c).
Figure 6. Results of direct shear tests of soil NS and soil contaminated with oil and lime: a) behaviour of shear strength curves ($\tau$) versus horizontal displacement ($\delta_h$); b) normalized shear strength curves versus horizontal displacement ($\delta_h$); c) Mohr envelope while for simplification it was considered a linear function

The dilatancy angle ($\psi$) on this artificial soils group is higher than on the natural soil used, which means that the mechanical behaviour of these soils is led by the dilatancy angle, which explains the increase of the peak friction angle ($\phi_p$), i.e., to low stresses $\phi_p = (\phi_{cs} + a.\psi)$.

Initially there is a resistance increase on the M10 to 20 soils due to the ionic exchange and consequent particles flocculation where even the clays may take on a typical granular soil behaviour. The effective cohesion value ($c'$) decreases and $\phi_p$ increases as according to the increase of mixture proportion on the soil, figure 7. The possible effective cohesion coming from the interpeculiar connections becomes hidden due to the dilating phenomenon that especially makes the control of behaviour presupposing the $\psi$ increase and the $c'$ decrease rate.
Figure 7. Evolution of angle of internal friction and effective cohesion apparent with mixture content. \([\text{failure criterion } \tau'_{\text{max}} \text{ and } (\tau/\sigma_n)_{\text{max}} - (\tau'/\sigma'_{n})_{\text{max}}]\)

6. Conclusions
The presented researches allow us to draw the following conclusions:

- The classified granitic soil moisture belongs to group SW-SP with gravel. The granulometric curves of natural soil and artificial soils shows that the addition of the mixture changes the particles original dimension in a great deal. The thin particles of soil agglutinate themselves due to the lime and oil effect.

- The addition of oil and lime has generated a reduction on the compaction value when compared to the natural soil. The reduction of a dry unit weight, with increasing waste percentage is due to the effect of dispersion and lime expansion overlapping, the increased viscosity due to the lubricating oil. With a dispersed soil structure, it is difficult to produce a dense matrix with compactive action.

- From the uniaxial compressibility test results it is noticeable an increase of virtual preconsolidation stress \((\sigma'_{p*})\) as the percentage of mixture is increased. The comparative compression index \((C_c)\), exhibits increased difficulty on stabilization for artificial soils. The artificial soils for tension levels below \(\sigma'_{p*}\) reveal higher \(C_c\) values than the NS and OS5 soils which means a slight improvement on stiffness.

- The dilatancy angle \((\psi)\) on this artificial soils group is higher on the natural soil used which means that the mechanical behaviour of these soils is led by the dilatancy angle, which explains the increase of the peak friction angle \((\phi_p)\). The effective cohesion value \((c')\) decreases and \(\phi_p'\) increases according to the increase of mixture proportion on the soil. The possible effective cohesion coming from the interpeculiar connections becomes hidden due to the dilating phenomenon that especially makes the control of behaviour presupposing the increase of \(\psi\) and decrease of \(c'\) rate for the stress levels studied.

- Finally we wish to point out that the use of lime and lubricating oil grants an improvement on the mechanical behaviour in a slight way making them more resistant and less compressible for stress levels below \(\sigma'_{p*}\), which gets better with time of cure.

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