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Influence of rigid inclusions on the mechanical behavior of compacted residual soils

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SUMMARY:Rigid inclusions in the soil matrix are particulate material that causes serious problems in engineering applications. Generally, the inclusions in the soil are characterized by a heterogenic structure which depends on the size distribution of the inclusions, the relationship between soil and inclusions stiffness, the volume ratio and the orientation of inclusion in the soil matrix. In this article is studied the effect on the mechanical behavior of rigid inclusions (steel beads) in a residual soil. The small-strain oedometric modulus and shear stiffness were measured through the bender element technique. Inclusions were steel beads 4.2 mm in diameter, used in different percentages during soil compaction. With the result was possible to identify the effect of incorporating inclusions in soil matrix.

KEYWORDS: Residual soils, soil mixture, bimsol, stiffness

1 INTRODUCTION

The inclusions in the soil matrix are a particular material, which creates serious problems in engineering applications because of the great heterogeneity and chaotic structure (Kalender et al. 2014). There are numerous studies of how inclusions affect the behavior of the soil matrix, which some authors called "BimRock" (Medley 1994, Kalender et al. 2014, Afifipour and Moarefvand 2014). Furthermore, some authors as Medley (1994), called bimsoils to complex mixtures of rock blocks surrounded by a soil matrix. Generally, the mechanical behavior of the soil inclusions is highly dependent on the size distribution of inclusions, stiffness ratio between soil and inclusions, volume ratios and orientation, strength and deformability of the inclusions (Medley 1994).

Residual soils are products of weathering; therefore it is possible to find clasts of weathering products in the soil matrix. The great majority of clasts are iron nodules (Fe) which are characteristic of many weathered soils profiles in tropical, subtropical and even temperate regions. In most cases, iron nodules (Fe) consist of quartz cemented by various oxyhydroxides of aluminum (Al) and Fe (Wei et al 2014)

The purpose of this article is to evaluate how rigid inclusions affect the mechanical behavior of residual soil. The small-strain shear stiffness of different soil-inclusion mixtures are measured in an oedometric cell with bender elements mounted in both caps. Different soil-inclusion mixtures were prepared with steel beads 4.2 mm in diameter and a residual soil from the Northeast of Argentina that arises from the weathering of basalt. Obtained results allowed identifying the influence of rigid inclusion on the shear wave and small strain elastic modulus of compacted residual soils.

2. FINES CONTENT

The fines content in soil mixtures has a critical role because it modifies the mechanical and hydraulic behavior (Carraro et al. 2009). Figure 1 shows a schematic volumetric and gravimetric analysis of a mixture between large particles with fines, where Vv= void volume, Vf= volume of fines particles, Vi= volume of inclusions, Wf and Wi weight of fine particles and inclusions respectively, Gsi= specific gravity of inclusion and Gsf= specific gravity of fines particles.

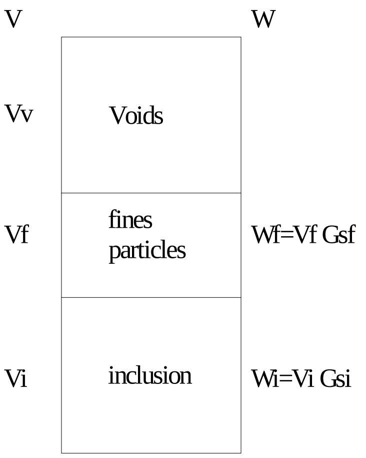

Figure 1. Three phase diagram for a soil mixture.

Considering the phase diagram of Figure 1 and according to Lade et al. (1998) the fines content *Fc* can be expressed by Equation 1

$$\mathrm{Fc} = \frac{\mathrm{W_{fines}}}{\mathrm{W_{total}}} 100 \qquad (1)$$

Simplifying and combinig equation of G_{sf} y G_{si} obtained the equation 2

$$\mathrm{Fc} = \frac{G_{sf} \cdot e_i}{G_{si} \cdot (1 + e_f) \cdot + G_{sf} \cdot e_i} \qquad (2)$$

where e_i *and* e_f are the void ratios of inclusion and fines, respectively.

The global void ratio for the mixture can be expressed by the following expression (3):

$$\mathrm{e} = \frac{V_v}{V_t} = \frac{V_t - V_f - V_i}{V_f + V_i} \qquad (3)$$

2.1 Intergranular Void radio

The application of a global void ratio to binary mixtures containing large and small particles is limited, because the void ratio does not reflect the mechanical behavior of coarse-grained soils with smaller particle, as fine particles are in the pore space between the larger particles (Thevanayagam, S., 1998) Therefore some authors defined a relationship for intergranular voids by:

$$\mathrm{e_g} = \frac{V_v + V_f}{V_i} \qquad (4)$$

If the volume of inclusions V_i is expressed in terms of W_l and G_{sl}, the following expressions are obtained:

$$\mathrm{V_L} = \frac{W_i}{\gamma_w \cdot G_{si}} = \frac{W_t - W_f}{\gamma_w \cdot G_{si}} \qquad (5)$$

$$\mathrm{e_g} = \frac{G_{si} \cdot \gamma_w \cdot V_t}{W_t - W_f} - 1 \qquad (6)$$

$$V_t = (1 + e)(V_i + V_f) \qquad (7)$$

Combining previous equations will yield:

$$\mathrm{e_g} = \frac{e\left[F_c \cdot (\frac{G_{si}}{G_{sf}} - 1) + 1\right] + \frac{G_{si}}{G_{sf}} \cdot F_c}{1 - Fc} \qquad (8)$$

The equation 8 can be simplified as (Thevanayagam 1998):

$$\mathrm{e_g} \approx \frac{e + (\frac{Fc}{100}) \cdot}{1 - (\frac{Fc}{100})} \qquad (9)$$

2.2 Fines critical content

The fines content critical is defined as the weight ratio between the fine particles and the total weight of the mixture when the voids between the large particles are fully filled by fine particles (Lade et al., 1998) and it can be calculated by the expression:

$$Fc^{*} = \frac{e_i \cdot}{1 + e_f + e_i} \quad (10)$$

2 MATERIALS AND METHODS

2.1 Residual soil

The residual soil used in this study comes from the north of the province of Misiones, Argentina. The residual soil was obtained from a 2 meters deep excavation, in Oberá-Misiones-Argentina. The residual soil has a unit weight of 18.3 kN/m^3. It is classified primarily as CL according to unified soil classification system USCS. The clay minerals include kaolinite as the main component, hematite and smectite (Bogado 2014). An SEM image of the residual soil is shown in Figure 2, while Figure 3 presents the mixture of soil-inclusions.
Soils with bimrocks inclusions, or bimsoils, are difficult to evaluate. It is almost impossible to obtain undisturbed samples or to recreate similar field characteristics in remolded samples Kalender (2014). In this study, inclusions in the soil were carefully prepared in an oedometer cell, in order to prevent the effect of segregation in the dry state. First samples were dosed and compacted statically to reach the volume of the used oedometer (ϕ= 63 mm and H = 35 mm). The inclusions tested volumes were 0, 10, 20, 30, 40, 50 and 60 percent of the total volume (oedometer). The 70% volume was not exceeded in order to prevent the segregation phenomenon (Kim and Santamarina 2008)

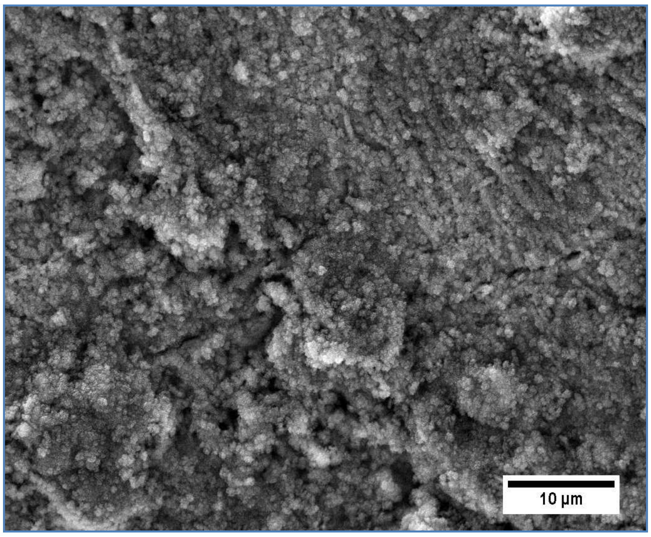

Figure 2. SEM residual Soil.


Figure 3. Mixture residual soil-steel spheres

2.2 Device

The oedometer tests were performed following the ASTM (2435-03) procedure. During the oedometric test, the shear wave velocity was measured by the incorporation of piezoceramic crystals (Bender elements, BE). The dimensions of the bender elements are 11 mm long, 5 mm wide, 0.4 mm thick. The oedometer is of flexible wall, with a bender element at the top (exciter) and lower ring (receiver). Each bender element was isolated with a protective paint against moisture, and conductive paint was applied subsequently to isolate and prevent the cross talking effect, as indicated by

(Santamarina et.al. 2001, Lee and Santamarina 2005). Subsequently they were covered with transparent epoxy resin.

The shear wave velocity was measured at the end of each load. A signal generator RIGOL DG1002 is used to generate the signals, by exciting the inferior BE. The input signal is received by an amplifier SRS filter (Standford research system). The signals were digitalized by a Rigol DS432 oscilloscope, and in order to remove noise, signals were averaged 256 times. The determination of the shear wave arrival was measured following the guidelines of Viggiani and Atkinson (1995)

3 RESULTS

3.1 Intergranular Void Ratio

Figure 4 shows the variation of the ratio of intergranular voids, eg, as a function of the fines content calculated by the expression 9.

The critical value of fines content calculated by expression (10) is equal to Fc^*=32. The ratio of intergranular voids has a maximum that agrees with the critical fines content Fc≈30%. For fines content lower than 30%, intergranular void ratio decreases with fines content, obtaining a value e_G=0.68. For fines content above 30%, the void ratio decreases with increasing percentage of fines up to the void ratio e_G =1.10 (for the residual soil only). In this case study, from Fc≈30% smaller particles (residual soil) began to fill in the voids of the inclusions.

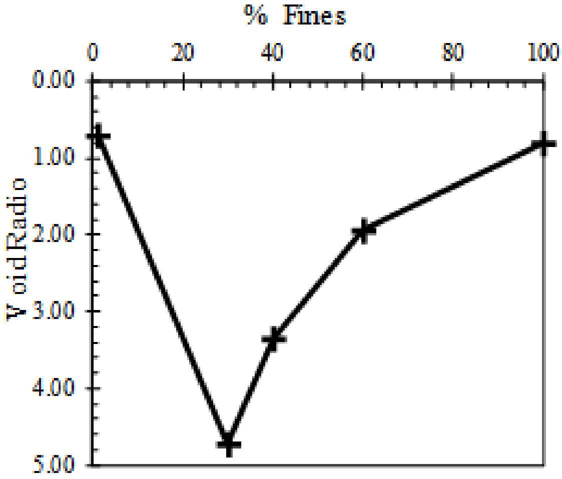

Figure 4. Variation of e_G whit fines content.

3.1 Compressibility Soil-Mixture

Figure 5 indicates the compressibility curve of the soil mixture with different contents of inclusions, where the Y axis is normalized by the ratio e/e0. When decreasing the content of inclusions (increased volumetric content of fine) there is a tendency to increase the compressibility. Compressibility and recompression coefficients, Cc and Cr, are shown in Table 1.

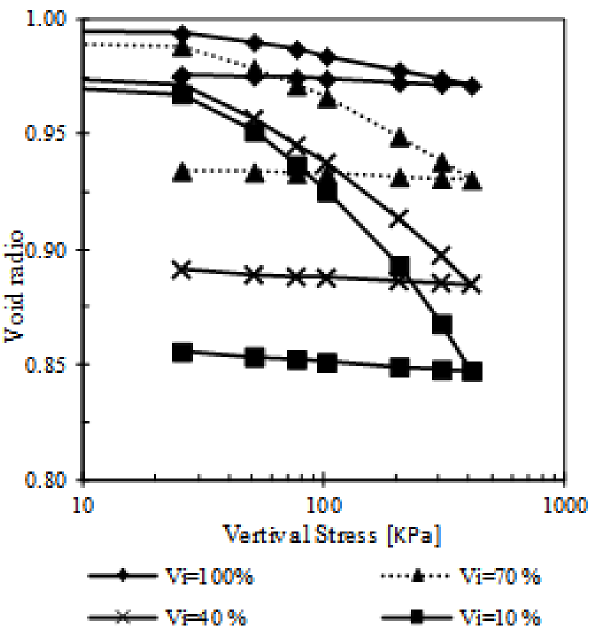

Figure 5. Compressibility curve.

Table 1. compresibilidad.

Vi [%]	E	Cc	Cr
100	0.70	0.007	0.018
70	4.72	0.137	0.012
40	1.94	0.067	0.007
10	1.23	0.060	0.007

3.1 Shear Wave Propagation

The shear wave propagation (S-wave) in a particulate medium depends on the fabric and packing density (Santamarina et al 2001). By measuring the travel time of the S-wave and the tip-to-tip distance between transmitting and receiving bender element (L), the S-wave velocity of the specimen (Vs) is obtained as:

$$V_s = \frac{L}{t} \quad (10)$$

S-wave velocity can be related to the effective isotropic stress in the polarization plane σ'_0 as follows:

$$V_s = \alpha \left(\frac{\sigma_0'}{1kPa} \right)^{\beta} \quad (11)$$

Were α and β are fitting parameter usually determined experimentally (Hardin and Black 1969; Fernandez and Santamarina 2001).

The variation of shear wave velocities of the mixture indicates that this parameter initially decreases with the decrease of the inclusions content. Moreover, in general, the inclusions have higher Vs values compared to the soil-inclusion mixture.

In addition, the shear wave velocity increases with effective stress, reflecting the increased coordination that is produced. This increase is reflected by increased rigidity through the soil matrix, produced by the reduced volume.

The variation of Vs with intergranular void ratio is reflected in Figure 7. Note that void ratio increases as indicated by the arrow in the figure. At greater content of fines lower values of shear wave velocity are observed, indicating that the rigidity is dominated by the soil matrix.

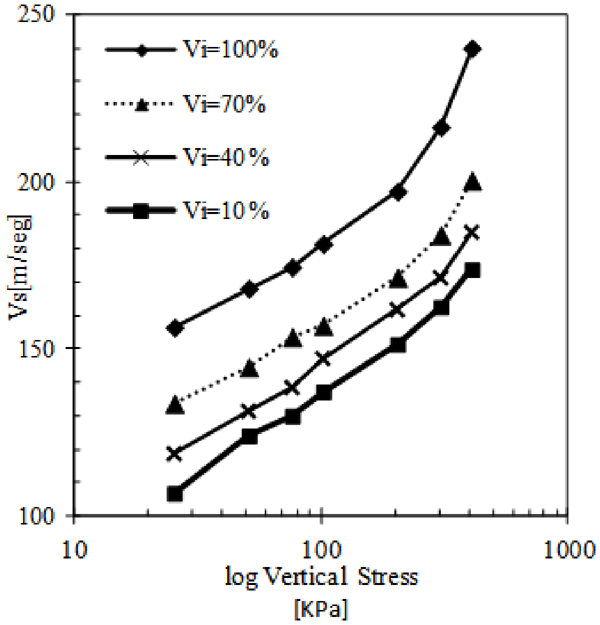

Figure 6. Shear wave propagation vs. vertical load stress

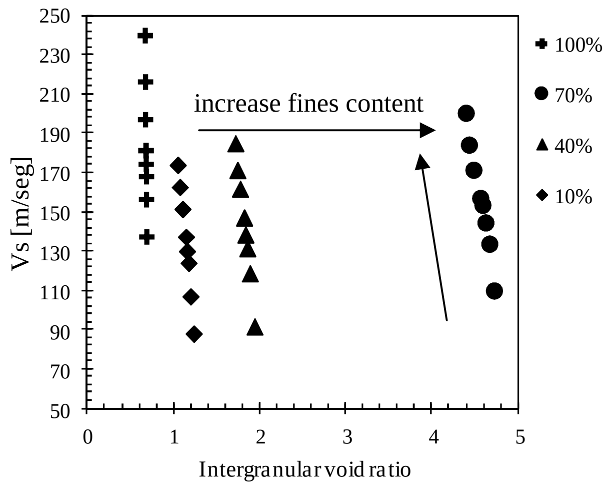

Figure 7. Variation of shear wave propagation with intergranular void ratio

4 Analysis y Discussion

Compressibility

Figure 8 shows evolution of edometric module function of the vertical stress, the module M increases to more effective vertical tension indicating the hardening of the mixture, the trend resulted not linear. On the other hand, there is a marked difference between the deformations Vs = 100 and Vs = 70, 40, 10, so that by increasing the content of inclusions is possible to obtain greater rigidity in the inclusion soil mixture. This effect may occur by increased inclusions contacts which provide increased resistance.

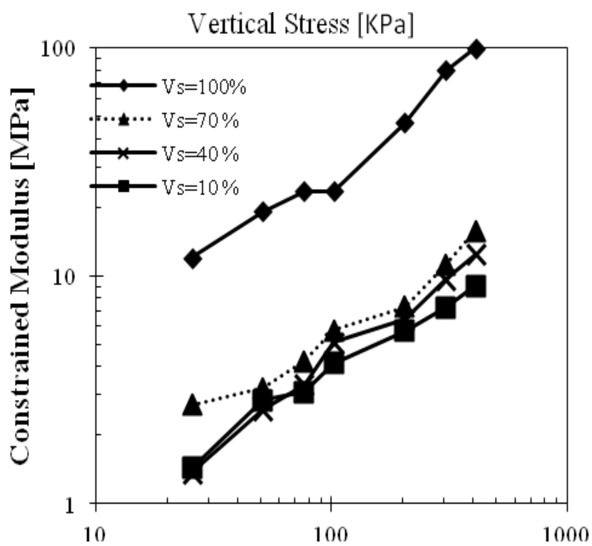

Figure 8. Constrained Modulus vs. vertical load stress

Shear wave of propagation

The parameters are indicators of soil contact Santamarina et al. (2001). Figure 9 shows the values calculated using the expression 11 of α and β parameters obtained from experimental tests. The β parameter has values of 0.24 to 0.27, these values are typical granular soils Santamarina et al (2001) while the α parameter ranges 41-47. The effect of introducing inclusions produces a hardening in the mixture which is reflected in the increased coefficient α (Figure 9). As the constrained module, the wave propagation velocity has a tendency to increase with increasing content of inclusions.

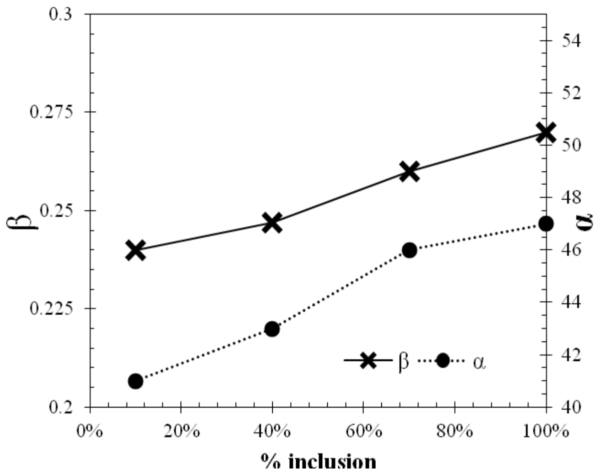

Figure 9. Variation of parameter α and β with % inclusion

5 SUMMARY AND CONCLUSIONS

In this article the mechanical behavior of soil with inclusions is studied. It was prepared soil mix with residual steel balls 4.2 mm in diameter with different contents.
The results obtained through oedometric tests and the measurement of the wave propagation velocity (S-wave8) by the bender element technique showed:

1) The content of fines has a fundamental role on the behavior of soil mixtures.
2) The compressibility of the samples was affected by the inclusions content. The increase constrained module may be related to the greater number of contacts between the inclusions which have greater stiffness than the residual soil.
3) The shear wave velocity has a tendency to increase with increasing inclusions content. This is because the presence of more contacts between inclusions, which have increased rigidity in the same manner that the compressibility.
4) There is a transition when the fines content Fc> Fcr, from which the rigidity of the mixture is dominated by the fines content.

The use of rigid inclusions may have a potential use for engineering applications primarily to improve geomaterials with required strength and rigidity.

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