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Compressibility transition between a marine onshore clay to artificial carbonate silt soil behaviour

Transition de compressibilité entre le comportement d'un sol argileux marin onshore et le comportement d'un sol limoneux carboné artificiel

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ABSTRACT: Wind turbines are rapidly moving to offshore environments to lessen onshore land use, reduce visual impact, and take advantage of higher and more constant wind speeds. A clear example is the Gulf of Mexico and its surroundings, which have a high potential for offshore wind farms. The most attractive offshore areas have shallow water depths, such as Florida, the Yucatan shelf, and the Bahamas, which are characterized by crushable carbonate sediments. Since it is expensive to obtain *in situ* carbonate sediment samples, the creation of an artificial simulant consisting of calcite particles and clay soil was used for this research. Compressibility tests were carried out to identify the compression responses of several clay – calcite and silicate silt mixes were used to provide an initial screening of suitable materials. The results show an improvement in the void index with addition of silica and calcite particles to the reconstituted clay, and although both forms of silt particles decreased the compression index; the calcite mixtures with higher than 85% of calcite particles reached and exceeded the C_v of the reconstituted clay. Moreover, the calcite particles decreased the liquid limit to a lesser extent than the silicate mixtures.

RÉSUMÉ: Les éoliennes se déplacent rapidement vers les environnements offshore pour réduire l'utilisation des terres terrestres, réduire l'impact visuel et tirer parti de vitesses de vent plus élevées et plus constantes. Un exemple clair est celui du golfe du Mexique et de ses environs, qui présentent un fort potentiel pour les parcs éoliens offshore. Les zones offshore les plus attrayantes ont des eaux peu profondes, comme la Floride, le plateau du Yucatan et les Bahamas, caractérisées par des sédiments carbonatés écrasables. Comme il est coûteux d'obtenir des échantillons de sédiments carbonatés in situ, la création d'un simulant artificiel composé de particules de calcite et de sol argileux a été utilisée pour cette recherche. Des tests de compressibilité ont été effectués pour identifier les réponses à la compression de plusieurs mélanges d'argile – calcite et limon silicaté afin de fournir un premier criblage de matériaux appropriés. Les résultats montrent une amélioration de l'indice de vide avec l'ajout de particules de silice et de calcite à l'argile reconstituée, et bien que les deux formes de particules de limon diminuent l'indice de compression ; les mélanges de calcite avec plus de 85 % de particules de calcite atteignaient et dépassaient le Cv de l'argile reconstituée. De plus, les particules de calcite diminuent la limite de liquidité dans une moindre mesure que les mélanges de silicates.

Keywords: Compressibility; carbonate silt; artificial offshore marine sediments.

1 INTRODUCTION

This study focuses on the geotechnical properties of soils in the near offshore carbonate areas of the Gulf of Mexico and Caribbean, more specifically on the Yucatan Shelf, Florida Shelf, Bahamian Platform and Gulf of Batabano in Cuba. These areas are of great interest because they are adjacent to existing offshore oil industry areas, such as the Campeche Bay or the continental shelf of Texas, and they have reasonable wind capacity factors (~40%) making them potentially viable for future offshore wind farms. The capacity factor is determined based on raw wind data obtained from the ERA-5 and MERRA-2 wind climate estimations and standard wind turbine power curves, enabling estimates of the energy production. It should be noted that the average capacity factor currently achieved offshore in Europe was 45% in 2018 (Hernández Galvez et al. 2022).

These offshore areas are characterized by either extensive shallow water depths with low wave energy, e.g. Florida Bay, Bahamian Platform and the Gulf of Batabano (because of their protected shelf lagoon singularities), or high energy wave environments with open, deeply submerged shelves, e.g. the West Florida Shelf and Yucatan Shelf (Logan et al. 1969).

The carbonate sediments in the Gulf of Mexico are generally formed from coral reefs, sands and mud materials, whose composition depend on wave energy and carbonate precipitation. The sediments are found to transit from sand and lime sands to lime muds, with increasing mud composition (clay size particles), for greater water depth and lower wave energies (Logan et al. 1969; Purdy 1963; Ginsburg 1956; Hoskins 1964).

There are four main particle size distribution (PSD) types in the carbonate areas of the Gulf of Mexico (See Figure 1). These are: 1) sand material with less than 12% silt and <5% clay particles; this is characterized by skeletal carbonate materials, such as mollusk grains or non-skeletal grapestone particles (shown with brown lines); 2) silty sand sediments with around 20% silt particles and <10% clay size particles, with the skeletal portions coming from coral algae particles, angular molluscan fragments and foraminifera, and the oölitic portion from non-skeletal particles (shown with red lines); 3) lime muds with 50% silt material with less than 20% clay size particles (shown with green lines); 4) carbonate mud sediments formed with clay size particles around 50% and less than 25% sand particles (shown with yellow lines). The carbonate silt and mud sediments are mostly non-skeletal silt grains, such as faecal pellets, peloids and ooids, while clay size grains are often aragonite precipitated particles and some terrigeneous clays close to Campeche bay, the Texas shelf and southeast Cuba, (Logan et al. 1969; Purdy 1963; Ginsburg 1956; Hoskins 1964).

As can be seen in Figure 1, although these materials are generally all carbonate in nature, there is a significant range of particle size distributions along the Gulf of Mexico, e.g. carbonate muds (4) can be found on the Yucatan Shelf with Campeche Calcilitutie, as well as in Florida and Bahamas, with Cudjoe Keys and South Bright, respectively. Whilst silty sands (2) are in Progreso, Yucatan, Florida Bay and the Bahamas.

Most geotechnical investigations for carbonate soils have been carried out with sand or silty sands (e.g. Coop 1990; Wang et al. 2020) to determine the crushability influences of these weak particles, leaving a gap in the literature with very few carbonate silts and mud samples being investigated and particularly those of the Gulf of Mexico. This paper describes a study of the variations in compression behaviour observed and other basic geotechnical properties of an artificial offshore sediment made from a high sensitivity terrigenous clay with additions of crushable carbonate silt particles. These carbonate silt-clay mixtures are also compared with similar silicate silt-clay mixtures to determine any behavioural differences due to the calcite minerals. Thus, this paper investigates the transition behaviour between lime mud or Marquesa Lagoon sediments to the Cudjoe keys or South Bright carbonate mud sediments, as shown in Figure 1.

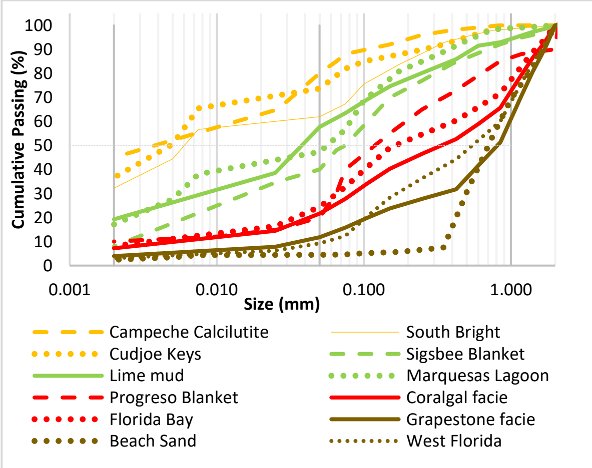

Figure 1. PSD of carbonate sediments in the Gulf of Mexico.

2 MATERIALS AND METHODS

Since it is expensive to obtain offshore marine *in situ* sediments and because carbonate minerals have high sensitivity values from 2 to 50 leading to significant disturbance during sampling, some researchers have attempted to better understand calcareous and carbonate soils based on artificial soils (e.g. Chen et al. 2013; Liu et al. 2016). In this paper, the same approach has been taken as a first step to creating realistic simulants for artificial offshore carbonate clayey-silt materials and provides a good screening tool to assess the most promising materials.

The clay material used to make the soil mixtures is an onshore clay from Eastern Canada (Ottawa), which was selected as a reference material due to its glaciolacustrine sediment characteristics (Nader 2014); comparable in relation to its sedimentation processes to some marine sediments. This high plasticity clay (CH) has a liquid limit of 55%, plastic limit of 26% and a plastic index of 29%.

2.1 Calcite and silicate mixtures

Artificial calcite particles were created in a chemistry laboratory at Western University based on Na_2CO_3 and $CaCl_2$ adjusting the pH to 10 with HCl, to produce a uniformly graded carbonate silt material. SEM images of these particles show them to have hexagonal and rhombohedral shapes, a tendency to aggregate and a crushability index Br of 0.54 (Conrado-Palafox et al. 2023). The silicate silt is a commercial Sil-Co-Sil-106 sub-angular ground quartz (Schmidt 2015).

Both types of silt particle were mixed with the Ottawa clay soil at different percentages: 25%, 50%, 75%, 87.5% and 93.5%, to obtain the resulting compressibility and other basic geotechnical behaviour of the clay. Figure 2 shows that the pure artificial calcite particle size distribution (PSD) has a generally uniform grading, while the silicate silt material has a more well-graded curve (Table 1 shows d_{50} values), with 25% of the particles smaller than 0.002mm. The Ottawa clay soil has 70% of its particles smaller than 0.002mm.

The carbonate silt mixtures show better graded curves for 25% and 50%, while the curve with 75% calcite lies closer to the uniform distribution; the corresponding d_{50} and uniformity coefficients (C_u) are shown in Table 1. This is important because the particle sized distribution in the sample plays a significant role in the compressibility behaviour.

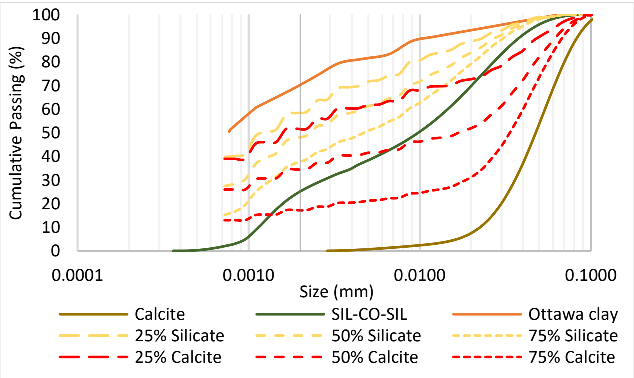

Figure 2. PSD of silicate silt, calcite, and Ottawa clay mixes.

Table 1. PSD characteristic parameters.

Soil sample	Silt (%)	d_{50} (mm)	C_u
Reconstituted clay	0	0.0080	
Silicate	25	0.0015	2.65
Silicate	50	0.0022	5.18
Silicate	75	0.0050	10.48
Silicate	100	0.0100	
Calcite	25	0.0018	5.18
Calcite	50	0.0180	36.14
Calcite	75	0.0340	48.19
Calcite	100	0.0500	

2.2 1-D oedometer test

Oedometer tests were carried out with reconstituted samples formed at 1.5 times their liquid limit, to determine the compressibility variations (void ratio vs stress) due to the calcite and silicate admixtures. To visualize any potential bonding and structure behaviour of our mixes, the intrinsic compression line (ICL) and sedimentation compression line (SCL) after Burland (1990) was determined using the void index (I_v) approach with the following equations (1 – 3) and compared to the void index relationships of the different mixtures;

$$I_v = \frac{e - e_{100}}{C_c *} \quad (1)$$

$$e_{100} = 0.109 + 0.679e_L - 0.089e_L^2 + 0.016e_L^3 \quad (2)$$

$$C_c *= 0.256e_L - 0.04 = e_{100} - e_{1000} \quad (3)$$

where e_L is the void ratio at the liquid limit and e_{100}, e_{1000} are the void ratio at 100 kPa and 1,000 kPa.

3 RESULTS

3.1 Compression behaviour

The initial void ratios (e_0) and void ratios at 25 kPa (e_{25}) for the intact clay and reconstituted clay are e_0 = 2.07, 1.39 and e_{25} = 2.04, 1.27 respectively. The silicate mixtures presented initial void ratios from 1.46 to 0.76, decreasing with higher silicate % and their e_{25} range are from 1.25 to 0.67; while e_0 of the calcite mixtures are 2.03 to 1.18 and e_{25} are 1.87 to 1.01.

Figure 3 (a) shows the 1-D oedometer compression curves of the calcite-clay mixtures, while 3 (b) shows the results of silicate-clay mixtures. The void ratio (e) was normalized by the void ratio at 25 kPa (e_{25}). Two distinct behaviours are seen, with calcite compressibility curves moving upwards (increasing e/e_{25}) with increasing silt %, while the silicate mixes went downwards (reducing e/e_{25}), in comparison to the reconstituted Ottawa clay material reference.

The compressibility indices (C_c) of the silicate materials show a reduction with silicate percentage increases, while the C_c values for the calcite mixes keep increasing until 93.5%, where it actually exceeds the reconstituted clay value. On the other hand, the swelling index decreased with both the addition of the silicate and calcite minerals; the silicate mixes reduce their C_s with higher percentages of silicate, while the calcite mixes presented lower C_s values with lower calcite percentages (see Table 1).

Figure 4 shows compressibility index (C_c) with liquid limit (LL). As expected, LL decreases with silicate or calcite addition. However, the silicate reduced the LL more than the calcite. It can be seen in Figure 4 that LL of the calcite mixes range from 35-42%. Intact samples from Mexico and other offshore regions show higher LL, thereby increasing their compressibility indices. This is likely to due to the minerology and chemistry of the offshore materials.

Figure 5 shows the ICL and SCL developed by Burland (1990) obtained with a meta-study of natural clay results. According to Cotecchia and Chandler (2000) the sensitivity can also be determined with the SCL and ICL curves. Therefore, the SCL obtained by Burland (1990) with intact clay samples shows a sensitivity of approximately S_t=5 in respect to its ICL. The undisturbed Ottawa clay is far above the SCL meaning that the clay tested has a sensitivity higher than 5 at lower stresses. At a vertical effective stress (σ'$_v$) above 500 kPa, the line converges on the SCL, while for reconstituted Ottawa clay void index (I_v) lies between the SCL and ICL lines, showing the influence of structure on the intact clay compression behaviour.

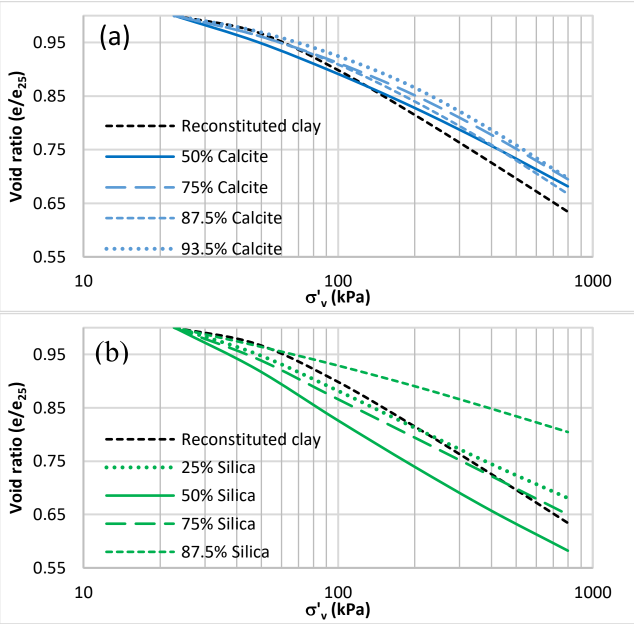

Figure 3. Normalized compression curves of calcite (a) and silicate (b) mixes with Ottawa clay.

Table 2. Compression index (C_c) and swell index (C_s).

Soil sample	Cc	Cs
Reconstituted clay	0.348	0.036
25% Silicate	0.263	0.027
50% Silicate	0.251	0.016
75 % Silicate	0.146	0.011
87.5% Silicate	0.091	0.010
50% Calcite	0.222	0.016
75% Calcite	0.269	0.018
87.5% Calcite	0.325	0.024
93.5% Calcite	0.455	0.026

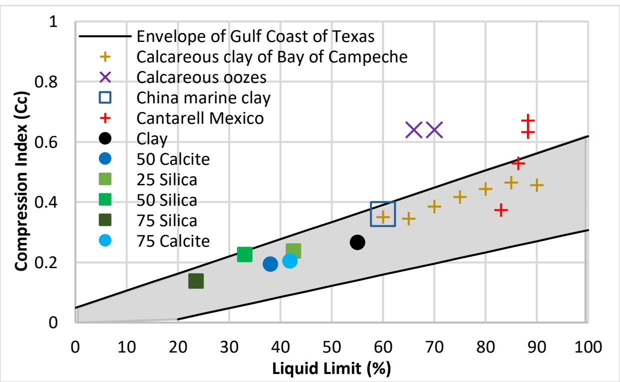

Figure 4. Compression index with limit liquid.

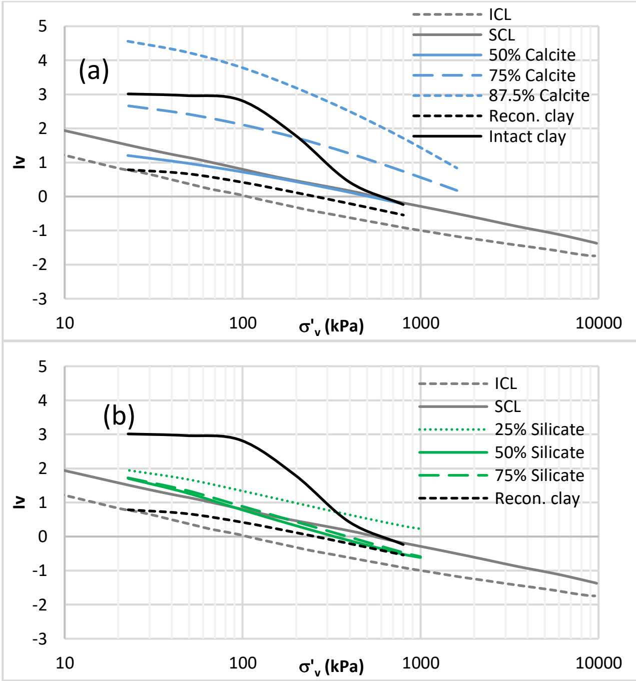

Figure 5. Void indices (I_v) of clay and calcite (a) and silicate (b) mixes.

The calcite mixture curves have increased void index values with calcite % increases, lying well above the reconstituted clay curve. At higher calcite contents (>75%), the calcite curves reach the undisturbed clay curve and eventually exceed it. In contrast, the silicate mixtures with less than <75% present similar curves laying around or beneath Burland's SCL, reproducing the similar behaviour to the very low % calcite mixes.

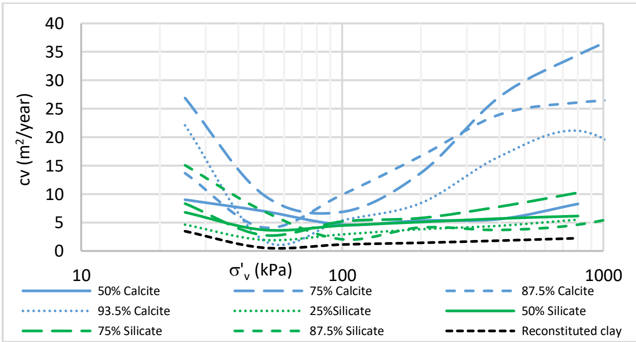

Figure 6. Coefficient of consolidation (C_v) with stress.

The values of coefficient of consolidation (C_v) are shown in Figure 6 and show lower values for silicate mixtures compared to the calcite. The 50% calcite mixture presents the lowest C_v in comparison with the other mixtures. The highest C_v values are the calcite mixtures greater than 75%, although at 50 kPa the values are about the same as the silicate or 50% calcite.

4 CONCLUSIONS

This study shows the changes in basic geotechnical behaviour of a high plasticity terrigenous clay due to the addition of precipitated calcite particles and manufactured silicate particles. Firstly, the addition of 50%, 75% of silicate and 50% calcite shows PSDs similar to the upper limits found in the Gulf of Mexico marine sediments. Adding more calcite particles (75% and 87.5%) provides PSD curves similar to the Coral facies or Progresso Blanket curves. The clay – silicate mixes are less compressible than the clay – calcite mixes, and sediments with more than 85% of calcite particles present compressibilities and void ratios higher than a structured intact high plasticity clay. Moreover, the calcite particles do not reduce the clay plasticity as much as silicate particles, and the calcite addition increases the coefficient of consolidation more than the silicate material. Although not tested in the study, it is expected changes in the shear strength and sensitivity of the silicate and calcite mixes will occur, based on the ICL and SCL curves of the clays. Further testing using more sophisticated stress-strain approaches will be used to further validate the obtained materials.

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