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Use of *Cα / Cc* ratio as a criterion for cementitious stabilization of highly organic subgrade soils

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ABSTRACT: Organic soils and peats at shallow depths are considered as problematic subgrade soils for pavement applications due to their high void ratio and secondary compression characteristics. Effect of cementitious stabilization on the time-stress-compressibility behaviour of three different organic soils were evaluated in this study. The primary objective was to determine if the secondary compression characteristics of organic soils and peats can be stabilized with (i) cement only, (ii) binary blends of cement/slag (C-S), cement/gypsum (C-G), and cement/cement-kiln-dust (C-CKD), and (iii) ternary blend of cement-slag-gypsum (C-S-G) in equal proportions. Based on laboratory consolidation tests, it was found that a unique relationship exists between C_α (secondary compression index) and C_c (primary compression index) for any given combination of time, stress level and void ratio. Cementitious mixes containing various waste materials is found to be effective in control-ling the secondary compression, and C_α / C_c ratio may be used as a criterion for optimizing cementitious materials content in soil stabilization projects.

1 INTRODUCTION AND BACKGROUND

Soils rich in organic matter can be found at relatively shallow depths throughout southern Florida. Organic soils and peats in this area are characterized by high void ratios and moisture contents, and large second-ary compression due to sustained overburden stress from the pavement structure (Sobhan et al. 2007). Maintenance of roadways built over soft organic sub-grade is costly due to pre-mature cracking, rutting, and differential settlement of the pavement. In the re-cent years, a lot of attention has been given to deep mixing technologies using cement and other chemical stabilizers as possible remedial measures for soft and problematic subgrade soils. Current practice of deep mixing methods is broadly based around Japanese and Scandinavian efforts dating from the late 1960s to the present day, focusing primarily on stabilization of organic soils and peats (Bruce and Bruce, 2003). These efforts mostly used unconfined compressive strength (UCS) as the primary indicator for the success of deep mixing, and the selection of optimum mix design (EuroSoilStab, 1997, 2002; Ahnberg et al. 1995; Ahnberg and Johansson, 2005; Ahnberg, 2006; Axelsson et al. 2002; Esrig et al. 2003; Hebib and Far-rell, 1999; Holm, 1999; Rathmayer, 1996). Timoney et al. (2012) investigated the use of cement, ground granulated blast furnace slag, gypsum, lime, fly ash, and silica sand filler as soil stabilizers and concluded that cement/slag combinations are the most suitable for peat stabilization in terms strength development. Since organic soils and peat are susceptible to long-term secondary and tertiary creep compression, it is hypothesized that a compressibility based criterion such as the ratio of socondary compression index to primary compression index (more commonly known as the C_α / C_c ratio) may serve as an additional indicator of the performance of treated soils, and could be used for developing optimized design for field deep mixing projects. Extending the work of Timoney et al. (2012), the current study developed a compressibility based criteria for stabilization of highly organic soils using cement (C) only and blended mix cement/slag (C-S), cement/gypsum (C-G), cement/cement-kiln-dust (C-CKD), and cement-slag-gypsum (C-S-G) in equal proportions. It is to be noted that these non-traditional stabilizers are mostly derived from waste materials or by-products and used for partial replacement of cement. Blast furnace slag is a material formed when iron ore, coke and limestone are mixed and melted in a blast furnace; cement Kiln Dust is the fine-grained, powdery, solid, highly alkaline waste material that is obtained from cement kiln; gypsum is calcium sulfate dehydrate consisting of calcium, sulfur, oxygen and water. Approximately 75.3 million metric tons of CKD, 15.5 million metric tons of slag, and 9.9 million metric tons of gypsum are produced annually in the US (USGS, 2017; 2018).

2 SITE CHARACTERISTICS

The American Association State Highway and Trans-portation Officials (AASHTO) standards guide clas-sifies organic materials as type A-8 soils. Florida De-partment of Transportation (FDOT) defines organic materials as any soil for which an individual organic content test results exceeds seven percent (Sobhan, 2007). In Florida, organic soils are found throughout the coastal lowlands of the Florida peninsula, which includes the Florida Everglades. Organic deposits have accumulated in the region due to its close proximity to the ocean, which generates heavy rainfall and high relative humidity. The muck soils found throughout the Everglades Agricultural Area (EAA) were formed under flooded conditions that inhibit the decomposition of organic material, allowing them to form organic soils. Soils in the EAA vary greatly as the depth of the organic material generally decreases with distance from Lake Okeechobee.

Undisturbed soils were collected from underneath existing roadways and vicinities located in the western Palm Beach County in southeastern Florida. Based on previous laboratory and field tests, (Sobhan et al. 2007) reported the following properties of the subsurface organic soil in this region: organic contents = 25% – 92%; moisture content ranges from 160% - 650%, void ratio ranges from 3.2 - 13.9, and un-drained shear strength ranges from 17 - 40 kPa. The site consists of organic silts (OL) with a spongy texture from depths of 1.5-3 m, and fibrous peats (OC > 75%) from 3-6 m. Figure 1 shows the organic soils and peats used in this study.

(a) (b)

Figure 1. (a) Silty organic layer from 1.5m to 3.0m; (b) Fibrous peat layer from 3.0m to 6.0m

3 OBJECTIVES

The objective of this study were: (1) To determine if the secondary compression characteristics of organic soils and peats can be stabilized with (i) cement only, (ii) binary blends of cement/slag (C-S), cement/gypsum (C-G), and cement/cement-kiln-dust (C-CKD) in equal proportions; and (iii) ternary blend of cement/slag/gypsum (C-S-G) in equal proportions; (2) To quantify the effectiveness of cementitious stabilization by evaluating the time-stress-compressibility (t-log σ'_v - e) relationship in terms of the C_α / C_c ratio, where C_c and C_α are the primary and secondary compression indices, respectively; and (3) To provide some guidelines for selecting optimum dosage of cementitious materials in deep mixing methods when organic soils and peats are encountered.

4 EXPERIMENTAL PROGRAM

The current study is divided into three Phases:

- Phase I included consolidation and secondary compression testing of three control soils, two with high organic contents in the amounts of 59% (soil ID S-59) and 68% (soil ID S-68), and a peat with organic content of 90% (soil ID S-90);
- Phase II involved consolidation testing on cement stabilized S-59, S-68 and S-90 soils, with cement contents ranging from 11% to nearly 90% by dry weight of the soil (note: the dry unit weight of these soils are extremely low and approximately 9.9 kN/m^3).
- Phase III involved consolidation testing of S-59 soil stabilized with 20%, 40% and 60% cementitious materials containing (i) cement (C) only; (ii) binary cementitious mixes containing equal pro-portions of cement/slag (C-S), cement/gypsum (C-G), and cement/cement-kiln-dust (C-CKD); and (iii) a ternary cementitious mix containing equal proportions of cement/slag/gypsum (C-S-G).

Organic contents were determined approximately in accordance with ASTM D 2974-13. Type I Portland cement was used in all mixes. The mix designs for all three phases are shown in Table 1.

Table 1. Mix Designs

Soil ID	Composition
Phase I: Control Soils	
S-59	OC = 59%
S-68	OC = 68%
S-90	OC = 90%
Phase II: Cement-stabilized Soils	
S-59	C (%) = 20, 40, 60
S-68	C (%) = 11, 25, 38, 50, 57
S-90	C (%) = 17, 39, 59, 78,90
Phase III: S-59 with Blended Stabilizers	
C-S-20	Soil+10%C+10%S
C-S-40	Soil+20%C+20%S
C-S-60	Soil+30%C+30%S
C-G-20	Soil+10%C+10%G
C-G-40	Soil+20%C+20%G
C-G-60	Soil+30%C+30%G
C-CKD-20	Soil+10%C+10%CKD
C-CKD-40	Soil+20%C+20%CKD
C-CKD-60	Soil+30%C+30%CKD
C-S-G-60	Soil+20%C+20%S+20%G

The sample preparation consisted of four main tasks including: mixing, compacting, curing, and the control of any swelling pressure during the curing period. The mixing process was carried out at the soil's natural moisture content and the stabilizing agent was introduced in a dry state in an effort to simulate field conditions (Dry Soil Mixing technique) practiced in Deep Mixing Method. Specimens were compacted in the consolidation mold in three equal layers using the same compaction energy applied to each layer. The energy of compaction was determined by a trial and error procedure until the desired compaction level was achieved. For all specimens used in this study, the compacted dry unit weight was maintained at about 9.9 kN/m^3, which was close to their natural state. The samples were then inundated with water and cured for a period of 7 days prior to the consolidation testing program. Investigating the effects of curing time in the properties of stabilized material was beyond the scope of this study.

The testing program was composed of a conventional incremental loading stage and a creep stage (secondary compression). The Increment Load Ratio (ILR) utilized was unity, using effective consolidation stresses ($_v$) of 6 kPa, 12 kPa, 24 kPa, 48 kPa, 96 kPa, 192 kPa, and 384 kPa, with each stress held constant for a period of 24 hours.

5 RESULTS AND ANALYSIS

Phase I of the research study includes one-dimensional oedometer testing for the soil samples (S-59, S-68, and S-90) with no cement added. The void ratio vs effective pressure for all three specimens are shown in Figure 2. More details are available else-where (Ramirez, 2009).

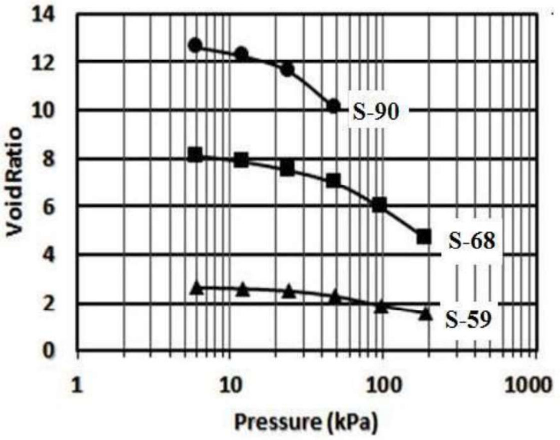

Figure 2. Void ratio vs effective pressure for soil samples

Mesri and Godlewski (1977) postulated that for any given soil, there is a unique relationship between secondary compression index ($C_\alpha = \Delta e / \Delta log\ t$) and primary compression index ($C_c = \Delta e / \Delta log \sigma'_v$), that holds true at all combinations of time (t), effective stress (σ'_v), and void ratio (e). At any given effective stress, the value of C_α from the first log cycle of secondary compression and the corresponding C_c value computed from the e-$log\ \sigma'_v$ curve (at the end of primary consolidation) are used to define the relation-ship between C_α and C_c. It is to be noted that the pro-cess of primary consolidation for the highly organic soils is very quick, and ends approximately in one minute (Ramirez, 2009). The computed C_α and C_c values for each soil at any stress level are plotted in Figure 3. It is found that for each soil, an approximate linear relationship could be established with constant C_α / C_c ratio. The C_α / C_c ratio ranged between 0.045 and 0.06, which is consistent with the ranges suggested by Terzaghi et al. (1996) for organic soils and peats. More details of the methodology have been reported by Sobhan et al. (2012).

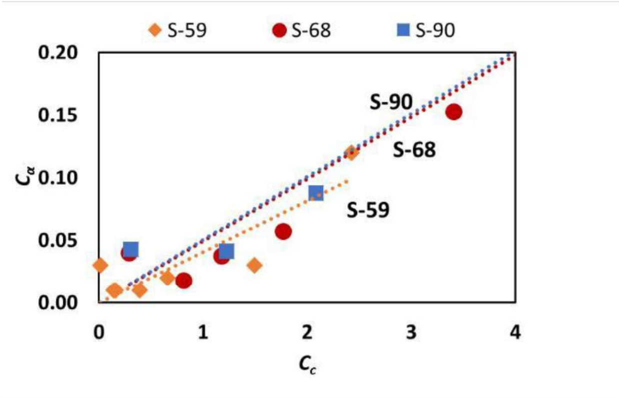

Figure 3. Relationship between C_α/C_c.

Phase II of the study consisted of one dimensional oedometer testing of S-59, S-68 and S-90 soils stabilized with various percentages of cement (Table 1). Figure 4 demonstrates the relationship between C_α/C_c ratio and percent cement content for the all three samples. Also superimposed on this Figure are the proposed ranges of C_α/C_c ratios characterizing various soil types in terms of their probable engineering behaviour (Terzaghi et al. 1996). It is found that the C_α/C_c ratio decreases with increasing cement content. As the C_α/C_c ratio decreases, the soil engineering behaviour is known to shift from that of peaty soils, to organic clays and silts, to inorganic clays and silts, to shale and mudstone and finally to a granular material.

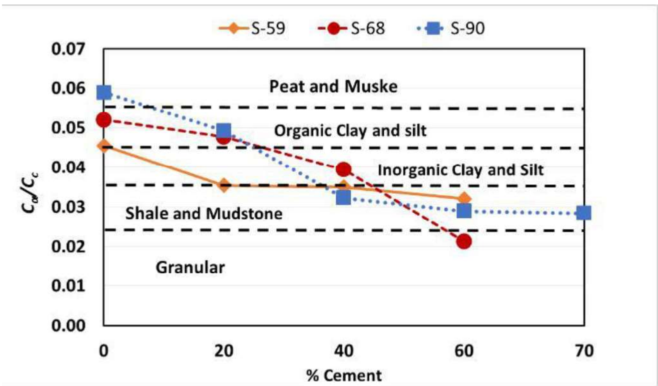

Figure 4. C_α/C_c vs. percent cement

For the S-59 soil, it is found that the C_α/C_c ratio decreased to a near constant value at about 20% cement content, while S-68 and S-90 soils required higher cement content (40 to 60%) to be sufficiently stabilized such that it demonstrates desirable engineering characteristics. With cement additions in excess of these dosages, no noticeable improvement was observed. These results are encouraging, since it appears that the compressibility behaviour of highly organic soils can be fundamentally improved (by cement stabilization) to resemble almost a granular soil, which is considered to be an excellent foundation material by the geotechnical and pavement engineers.

In phase III, soil S-59 was stabilized with 20%, 40% and 60% blended cementitious mixes containing equal proportions of cement and one or more stabilizers derived from waste materials such as blast furnace slag (S), cement kiln dust (CKD) or gypsum
(G). Figures 5 through 7 demonstrate the relationship between C_α and C_c for these soil-cement mixtures. Following Mesri and Goldewski (1977) procedure, linear correlation was established with constant C_α/C_c ratio for all soil-cement mixes. These values are provided in Table 2, which also lists the probable characteristics of the stabilized soils based on the suggested ranges of C_α/C_c ratios for engineering soils provided by Terzaghi et al. (1996). Finally, in Figure 8, the C_α/C_c ratios for all mixes are compared with the ranges proposed by Terzaghi et al. (1996) for evaluating the effectiveness of the various blended stabilizers in transforming the compressibility characteristics of the organic soil S-59 to that resembling a more desirable construction material. As expected, the C_α/C_c ratio of the control soil was significantly reduced due to cementitious stabilization. This was true for all types of blended stabilizers at all cementitious contents (except the 40% C-S blend). The ternary mix of cement-slag-gypsum was also quite effective although at high stabilizer content; on the other hand, it also indicates an opportunity for recycling waste materials in high volumes. Considering that the blended stabilizers are used in this study for partial replacement of cement with waste materials and by-products, the results of this study identify promising alternative materials that will support sustainable and environmentally friendly construction practices.

6 CONCLUSION

The organic soils and peats studied in this research broadly belong to a general class of soft soils which are considered problematic foundation materials by engineers involved in the design, construction and maintenance of geotechnical and pavement structures. Soft soils are usually characterized by low strength and high compressibility, which may cause major premature distresses in highway pavements. The issues related to soft soils are encountered in many parts of the world, including Australia, where researchers are conducting field and laboratory investigations for improved design of geotechnical structures on soft soils (Gaone et al. 2018; Kelly et al.

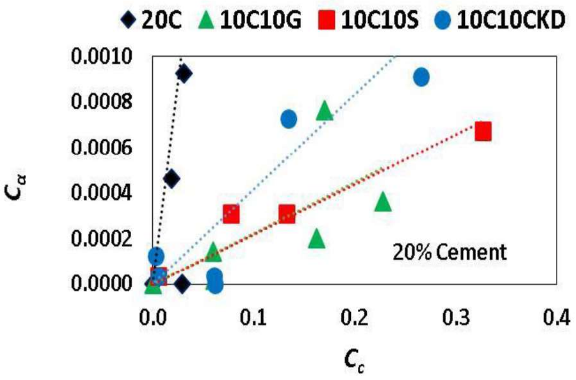

Figure 5. C_α vs C_c (20 % Cement)

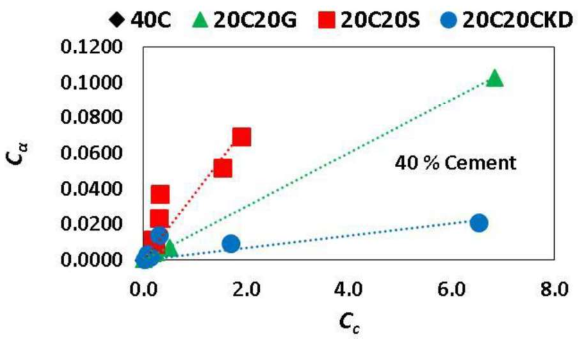

Figure 6. C_α vs C_c (40 % Cement)

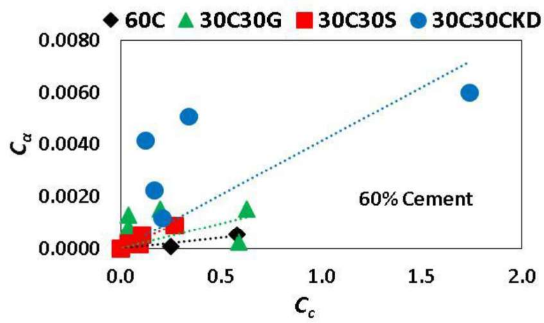

Figure 7. $C\alpha$ vs Cc (60 % Cement)

2018; Buttling et al. 2018; Pineda et al. 2016; and Kelly et al. 2008). The compressibility characteristics, particularly the long-term secondary compression behaviour of soft soils may be effectively con-trolled by chemical stabilization. The current study evaluated the effectiveness of blended cementitious stabilizers in controlling the compressibility characteristics of highly organic subgrade soils. The time-stress-compressibility relationships expressed in terms of the C_α/C_c ratios proposed by Mesri and Godlewski (1997) was used as the primary criterion to assess the success of the stabilization process. The characteristics of the stabilized soils were compared with the suggested ranges of C_α/C_c ratios of engineering soils to assess the probable engineering behaviour of the stabilized soils (Table 2 and Figure 8).

The following conclusions could be derived from this study:

- Regardless of the organic content, cementitious stabilization is an effective tool for controlling the compressibility behaviour of organic soils and peats. The optimum dosage of cementitious stabilizer may vary between 20 to 60 percent (by dry weight, noting that these soils have very low dry unit weight) depending on the organic content.
- C_α/C_c ratio can be used as a laboratory-derived criterion for evaluating the effectiveness of cementitious stabilization of highly organic soils that exhibit secondary compression behaviour.
- Alternative materials derived from waste materials and by-products such as cement kiln dust, blast furnace slag and gypsum blended with cement show promise as chemical stabilizers for organic soils, thus supporting sustainable construction practices.

Table 2. $C\alpha/Cc$ ratios for Phase III

Phase III		
Soil ID	**C_α/C_c**	**Organic Soils Converted to**
S-59	0.0455	Inorganic clay and silt
C-20	0.0354	Shale and mudstone
C-40	0.0294	Shale and mudstone
C-60	0.0009	Granular
C-S-20	0.0022	Granular
C-S-40	0.0376	Shale and mudstone
C-S-60	0.0034	Granular
C-G-20	0.0022	Granular
C-G-40	0.0150	Granular
C-G-60	0.0019	Granular
C-CKD-20	0.0042	Granular
C-CKD-40	0.0034	Granular
C-CKD-60	0.0041	Granular
C-S-G-60	0.0154	Granular

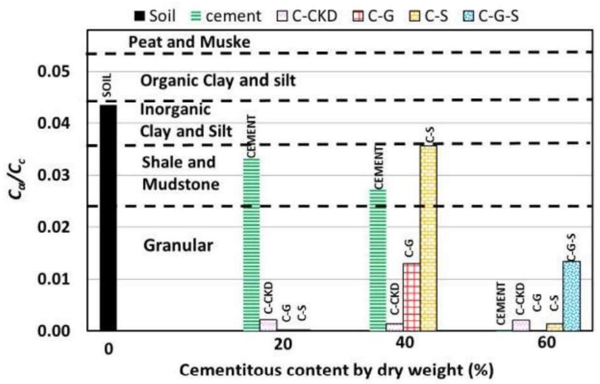

Figure 8. $C\alpha/Cc$ vs percent cement by dry weight

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