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Research paper

Thixotropic aging and its effect on 1-D compression behavior of soft reconstituted clays

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ABSTRACT

The present study investigates the moisture content at which the thixotropic effect is maximum, as well as the effect of such aging on compression. For this research, samples were prepared at moisture contents ranging from 0.55–1.25 times their corresponding liquid limits, and fall cone and vane shear tests were administered to determine the shear strength. Oedometer tests were performed on both thixotropically aged and unaged samples to observe the effects of thixotropic aging on 1-D compression characteristics. It was observed that the maximum thixotropic strength was obtained at a moisture content close to 0.75 times the corresponding liquid limit for all samples, and thixotropic strength recovery was negligible at a moisture content of 0.55 times the corresponding liquid limit. Vane shear strength was found to be lower than fall cone strength, and an increase in the rate of strain resulted in lower estimation of thixotropic strength recovery. The thixotropic strength ratio was observed to be dependent on the plasticity index and activity of the clay sample. Of all of the clays examined, the thixotropically aged sample provided the highest yield stress. The study suggests that in situations where the effective vertical stress is less than 100 kPa, the settlement calculation, using the conventional effective stress principle, needs to be rigorously revised. A scheme for considering both strength and compressibility behavior in design practice is also provided.

1. Introduction

To maintain navigation channels and/or increase the depth of water above the seabed, large amounts of very soft clays are often removed. These dredged clays are usually dumped into several disposal areas, or are used to fill reclaimed lands. The dredged clays have a high natural moisture content and compressibility, and very low shear strength. They are often considered as waste slurry because of their poor engineering properties, and their time-dependent strength and deformation characteristics are incomprehensible to geotechnical engineers. One such time-dependent strength characteristic is *thixotropic aging*. It is an isothermal, reversible, time-dependent process, whereby the material stiffens while at rest and softens or liquefies upon remolding (Mitchell, 1960). It occurs under conditions of constant composition and volume, and the properties of soil at its natural moisture content may significantly change due to this phenomenon. Thixotropic properties are also of great importance to the geotechnical investigation of offshore structures, as they make it possible for > 100% of the initial shear strength to be achieved within a few days. Thus, the increment of shear strength along a wall of driven piles or suction anchors can be relied upon only a few days after installation (Andersen et al., 2008).

Remolding is a disturbing force in the clay-water system, which causes the particle links to break down. It is primarily responsible for loss of strength, and as a result, the deflocculated clay fabric is no longer in equilibrium (Mitchell, 1960; Mitchell and Soga, 2005). The interparticle forces attain equilibrium by reorganizing the water-cation structure, causing the system to flocculate. It takes time, because the viscous are resistant to particles and ion movements (Barnes, 1997). Recovering the thixotropic strength is intimately connected to the restoration of particle links and reordering of the water phase (Jacobson and Pusch, 1972). Thixotropy is the result of the gradual rearrangement of particles, under the action of bonding forces, into positions of increased mechanical stability. Thus, thixotropy is a time-dependent return to its original harder state after being softened by remolding. The recovery of strength depends partly or wholly on the material properties (Skempton and Northey, 1952). Pryce-Jones (1934) noticed that thixotropy is more pronounced in systems containing non-spherical particles; thus, its importance is immense in fine-grained soils (e.g. clay). The effects of thixotropy in fine-grained soils have been studied by some researchers like Osipov et al. (1984), Park et al. (2014), and Jeong et al. (2015). The primary goal of these investigators was to determine the extent to which thixotropic aging could contribute to the

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sensitivity of clays, or to determine the reversibility of the system. To the authors' knowledge, no recent investigations have been conducted to determine the moisture content at which maximum thixotropic strength can be achieved or to determine the effect of such aging on the settlement behavior of clay. However, it is well documented that both natural and dredged clays possess time-dependent behaviors (Al-Zoubi, 2010; Yin et al., 2014). When the dredged clays with high initial moisture content are undisturbed, the mechanical behavior is subjected to thixotropic aging. Hence, it is rational to assume that the consolidation behavior will be affected by the thixotropic aging. In the past studies, such problems were seldom addressed (Mitchell, 1960; and Seng and Tanaka, 2012). Mitchell (1960) observed that aging of the thixotropic soil increases its resistance to compression. Seng and Tanaka (2012) concentrated on the thixotropic effect on shear modulus, and observed that the increment of shear modulus under secondary consolidation was lower than that developed during the thixotropic process. Very recently, the beneficial effect of thixotropy was explained by Farsakh et al. (2015), who noticed a significant discrepancy between the FE numerical simulation and the field test data while simulating a pile setup. They modeled a pile installation, using prescribed radial and vertical displacements on the nodes at the soil-pile interface, followed by vertical deformation to activate the interface friction of the soil pile. The thixotropic effects were incorporated by applying a time-dependent parameter proposed by Fakharian et al. (2013). It was observed that the consolidation effect and the thixotropic effect were in close agreement with the field test data, emphasizing the practical importance of the thixotropic phenomenon.

A review of the studies performed by Skempton and Northey (1952), Mitchell (1960), Farsakh et al. (2015), Shahriar (2015, 2016) and Shahriar et al. (2016) provides conclusive evidence that thixotropic strength recovery is a function of time, moisture content, and clay mineralogy, although to some extent, it also depends on temperature, initial grain structure, and method of compaction. In the present study, the parameters for investigating strength dependencies were moisture content, activity, and the plasticity index. Samples were prepared at a wide range of moisture contents, and strength recovery was measured using the fall cone and vane shear tests. An oedometer test was performed on both aged and unaged samples to assess the compressibility characteristics.

2. Materials and sample preparation

Clays from six locations in southern Bangladesh, predominantly formed of illitic or chloritic minerals (Islam et al., 2002), were collected for the current study. Table 1 provides the geotechnical properties of the clay samples, which contained a wide range of clay (47.74%–91.73%). Variations in liquid limits were observed to range from 65.4% to 146% and facilitated the examination of the properties of clays over a wide range. The natural moisture content was within the range of 52.9% to 126.3%. The large differences in the natural moisture content of samples from different disposal sites can be attributed to the variations in clay content, particle size, and stratification characteristics. Casagrande's plasticity chart and the *activity* of clay were used to determine the dominant clay minerals present in the samples. In this

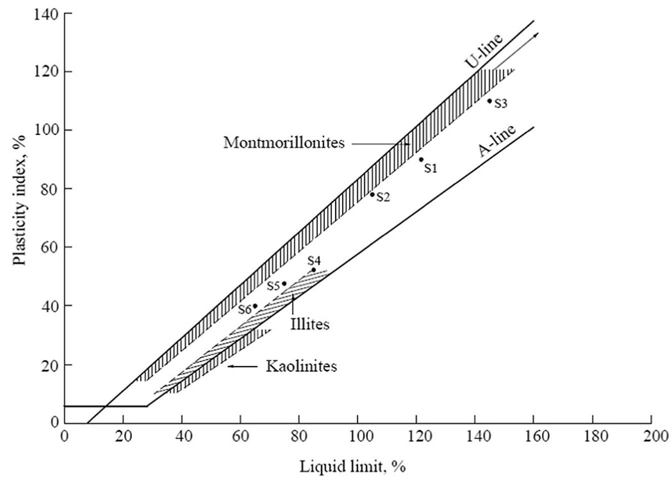

Fig. 1. Location of common clay minerals and the clay samples of current investigation on the Casagrande's plasticity chart.

approach, the location of the soil sample in Casagrande's plasticity chart is observed, and if the Atterberg limits plot high above the A-line, but near the U-line, the clay portion in the soil sample is determined to consist predominantly of montmorillonite, which has an *activity* > 1.0. The illitic clays (*activity*: 0.5–1.0) plotted right above the A-line, whereas the kaolinites (*activity*: 0.3–0.5) plotted below the A-line (Casagrande, 1948; Mitchell and Soga, 2005; Holtz et al., 2011). These zones are clearly identified in Fig. 1. Since the samples used in this study plotted nearly halfway between the A-line and U-line (Fig. 1) and the activity ranged from 0.84 to 1.21 (Table 1), it was concluded that the clay minerals in the samples were predominately illite or montmorillonite. Higher liquid limits of clays do not warrant the dominance of kaolinitic minerals (Mitchell and Soga, 2005); therefore, it was presumed that the samples used in the present study did not contain kaolinitic minerals.

To determine the effect of moisture content on thixotropic aging, each type of clay soil was prepared at nine moisture contents, within the range of 0.55–1.25 times their corresponding liquid limits. To characterize the compressibility behavior, three types of clay soils (S1, S3, and S5) were investigated, with the samples prepared at six initial moisture contents (w_o) within the aforementioned range. Targeted values of initial moisture content for the consolidation tests were 1.25, 1.05, 0.95, 0.75, 0.65, 0.55 times their corresponding liquid limits. The preparation of the samples included adding the appropriate amount of distilled water to completely dried clay, and thoroughly mixing it. Then the moist clay was kept in tightly sealed plastic bags for one day to achieve uniform moisture content. To eliminate strength gain during the storage period, an electric mixer with a steel stirrer was used to remold the clay just before it was placed in the molds. The slurry was then poured into molds of various sizes for different test programs, which was considered to be the beginning of the thixotropic aging. A 40 cm × 24 cm × 10 cm mold was used for the fall cone test, a 20 cm wide and 10 cm high bucket was used for the vane shear test, and a

Table 1
Engineering properties of the soils considered in the present study.

Sample ID	Liquid limit (ASTM D4318-17, 2010)	Natural moisture content %	Plastic limit (ASTM D4318-17, 2010)	Plasticity index (ASTM D4318-17, 2010)	Clay fraction < 2 μm (ASTM D422-63, 2007) %	Activity, *A*	Specific gravity (ASTM D854-14, 2014)
S1	122.0	98.2	31.8	90.2	81.08	1.11	2.68
S2	105.9	86.7	27.6	78.3	85.77	0.91	2.70
S3	146	126.3	35.2	110.8	91.73	1.21	2.69
S4	85.4	71.3	33.3	52.1	59.43	0.88	2.68
S5	75.0	61.4	26.8	48.2	55.44	0.87	2.71
S6	65.4	52.9	25.3	40.1	47.74	0.84	2.72