Journal of Engineering Science 14(1), 2023, 01-09
DOI: https://doi.org/10.3329/jes.v14i1.67631

JES
an international Journal

COMPRESSIVE BEHAVIOR OF RECONSTITUTED SOILS AT HIGH INITIAL WATER CONTENT: CASE STUDY ON SOUTH-WESTERN REGION OF BANGLADESH

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Received: 30 August 2022 Accepted: 10 January 2023

ABSTRACT

This study illustrates the experimental investigation of the effect of high initial water content on the compression behavior of reconstituted soil. For this attempt, disturbed soil samples were collected from two selected locations of the KUET campus, Khulna, Bangladesh. The reconstituted soils were prepared in the laboratory at different initial water content, ranging from 0.7 to 1.2 times their corresponding liquid limit. The main focus of this study was to investigate the compression behavior of reconstituted clays using oedometer tests. This work was complementary to the intrinsic compression line concept proposed by Burland (1990). In the laboratory, ASTM methods were followed to measure the initial properties of soils. Here, it can be observed that $e - log\sigma'_v$ *compression curves show an inverse "S" shape as a result of resisting deformation due to pressure. Moreover, some important correlations were developed based on the initial void ratio and the void ratio at the liquid Limit* e_0/e_L*. It has been observed that the void index is a dominating parameter to normalize the squeezability characteristics at different initial water contents in the plastic post-yield regime. A non-unique relationship is obtained for different soils to express the intrinsic compression line concept. However, there is a proportional relationship between intrinsic compressibility and initial water contents or liquid limits.*

Keywords: *Compressibility; Intrinsic concept; Initial water content; Plastic post-yield; Void index.*

1. INTRODUCTION

Bangladesh is the eighth largest country in the world in terms of population, located in the northeastern part of South Asia. Khulna is the third largest and southwestern divisional metropolitan city in Bangladesh, near the world heritage site, Sundarbans, circumscribed by the Bay of Bengal on the south, Jessore and Narail districts on the north and Bagerhat and Satkhira districts on the east and west, respectively (Rafizul *et al*., 2013). It is situated at a latitude of 22°48'35.24" north and a longitude of 89°33'51.8" east, about 48km away from the second largest port of Bangladesh. The ground of this region consists of coarse to very fine sand, silty clay, clay and very soft silt, which can be defined as 'compressible and collapsible sediments' having a thickness of topsoil is about 6 to 20 m or more (Ali *et al*., 2004; Adhikari *et al*., 2006). However, in most of the places of the Khulna region, the soil layer consists of a considerable amount of organic matter (about 5 to 70% or more at some times) at a depth of 10 to 25 ft (3m to 7.5m) from the existing ground surface outcomes obsessive settlement due to the characteristics of exalted compressibility and low shear strength (Mahamud *et al.,* 2008; Rafizul *et al*., 2009). The compression behavior of soils is a fundamental parameter in geotechnical engineering problems, soil deformation, or settlement analysis, specifically if clayey matters are encountered in the foundation (Skempton and Jones, 1944; Hough, 1957; Terzaghi and Peck, 1967). However, numerous researchers studied the mechanical behavior of natural soils (Nagaraj and Srinivasa Murthy 1986; Burland 1990; Chandler 2000; Cotecchia and Chandler 2000; Corkum and Martin 2007). Some researchers presented that reconstituted soils exhibit dissimilar characteristics than natural soils owing to the formation of soil structure in the course of their depositional and post-depositional processes (Burland, 1990; Liu and Carter, 1999; Chandler, 2000; Cotecchia and Chandler, 2000; Hong *et al*., 2012). Reconstituted soil can be defined as soil with a mixture of water content equal to or greater than the liquid Limit (Burland, 1990). The soil structure can be defined as the arrangement and bonding of the soil elements and for effortlessness, it encompasses all the features of soil that are not quite the same as those of the related reconstituted soil (Burland, 1990; Liu *et al*., 2003). Burland (1990) proposed a remarkable concept to differentiate the compression behavior of reconstituted and natural soils by introducing the concept of a normalized void index (effective vertical stress ranging from 10-4000 kPa) as the intrinsic compression line (ICL) with initial water contents of 1 to 1.5 (ideally 1.25) times the liquid limits, which is widely used to illustrate the compression characteristics of structured soils (Rao and Shivananda, 2005;

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Horpibulsuk *et al.*, 2011; Yin and Miao, 2013). However, Buchan and Smith (1999) reported that the natural water content of natural soils is not restricted in that range and varies in a wide range of liquid limits. However, several studies presented that the initial water content of the reconstituted soil sample, sample disturbance and mineralogy of soil samples quantitatively affect the compression behavior in addition to the liquid limit (Cerato and Lutenegger, 2004; Hong *et al.*, 2010, 2012, 2013). Hong *et al.* (2010) stated that the shape of the compression curve of reconstituted soil samples is analogous to the natural soils and from their experiment work (consolidation tests on three types of dredged soil samples having initial water contents of 0.7 to 2.0 times their liquid limits, with modified oedometer) it was observed that the compression curves differ with respect to the initial water content and the void ratio and compression index of reconstituted soil was increased with the increase of initial water contents. The distinction of void proportion between reconstituted and natural soils was mainly increased when consolidation stress was equal to consolidation yield stress and decreased while functional stress exceeded the consolidation yield stress (Liu and Carter, 1999, 2000). In this manner, it can be concluded that fine-grained soils do not present a completely virgin state at their liquid limits. In particular, due to the compression behavior, the soil perceived pre-consolidation stress owing to the negative pore water pressure sometimes referred to as soil suction. Although numerous works were done using consolidometer on soil samples by several researchers, limited studies on reconstituted soils with high initial water content exist in the literature. The main focus of this study is to investigate the compression behavior of typical reconstituted soils at high water content using consolidometer test in the southwestern region of Bangladesh.

2. MATERIALS AND METHODS

2.1 Sample Collection and Classification

Two disturbed soil samples were collected from two different locations of the Khulna University of Engineering & Technology (KUET) campus. The soil samples were obtained from a depth of about 5 feet from the existing ground surface. The basic physical properties of the collected soil samples are presented in Table 1 following ASTM (2004). The plasticity chart for the investigated soils is represented in Figure 1. It is observed that all values are slightly above the A-line, which can be designated as PI= 0.73 (LL-20) but below the U-line of PI = 0.9 (LL-8), where PI represents the plasticity index and LL is the liquid limit. The soil sample 1 and 2 can be classified as fat clay (CH) and lean clay (CL), respectively, according to the Unified Soil Classification System (ASTM D2487, 2017).

Table 1: Basic physical properties of reconstituted clays.

Soil	Sample 1	Sample 2
Specific Gravity	2.75	2.68
Liquid Limit: (%)	55	29
Plastic Limit: (%)	21	18
Sand (0.06-2 mm): %	2	7
Silt (0.002-0.06 mm): %	74	72
Clay (< 0.002 mm): %	24	21
USCS Symbol	CH	CL

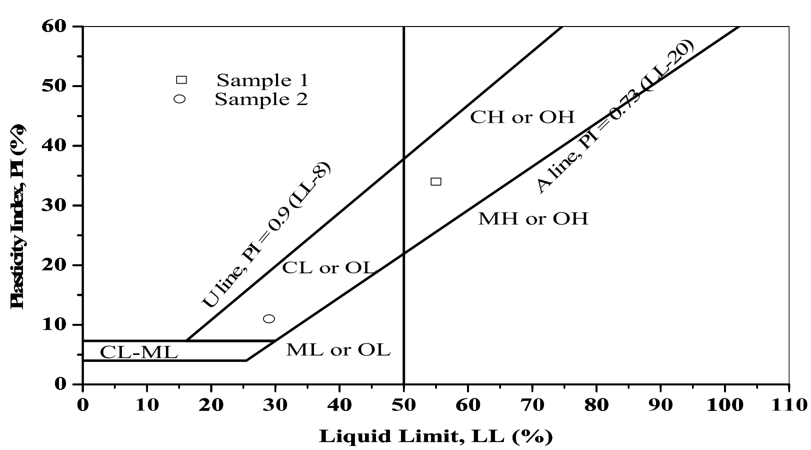

Figure 1: Plasticity chart.

2.2 Sample Collection and Classification

At first, the samples were air-dried and then converted it to powdered form. The powdered samples were then sieved through No. 40 sieve in accordance with the standard procedure as described by Bashar (2002) and the samples were then mixed with a water content equal to 0.7 to 1.2 times of liquid limits, which was adequate to yield uniform and homogeneous slurry. The initial water contents of reconstituted soil samples are presented in Table 2. The details of the preparation of the samples were obtained from Alamgir et al. (2006) and Islam (2006). The slurry at an initial water content of 0.7, 0.8, 0.9, 1.0, 1.1, and 1.2 times of liquid limits, respectively, was consolidated to form a uniform reconstituted soil cake in a cylindrical consolidation mold of 2.5 inch diameter and 1 inch height. An axial load of 25 kPa was applied gradually for 24 hours to the sample using a loading frame. Also, the pressure was increased gradually by about 50, 100, 200, and 400kPa and ultimately to the final value of about 800 kpa. Until the end of primary consolidation, the 800 kPa pressure was maintained.

Table 2: Initial water contents of reconstituted soils.

Soils	Initial water content, W_0 (%)	Liquid limit, LL (%)	W_0/LL
Sample 1	66	55	1.2
	61	55	1.1
	55	55	1.0
	50	55	0.9
	44	55	0.8
	39	55	0.7
Sample 2	35	29	1.2
	32	29	1.1
	29	29	1.0
	27	29	0.9
	24	29	0.8
	21	29	0.7

3. RESULTS AND DISCUSSIONS

3.1 Compression curves

The variations of void ratio with respect to effective vertical stress for the two reconstituted clays are presented in Figure 2 in a semi-logarithmic ($e - log\sigma_v'$) plot. Several researchers presented in their study that soft natural clays exhibit an inverse "S" shape curve (Butterfield 1979; Pelletier *et al.,* 1979; Pestana and Whittle, 1995) with yield consolidation stress. It is observed from the illus,ration (Figure 2) that all plots indicate inverse "S" shape curves changing at a point, which can be regarded as turning point (yield consolidation stress) as reported by Hong *et al.* (2010) for reconstituted soils at high initial water contents. Numerous researchers provided several empirical procedures to determine the yield consolidation stress from standard oedometer tests (Burland, 1990; Butterfield, 1979; Jacobsen, 1992; Sridharan, 1991; Wang and Frost, 2004). The noteworthy difference between these studies and the present study lies in the initial effective stress. According to Dineen (1997) and Bardanis (1998, 1999), the compression curves of reconstituted clays are practically linear. However, Burlnad (1990) and Chandler (2000) reported that the compression curves of reconstituted soils are slightly concave upwards. Burland (1990) described that if the reconstituted soil specimens are fully saturated initially, there is no possibility of encountering the turning points. Research work by Bardanis (1998, 1999) on reconstituted soils at different initial water contents revealed that turning point appears in intrinsic compression curves at very low stresses. They reported that the appearance of turning point on intrinsic compression curves of reconstituted soils is analogous with the compression curves of natural soils may be due to the degree of saturation values being lower than 1, initially. Figure 2 presented that the void ratio, e decreases slightly with the increase of effective vertical stress up to the elastic pre-yield regime, and a sharp decrease is observed when exceeding the yield regime, which can be regarded as the plastic post-yield regime. The identical features of the shape of the compression curves of the reconstituted and natural soils may be due to the analogous consolidation stress or sometimes referred to as 'pore water suction' (Mitchell, 1993) or 'suction pressure' (Hong *et al.,* 2010) or 'remoulded yield stress' (Hong *et al.,* 2012). However, the compression curves of the specimens with a higher initial water content lie over those with a lower initial water content. This observation likewise agreed with the previous studies (Carrier and Beckman, 1984; Cerato and Lutenegger, 2004; Hong *et al*., 2010) in which it is depicted that increasing the adjusted initial water content of the clay specimens tended to increase the void ratio and to increase the compressibility of the reconstituted clay specimens for a given change in the vertical effective stress values.

The present study is also focused on the bi-logarithmic method, originally proposed by Butterfield (1979), to determine the remoulded yield stress or yield consolidation stress as being responsible for the critical state of structure collapse. Numerous researchers (Sridharan and Prakash, 1996; Hong, 2007; Hong *et al.,* 2010) presented this bi-logarithmic method to represent the semi-logarithmic plot ($e - log\sigma_v'$) by a set of two straight lines ($\ln(1+e) - log\sigma_v'$ plot), whereas, the intersection point of those lines is the remoulded yield stress, as shown in Figure 3. Based on the multiple studies on reloading cycles by Umar and Sadrekarimi (2017), it can be stated that the bi-logarithmic method provides exact results. However, the bi-logarithmic method was validated by numerous researchers for natural soils in their undisturbed state (Hashiguchi and Ueno, 1977; Sridharan and Prakash, 1996; Hong, 2007) as well as in this study. However, Hong *et al*. (2013) introduced effective isotropic consolidation stress in place of effective vertical stress. Several studies also revealed that the squeezability characteristics of the reconstituted soil progressively increased when the effective stress exceeded the remoulded yield stress (Butterfield, 1979; Pelletier *et al*., 1979; Burland, 1990; Hong *et al.,* 2012), as demonstrated in Figure 2.

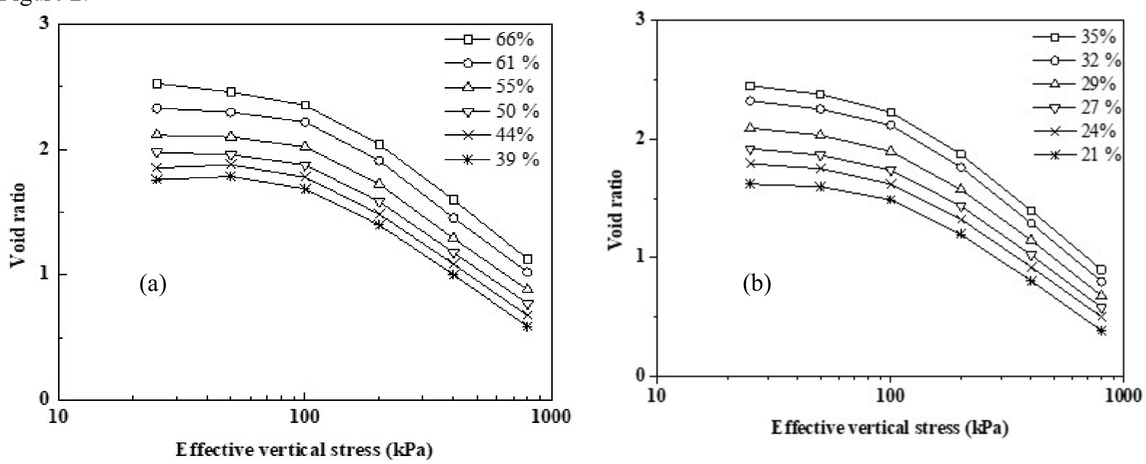

Figure 2: Compression curves of two reconstituted soils at different initial water contents: (a) Sample 1; (b) Sample 2.

These characteristics exclusively depend on the water content at the yield consolidation stress, starting point of the compression curve and the liquid limit. Reconstituted clays having different liquid limits at the same initial water content results in different starting points of the compression lines when effective vertical stress is exceeded the remoulded yield stress (Hong *et al.*, 2012). Sridharan and Nagaraj (2000) reported that soils having different plasticity with the same liquid limit represent diversive compressibility properties and closely depend on shrinkage index than plasticity index or liquid limit. However, the compression curves indicate that higher initial water content results in higher values of remoulded yield stress which may be due to the samples having a relatively higher void ratio at the same level of effective vertical stress with the adjusted initial water contents as discussed by some scholars (Carrier and Beckman, 1984; Cerato and Lutenegger, 2004; Hong *et al.,* 2010). As stated by numerous researchers (Olson, 1962; Martin and Ladd, 1978; Carrier and Beckman, 1984), the use of different levels of initial water content to "remold" (Olson, 1962) or "reconstitute" (Burland, 1990) the soil specimens will influence the mechanical behavior of these specimens due to the significant changes in the structure of the soil. Soil structure can be defined as the combination of texture and interparticle holding capacity of the soil (Mitchell and Soga, 2005). However, Lambe and Whitman (1969) stated that flocculated (random arrangement) structures or dispersed (parallel arrangement) structures are dominated in clay soils. As stated by Cerato and Lutenegger (2004) and Hong *et al*. (2013), the effect of the initial water content on the compression behavior of reconstituted clay specimens depends on the mineralogy of the soil specimens and the soil properties such as liquid limit, cation exchange capacity, activity, and specific surface area. Therefore, different soils result in different void ratios at the same initial water content.

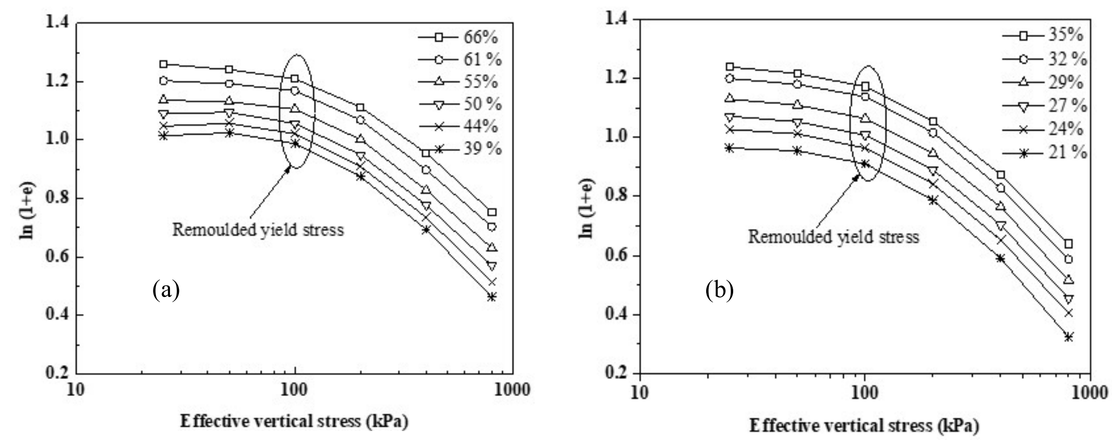

Figure 3: Bi-logarithmic compression curves of two reconstituted soils at different initial water contents: (a) Sample 1; (b) Sample 2.

3.1 Intrinsic Compression Line

Nagaraj and Srinivasa Murthy (1983, 1986) originally proposed the concept of normalized void ratio to effective vertical stress. The term "intrinsic" was presented by Burland (1990) to describe the properties of a reconstituted soil specimens at an initial water content ranging from one to one and half times (ideally one-quarter) the liquid limits (LL) of the given soil and preferably consolidated one dimensionally. The intrinsic properties of the reconstituted soil specimens are inherent to the soil and independent of the natural state, as reported by Burland (1990). The normalized compression curve can be expressed by a unique line can be defined as intrinsic compression line (ICL) in terms of a powerful normalizing index designated as void index I_v when the effective vertical stress is higher than the remoulded yield stress as proposed by Burland (1990). The void index is a measure of the compactness of a reconstituted clay specimen. The void index proposed by Burland (1990), which was used in this study as follows:

$$I_v = \frac{(e-e^*_{100})}{(e^*_{100}-e^*_{1000})} \quad (1)$$

$$= \frac{(e-e^*_{100})}{C^*_c} \quad (2)$$

e^*_{100} and C^*_c can be expressed as follows

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

$$C^*_c = 0.256e_L - 0.04 \quad (4)$$

where, e^*_{100}, e^*_{1000} and e_L are the void ratios of the reconstituted clay specimens that corresponded to effective vertical stress (σ'_v) levels of 100 kPa, 1000 kPa and at the liquid limit, respectively and C^*_c is defined as intrinsic compression index. As the soils used in this study, lying above the A-line on the plasticity chart, I_v can be correlated to the void ratio at the liquid limit by putting the values of Equations (3) and (4) in Equation (2). The void index, I_v can be expressed as follows

$$I_v = \frac{(e-0.109+\ .679-0.089e_L^2+0.016e_L^3)}{(0.256e_L-0.04)} \quad (5)$$

Burland (1990) also proposed the following polynomial equation to define the intrinsic compression line (range of liquid limits is 35 to 128 in percent) as

$$I_v = 2.45 - 1.285 log\sigma'_v + 0.015(log\sigma'_v)^3 \quad (6)$$

However, this equation is valid only for the effective vertical stress (σ'_v) levels of 10 kPa to 4000 kPa.

Hong *et al.* (2010) proposed another empirical relationship to express the normalized compression curves of reconstituted clays at different initial water contents with different liquid limits is defined as extended intrinsic compression line (EICL) ranging from the effective vertical stress of 1.5 kPa to 1600 kPa and it is analogous to ICL when effective vertical stress is greater than 25 kPa. The EICL can be presented as follows

$$I_v = 3.0 - 1.87 log\sigma'_v + 0.179(log\sigma'_v)^2 \quad (7)$$

Yin and Miao (2013) proposed empirical relationships for the determination of intrinsic parameters (e^*_{100} and C^*_c) based on their collected test data, which was conducted on China soil having initial water contents of 1.0 to 1.75 times liquid limits of the soil and the liquid limits varied in the range of 42 to 128 in percent. The relationships are as follows

$$e^*_{100} = 1.13LL + 0.39\frac{W_0}{LL} - 0.084 \quad (8)$$

$$C^*_c = 0.91LL + 0.25\frac{W_0}{LL} - 0.461 \quad (9)$$

Zeng et al. (2015) proposed empirical relationships for the determination of intrinsic parameters (e^*_{100} and C^*_c) based on their experimental data and previously published data as follows

$$e^*_{100} = 0.223 + 0.261e_0 + 0.282e_L - 0.018{e_0}^2 - 0.05{e_L}^2 + 0.015{e_L}^3 \quad (10)$$

$$C^*_c = -0.064 + 0.153e_0 + 0.11e_L - 0.006{e_0}^2 \quad (11)$$

This equation is valid when the void ratio at liquid limits (e_L) is 0.66 to 5.72 at an initial void ratio (e_0) of 1.25 e_L. Horpibulsuk *et al.* (2011) introduced a modified void index (I'_v) to propose a new intrinsic compression line as follows

$$I'_v = \frac{(e - e^*_{50})}{(e^*_{50} - e^*_{1000})} \quad (12)$$

where e^*_{50} is the void ratios of the remolded clay specimens that corresponded to vertical consolidation pressure (σ'_v) levels of 50 kPa. The parameters e^*_{50} and ($e^*_{50}-e^*_{1000}$) were defined as follows (e_L was varied from 1.44 to 3.45)

$$e^*_{50} = 0.125{e_L}^3 - 0.727{e_L}^2 + 2.265e_L - 1.059 \quad (13)$$

$$e^*_{50} - e^*_{1000} = 0.203{e_L}^3 - 1.185{e_L}^2 + 2.864e_L - 1.889 \quad (14)$$

By linear regression analysis, Horpibulsuk et al. (2011) proposed the following equation to present the modified intrinsic compression line, where, σ'_v was varied from 10kPa to 1280kPa.

$$I'_v = 0.029(log\sigma'_v)^3 - 0.112(log\sigma'_v)^2 - 0.733(log\sigma'_v) + 1.427 \quad (15)$$

The relationship between void index and effective vertical stress for the reconstituted clay specimen 1 at different initial water contents is presented in Figure 4. It is evident that the e-log σ'_v plot can be normalized well using the void index concept for different reconstituted clays at different initial water contents at the aforementioned plastic post-yield regime. The data points of the plot are converged at effective vertical stress greater than 100kPa. Based on Figure 5, the experimental data of this study are, to a certain extent, scattered and lie above the ICL and EICL. This advocates that there is no unique relationship to express the intrinsic compression line for all soils and the effects of soil structure are predominant. For this reason, different researchers proposed different relationship to define intrinsic compression line. However, sample preparation procedure effects the reconstituted consolidation behavior of soil, as reported by Cerato and Lutenegger (2004). To achieve complete convergence, the study should be done on very high stresses. And so, authors proposed an empirical relationship by regression analysis which gives a coefficient of correlation (R^2) is 0.99 when normalizing the compression curves of the reconstituted clays. The proposed equation can be expressed as follows

$$I_v = -0.998\ln(log\sigma'_v) + 5.5561 \quad (16)$$

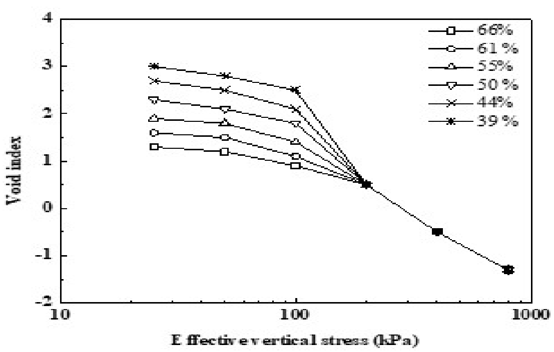

Figure 4: Relationship between void index and effective vertical stress for Sample 1 at different initial water contents.

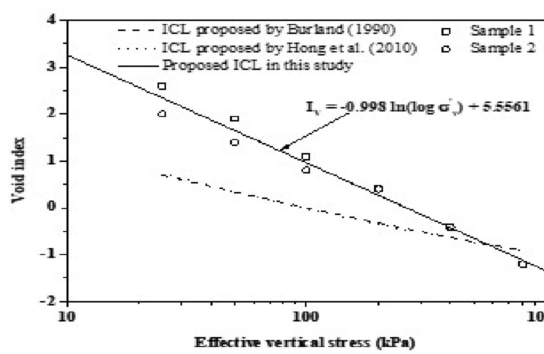

Figure 5: Comparison of normalized compression curves with ICL.

From the aforementioned discussions, it can be summarized that intrinsic parameters (intrinsic void rato, e^*_{100} and intrinsic compression index, C^*_c) are undoubtedly important to determine the void index. However, the equation of I_v (intrinsic compression line) is rarely measured (Hong *et al.,* 2010). Numerous researchers proposed different methods to determine the intrinsic parameters as described earlier when test results are unavailable. A research work by Certo and Lutenegger (2004) reported that the intrinsic void ratios (e^*_{100} and e^*_{1000}) are admittedly influenced by the initial water contents. However, these parameters for higher initial water content are located over the specimens with lower initial water content, as reported by Hong *et al.* (2010) (Figure 2). Figures 6 and 7 illustrate the relationship between the intrinsic compressibility parameters (e^*_{100} and C^*_c) with different initial water content of the investigated clays having different liquid limits. In both cases, the intrinsic compressibility parameters are increased significantly with the increase of initial water contents or liquid limits, which verified the outcomes of Certo and Lutenegger (2004) and Hong *et al.* (2010).

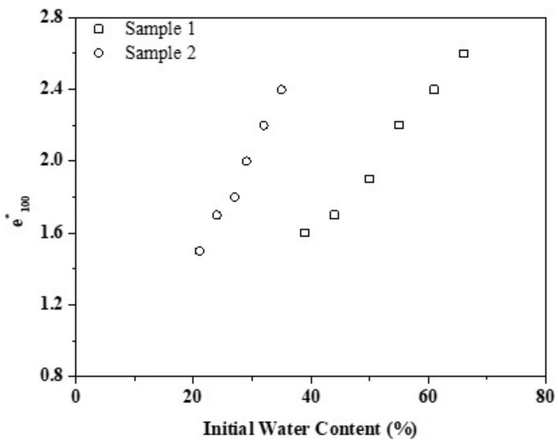

Figure 6: Relationships between e*100 and initial water content of different clays.

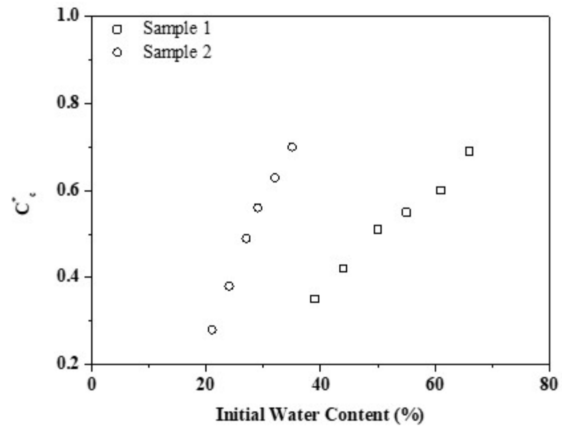

Figure 7: Relationships between C_c* and initial water content of different clays.

The comparison between the computed (by Equations 3 and 4, respectively) and measured values of intrinsic compressibility parameters are presented in Figures 8 and 9. The plots indicate that with the increase of the normalized void ratio, the values obtained from the calculations converge or are lower than the experimental data points. The calculated values are consistent with the measured values at an initial water content of 1.33 × LL. However, Hong *et al.* (2010) suggested that more experimental work has to be performed to obtain better outcomes and to perfectly account for the effects of different parameters on compression characteristics of reconstituted soil.

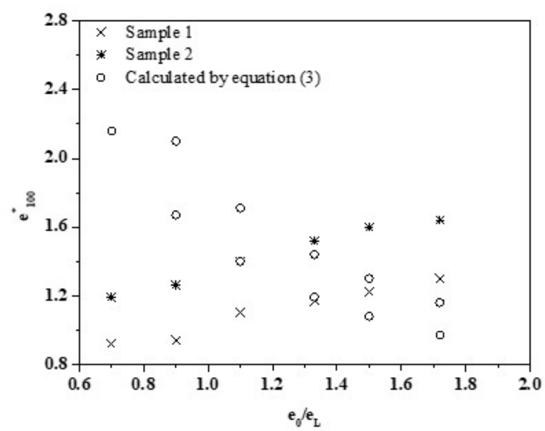

Figure 8: Relationships between e^*_{100} and normalized initial void ratio.

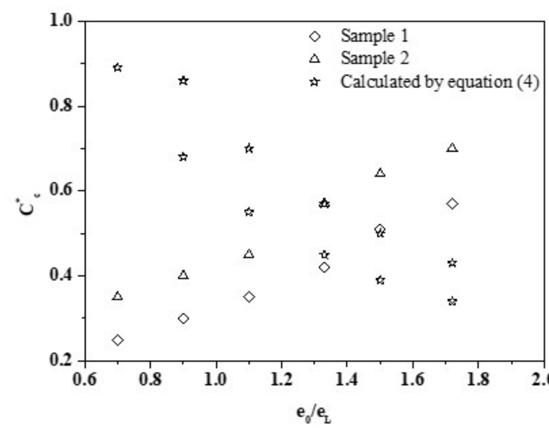

Figure 9: Relationships between C^*_c and normalized initial void ratio.

4. CONCLUSIONS

The compression curves of reconstituted soil samples are reflected in an inverse 'S' shape curve, analogous to the soft natural soil specimens at initial water contents of 0.7 to 1.2 times liquid limits starting from a very low effective vertical stress of 25 kPa. The void ratio decreases considerably with the increase of effective vertical stress, which is predominant in the plastic post-yield regime. The bi-logarithmic plot well represent the semi-logarithmic plot by two straight lines and the intersection point of these straight lines is remoulded yield stress. The concept of void index provides better outcomes at different initial water contents at the plastic post-yield regime. No unique relationship exists to express the intrinsic compression line for all soils. The intrinsic compressibility increases with the increasing of initial water contents or liquid limits and consistent results are observed at an initial water content of 1.33 times the liquid limits.

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