Determining the Intrinsic Compressibility of Fine-Grained Soils

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by
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Abstract

Results of laboratory oedometer tests on reconstituted specimens of four clays prepared at different initial water contents, ranging from the liquid limit to 1.75 times the liquid limit, show that Burland's (1990) intrinsic compression line (ICL) may not be "unique" for a given soil. This suggests that the "intrinsic" parameter, I_v, chosen by Burland (1990), which is based on the constants of intrinsic compressibility, e^*_{100}, (void ratio corresponding to $\sigma'_v = 100$ kPa), and C^*_c, (e^*_{100} - e^*_{1000}), may in fact not be a truly intrinsic parameter of the soil, but is dependent on sample preparation. The positioning of the normalized compression curve in e-log-σ'_v space is significantly influenced by the initial remolding water content, therefore resulting in differing values of e^*_{100} for a given soil depending on the initial water content. The influence of initial water content was greater for kaolinitic and illitic clay than for montmorillonitic clay. It is hypothesized that the difference in behavior may be attributed to differences in mineralogy. The results illustrate that caution should be used when comparing tests results from wide spread sources and suggest that a standard level of initial water content be used to evaluate the intrinsic compressibility.

Keywords: clays, compression index, soil compressibility, consolidation, remolded, kaolin, montmorillonite, mineralogy, oedometers

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Background – Intrinsic Compressibility

The compressibility and strength of remolded clays can be used as a frame of reference for the behavior of a natural, undisturbed sample. Burland (1990) introduced the concept of "Intrinsic Properties" to describe the strength and compressibility characteristics of twenty-six reconstituted clays using data compiled from the literature. He also defined the Intrinsic Compression Line (ICL) as the one-dimensional consolidation slope (in e-log-σ'_v space) of a clay sample that has been reconstituted from an initial water content equal to about 1.0 to 1.5 times the liquid limit. By reconstituting the sample at a high initial water content, the soil ideally looses all "memory" related to soil structure. This concept is well founded and has important implications for interpreting geologic effects on engineering behavior of fine-grained soils.

The properties of these reconstituted clays were termed "intrinsic" since they were thought to be inherent to the soil and independent of the natural state and should not be influenced by soil structure (fabric and bonding). This means that if one soil sample was remolded to a specific state and tested a number of times, (using a reconstituted sample at the same initial water content each time), the compressibility line should be identical in every test for that specific soil. Burland (1990) showed a reasonably unique ICL was achieved when the data were normalized using fixed values of e^*_{100} and e^*_{1000}. This normalizing parameter is defined as the void index, I_v, where

$$I_v = \frac{e - e^*_{100}}{e^*_{100} - e^*_{1000}} = \frac{e - e^*_{100}}{C^*_c} \qquad [1]$$

The "Intrinsic Compression Index," denoted as C^*_c is obtained numerically from a consolidation test on a reconstituted sample as:

$$C^*_c = e^*_{100} - e^*_{1000} \qquad [2]$$

where e^*_{100} and e^*_{1000} are void ratios corresponding to stresses of 100 and 1000 kPa, respectively, on the consolidation curve.

Figure 1 presents the intrinsic compressibility of 35 natural soils and 18 pure clays tested in the current study compared with the "unique" ICL presented by Burland (1990). A complete description of the soils can be found in Cerato (2001). All of these samples were mixed to a reconstituted state of 1.25 LL, to be consistent with the suggestion presented by Burland (1990). It should be noted that the majority of test results given by Burland were collected from the literature and it is likely that not all of the results represent remolding to an initial water content of 1.25 LL.

Burland's (1990) ICL is included on Figure 1 as a point of reference for the other soils tested in this study. Burland noted that "the available experimental evidence suggests that the ICL is insensitive to the test conditions," and presented the results of oedometer tests on three clays covering a wide range of liquid limits and pressures to support this statement. Contrary to Burland's (1990) results, the compression curves for each soil tested in the current study, as can be seen in Figure 1, diverge at pressures less than 100 kPa, converge at approximately 100kPa and diverge again above 100kPa. This suggests that there is not a unique intrinsic compression line for all soils and that mixing each soil to a water content of 1.25LL in itself may not define the intrinsic compression line.

Burland (1990) showed convincingly that the slope of the ICL, C^*_c, is strongly related to the value of e_L, the void ratio at the liquid limit, which has the numerical equivalent of:

$$e_L = G * LL \qquad [3]$$

where:
G = Specific Gravity (unit weight of solids)
LL = Liquid Limit

The void ratio at a water content equal to the liquid limit (e_L) is a constant for a remolded soil sample, depending only on the Liquid Limit and the Specific Gravity. However, Burland (1990) noted that the correlations between e_L and e^*_{100} and C^*_c should only be used for soils with Liquid Limits between 25 to 160 % and for soils with Atterberg Limits lying above the A-Line.

Prior to the work of Burland, Nagaraj and Murthy (1983) attempted to explain the fundamental basis for the compressibility of remolded clays using six remolded natural soil samples, with Liquid Limit values varying from 36 to 158 %. It was thought that the compression behavior of a normally consolidated, saturated, uncemented soil could be predicted using "easily measurable macroparameters such as liquid limit water contents and in situ void ratios," instead of trying to use microparameters, specific surfaces and half-space distances between clay platelets. They found that a plot of the void ratio normalized by the void ratio at the liquid limit, e_L, gave a "unique" relationship with log σ'_v, and the results of the six remolded clays compressed into a relatively narrow band. From the original six clays used in their study, a generalized e-log σ'_v relationship was calculated. However, subsequent tests by these investigators actually showed three different e-log σ'_v relationships (e.g. Nagaraj and Murthy 1986; Nagaraj et al. 1993; Nagaraj et al. 1995).

Burland (1990) used a similar relationship of initial water content to the liquid limit (w_i/LL) and presented results of three clays in which each clay was reconstituted at various initial water contents and showed that at pressures "less than about 100 kPa the compression curves for each soil diverged but for σ'_v greater than 100 kPa, the differences were less."

Therefore, he concluded that provided the soil is reconstituted at a water content of between LL and 1.5 LL, the ICL is "well defined for pressures equal to or greater than 100 kPa."

Figure 2 summarizes both Nagaraj and Murthy's (1983 etc.) and Burland's (1990) findings along with results of the current study which show the void ratio normalized by the void ratio at the liquid limit. The large scatter in the results of the 32 natural clays and the 18 pure clays as compared with results shown by others in the literature suggests that there may not be a "unique" relationship with log σ'_v as suggested by Nagaraj and Murthy (1983), and that the compression curves do not converge at stresses greater than 100kPa, as Burland's (1990) results show. It might be reasonable to expect that some variability in these results may be attributed to the variability in the determination of the Liquid Limit by the Casagrande cup. The variability may be between 2 to 5% of the actual value, which would create a band, not a line, of statistically normalizable compression curves. It seems that the consolidation behavior of normally consolidated, saturated, uncemented soils depends not only on sample preparation, but possibly on the geologic depositional environment.

As mentioned above, Burland (1990) recommended that a soil should be remolded using an initial water content in the range of 1 to 1.5 times the liquid limit, (i.e. liquidity index 1 to 1.5) but recommended that 1.25 times the LL of the soil be used. However, based on other tests performed by the authors, soils prepared using this value (1.25 X LL) of initial water content produced significant scatter in the resulting test data as shown in Figure 2. This suggested that the initial water content of a remolded sample may be important in evaluating the intrinsic compressibility. In fact, others (e.g. Mesri and Ali 1999; Tremblay et al. 2001) have suggested remolding to an initial water content as high as two times the liquid limit.

It is thought that the normalized parameter e/e_L in log σ'_v space for compression tests, as first presented by Nagaraj and Murthy (1983), and later by Burland (1990), shows the affects of sample preparation and test conditions. The parameters are also relatively easy to measure. Presenting the results of the compression tests in this manner shows that the initial water content of the sample affects the position of the e/e_L curve in log σ'_v space, and therefore also affects Burland's (1990) e^*_{100} "intrinsic" parameter. The void ratio of a remolded sample at individual incremental loading should vary due to the water content that the sample is mixed; the higher the initial water content, the higher the initial void ratio. If the void ratio is normalized by the void ratio at the liquid limit and plotted in e – log σ'_v space, the positioning of the line should change (Figure 3).

A soil mixed to an initial water content of 1.25 times the LL gives a ratio of e/e_L equal to 1.25; if mixed to 1.5 times the LL, the ratio of e/e_L would equal 1.50. Burland (1990) noted that the slope of the ICL, i.e., C^*_c, is only dependent on e_L. However, if the initial water content affects the positioning of the e/e_L – log σ'_v curve, then e^*_{100}, as defined by Burland (1990) may differ significantly, depending on the initial water content. It will be shown in this paper that Burland's (1990) "intrinsic" compression line (ICL) of fine-grained soils may be significantly influenced by the initial remolding water content and may not actually be an intrinsic soil property.

Experimental Program

To investigate this further, four of the soils tested were prepared at four varying water contents to determine to what degree the initial water content might influence the position of the e/e_L line in log σ'_v space. Two natural soils and two pure clays were tested; Boston Blue Clay from near Boston, Massachusetts, Atchafalaya clay from Louisiana, and Kaolinite and Attapulgite from the Source Clays Repository located at Purdue University. Boston Blue Clay is a low plasticity, illitic marine deposit from eastern Massachusetts and the Atchafalaya sample is a high plasticity Montmorillonitic clay from the Atchafalaya River Basin in Louisiana. The

Kaolinite used was mined from Washington County, Georgia and the Attapulgite (Palygorskite) was mined in Gadsden County, Florida. These four clays were chosen because of their widely different soil properties. Table 1 presents a summary of the index properties of these four soils. As can be seen, in addition to the large difference in plasticity, the cation exchange capacity and the specific surface areas of these four clays is very different.

One-dimensional consolidation tests were performed in general accordance with the procedure described in ASTM D 2435 Standard Test Method for *One-Dimensional Consolidation Properties of Soils* (ASTM 1998). Tests were conducted using rear-loading oedometers equipped with linear variable differential transformers (LVDT) connected to a data acquisition system. An oedometer ring with a diameter of 6.35 cm and height of 1.91 cm, was used for all tests.

The samples were prepared in a remolded state by mixing each specimen with distilled water, allowing the soil to temper overnight, and taking two water content samples in order to achieve the desired initial water content. For each of the 52 tests conducted in this study, distilled water was used to create a uniform testing process and it was assumed that a full exchange of fluid was achieved for simplicity.

Tests were conducted at initial water contents of 1 X LL; 1.25 X LL; 1.5 X LL; and 1.75 X LL. A seating stress of 2.2 kPa was applied to the specimen in order to assure proper cell alignment. A load increment ratio (LIR) of 0.5 was followed throughout the test until a target stress (σ'_v) of 1140 kPa was reached. An LIR of 0.5 was chosen because the substantial compression of the samples at high water contents made it necessary to increase the weight in smaller increments than would be possible with a LIR of 1. Each load was left on for approximately twenty-four (24) hours. The void ratio at the end of primary consolidation (EOP) was used. At the end of each test, the sample was removed from the ring and dried in the oven overnight to obtain a final water content and void ratio. The value of C^*_c was determined from the slope of the compression curve between the stresses of 100 and 1000 kPa. Incremental loading oedometer tests were chosen to be consistent with the test results presented by Burland (1990) that had been compiled from other literature sources and to be more realistic in terms of the equipment that practicing geotechnical engineers have available.

Results and Discussions

Figure 4a and 4b presents the results of the initial water content study for the four clays over a wide range of stresses. The results are split into two figures because of the large range in void ratios between the four soils. The slope of these lines equals the intrinsic compressibility index, C^*_c, which, as expected, is much different for three of the four soils. Figures 4a and 4b show that all of the soils will converge at high pressures, which is a well known phenomenon. However, within the range of applicable stresses found in geotechnical engineering, the slopes of the four soils are clearly different. The BBC and Kaolinite results are very similar because of a more closely related mineralogic composition. It can be seen that at any given effective stress there is a greater spread in void ratio for the BBC and Kaolinite samples than for the Atchafalaya and Attapulgite samples.

Figure 5 presents the e/e_L curves for all tests and shows that the initial water content of a specimen is important and significantly affects the position of the e/e_L line with respect to effective stress. The relative position of the e/e_L lines shown in Figure 5 follow the hypothesized trend shown in Figure 3; i.e., as the initial water content increases, the position of the compression curve shifts upward in order of increasing water content. From these data it can be seen that the value of e^*_{100} is directly affected by the initial water content and increases as the initial water content increases.

It can be seen that the initial water content influences the behavior of the BBC and the Kaolinite samples much more than it influences the behavior of the Atchafalaya and Attapulgite samples. It is believed that the primary difference in compressibility between the four soils is due to the difference in mineralogy. As shown in Figure 5, the Boston Blue Clay and Kaolinite samples present a much larger increase in e/e_L positioning with increase in water content than do the Atchafalaya and Attapulgite samples. This difference may be related to the mineralogy, i.e., the BBC sample is predominantly illitic while the Atchafalaya sample is montmorillonitic, which are noted by the difference in Activity. In a remolded state, illite and kaolinite generally exist in a flocculated structure and montmorillonite exists in a dispersed state. At the Liquid Limit the double layer is probably fully developed in the Atchafalaya sample and the Attapulgite clay, therefore any additional water is squeezed out easily during loading. The high cation exchange capacity also affects this compressibility because the net negative charge of each particle is large and therefore the diffuse double layer cannot take on any more water. Therefore, the pore water chemistry is not altered, and the samples compress to similar void ratios at the same stresses. The dispersed state of the particles allows the soil to compress almost as easily when prepared at 1.75 times the LL as compared to the sample prepared at 1.25 times the LL thereby giving a similar void ratio at any stress.

At the LL, the BBC sample and the Kaolinite clay may not have a fully developed double layer. The flocculated particles can take on additional water, changing the pore water chemistry and creating different states of compression depending on the initial water content of the sample. The more pore space that is introduced with the addition of water, the more pronounced the particle flocculation becomes. A larger stress would be needed to compress the sample to the same void ratio as a sample with a lower initial water content.

As mentioned briefly above, the Cation Exchange Capacity and the Specific Surface Area of the samples may help explain why the BBC and Kaolinite results are more affected by the initial water content increases than the Atchafalaya and Attapulgite samples. The samples have very different Cation Exchange Capacities (Kaolinite = 2.0 meq/100g, BBC = 7.7 meq/100g, Atchafalaya = 35.9 meq/100g and Attapulgite = 19.5 meq/100g) and Surface Areas (Kaolinite = 15 m^2/g, BBC = 43 m^2/g, Atchafalaya = 227 m^2/g and Attapulgite = 341 m^2/g).

Conclusions

Clay mineralogy and subsequently, the corresponding soil properties (i.e., LL, Activity, CEC and SSA), may influence the degree to which the initial water content affects the compression curve of a remolded soil and intrinsic compressibility. Montmorillonitic clay appears to be less affected than Kaolinitic and Illitic Clays.

Based on the intrinsic compressibility test results obtained in this study, it appears that the value of e^*_{100} of a soil is dependent on the initial water content of a reconstituted soil sample. Results from this study and from the literature suggest that for a given clay the initial water content affects the position of the e/e_L curve. The intrinsic parameter, I_v, suggested by Burland (1990) may not be a true intrinsic soil property since the reconstituted consolidation behavior is dependent on sample preparation as shown in the current study.

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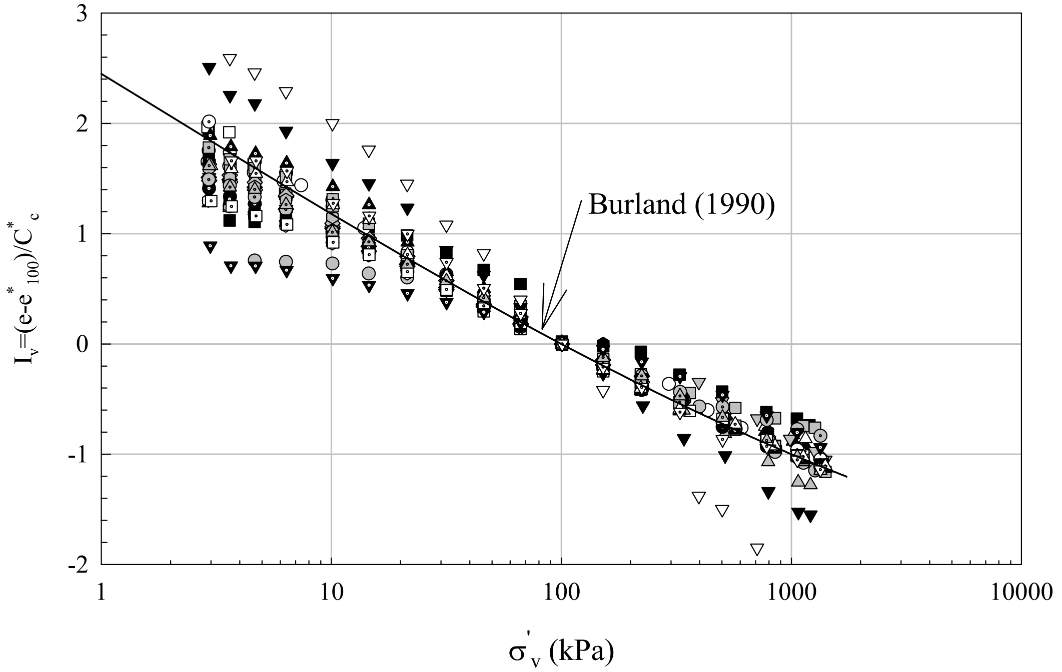
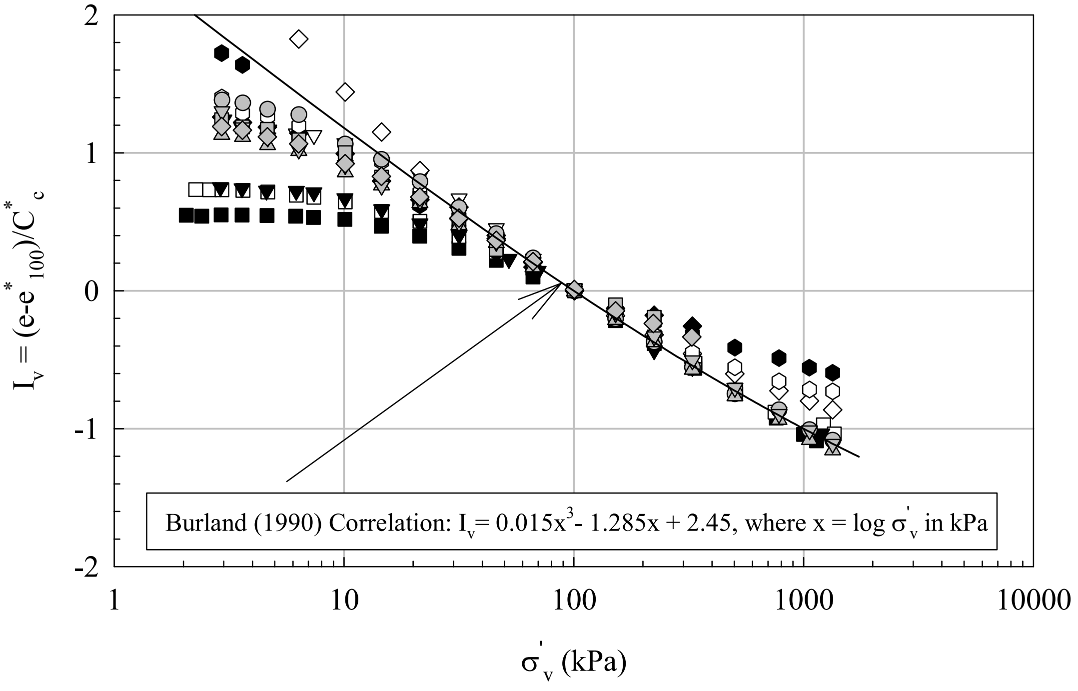
Table 1. Properties of Soils Used in Experimental Study.

Soil Description	Total SSA (m^2/g)	Carbonate Content (%)	Clay Fraction (%)	CEC (meq/ 100 g)	G	C^*_c (w_i = 1.25LL)	e^*_{100} (w_i = 1.25LL)	LL (%)	PL (%)	PI (%)	SL (%)	Activity PI/CF
Kaolinite	15	-	36.2	2.0	2.68	0.32	1.25	42	26	16	26	0.44
BBC	43	2.0	48.4	7.7	2.80	0.28	0.94	45	23	22	18	0.45
Atchafalaya	227	9.2	66.6	35.9	2.80	0.87	2.00	101	35	66	12	0.99
Attapulgite	341	-	67.3	19.5	2.83	1.60	3.82	202	108	94	51	1.40



A: Natural Clays Normalized with the Void Index, (I_v).



B: Pure Clays Normalized with the Void Index, (I_v).

Figure 1: Natural and Pure Clays Normalized with Burland's Void Index Parameter, I_v.

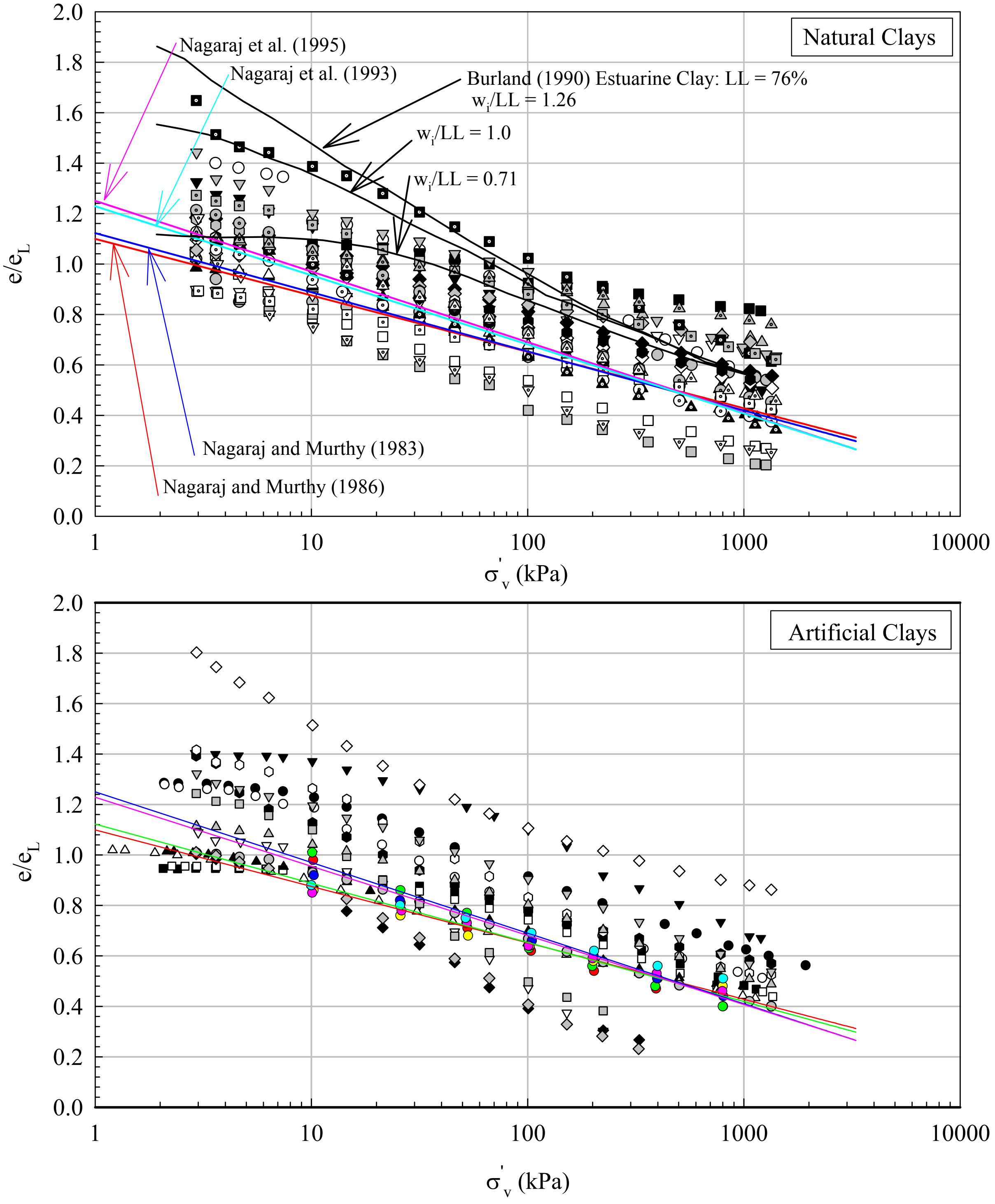


Figure 2. Test results showing significant scatter using the normalization parameter, e_L.

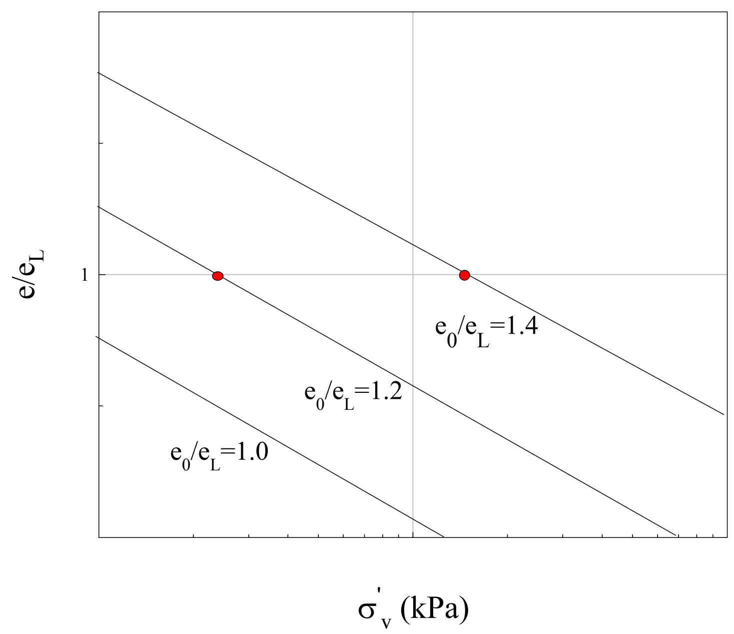


Figure 3. Hypothetical e/e_L plot for the same soil at different initial water contents.

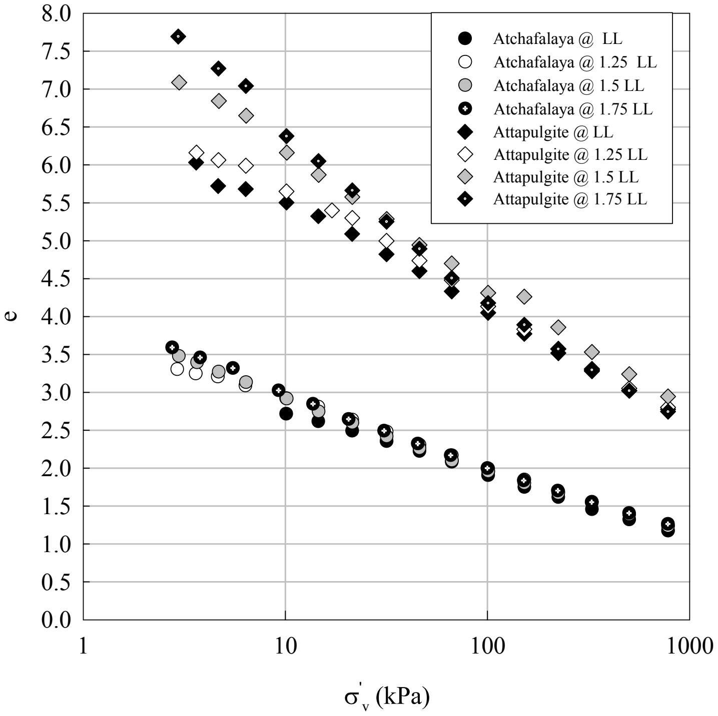


Figure 4a. Experimental e – σ'_v Curves.

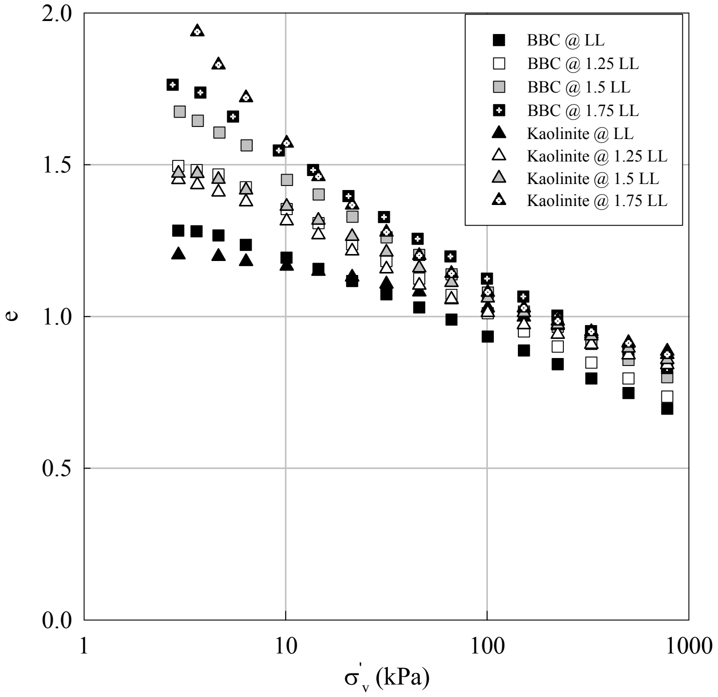


Figure 4b. Experimental e – σ'_v Curves.

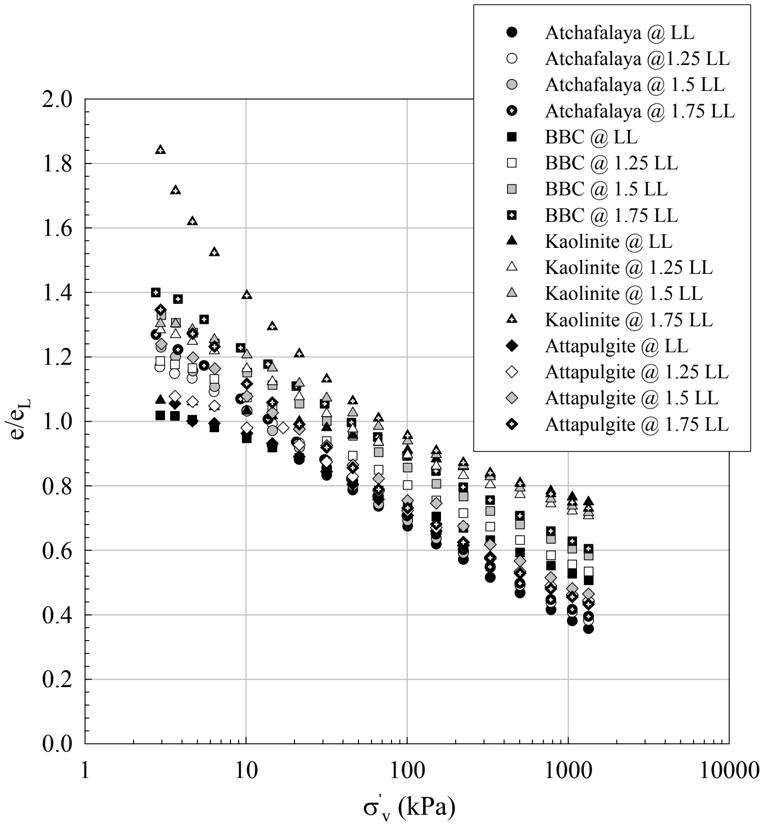


Figure 5. e/e_L- σ'_v Relationship.