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The BCD: A New Instrument for Compaction Control

Final Report for Highway IDEA Project 118

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EXECUTIVE SUMMARY

The BCD (Briaud Compaction Device) is a tool that can be used to control compaction quality for pavement subgrade, pavement bases, pavement sub-bases, embankments, retaining wall backfill, and any other earth work requiring compaction. The BCD is a very rapid tester of the soil modulus near the ground surface. It has a 150 mm diameter flexible plate at the bottom end of a rod. The operator leans on the handle at the top end of the rod, the plate bends, the bending strains are instantaneously measured by strain gages on the bottom plate. If the soil is hard, the plate does not bend very much, if the soil is soft, the plate bends more. It is shown that the strain measurements are directly related to the modulus of the soil underneath it.

In this report the design improvements of the previous prototype BCD are described. The finished product is BCD-4; it is built by Roctest who also sells the BCD under a licensing agreement with Texas A&M University. Numerical simulations were performed to evaluate the depth of influence of the BCD in the field and in the lab. It is shown that for materials with a modulus between 5 and 100 MPa the depth of influence is at least 150 mm. It is also shown that, fortuitously, the same equation can be used in the lab and in the field to obtain the BCD modulus from the strain gage readings. However, to use the BCD in the field it is recommended to use a wet sand cushion in order to reduce the BCD seating effects. The repeatability and linearity of the BCD was demonstrated by using calibrated rubber blocks in the lab. The BCD modulus was shown to give a good correlation with the plate reload modulus in the field. A series of compaction tests in the lab were carried out to compare the variation of the BCD modulus with the water content and with the dry density. A comparison was also carried out between the BCD modulus and the resilient modulus and showed excellent correlation for a given soil.

A typical sequence for compaction control with the BCD is as follows. After selecting the fill material, the compaction modulus criterion to be achieved in the field is established through lab tests. Modified Proctor or Standard Proctor tests are performed and the optimum moisture content as well as the maximum dry density are determined from the compaction curves. At the same time and for each Proctor test, BCD tests are performed on top of the Proctor mold sample to obtain the BCD modulus. The result of these Proctor tests is a BCD modulus vs. water content curve as well as a dry density vs. water content curve. The modulus curve is used to define the maximum BCD modulus and the corresponding optimum moisture content. Then the target BCD modulus and the target water content are selected and written in the specifications; they must be achieved in the field. The suggested target modulus value is 75% of the maximum modulus value. On the job site, the target value of the BCD modulus is verified by BCD tests and the water content is verified independently through field testing (e.g.: the new suitcase field oven). Note that it is critical to use the same tool to obtain the modulus in the lab and in the field as the modulus depends on many factors.

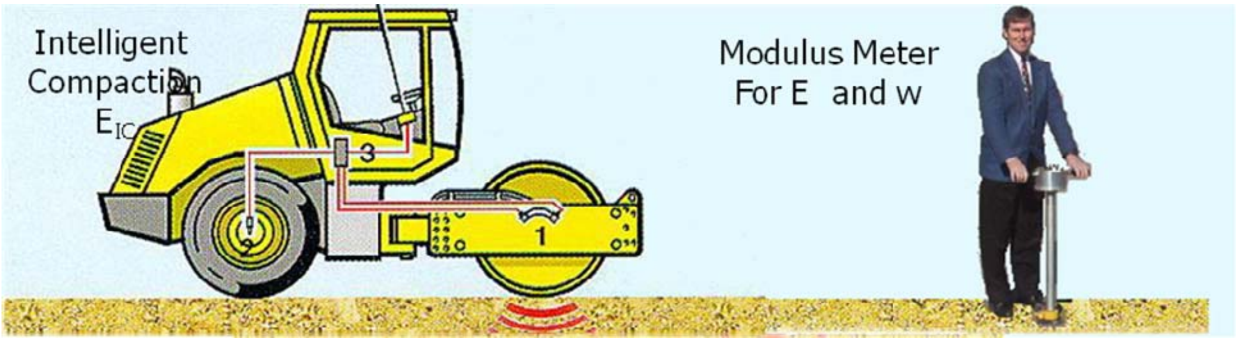


Fig. S.1 Proposed compaction control practice

CHAPTER 1- BACKGROUND

1.1. Compaction process

One of the first steps in the compaction process is to select the fill material. Then, the compaction criterion to be achieved in the field is established through lab tests and written in the specifications. In the field, the criterion is verified through field testing. Dry density and water content have been used almost exclusively for compaction control. This practice was adopted many years ago and dry density standard methods have been developed in the lab (Standard Proctor Test, ASTM D698 and Modified Proctor Test, ASTM D1557) and in the field (Sand Cone Method, ASTM D-1556, Rubber Balloon Method, ASTM D-2167, and Nuclear Density Meter Method, ASTM D-2922).

There is a trend towards the use of a soil modulus as an alternative parameter to the dry density for compaction control. This trend is based on two motivating factors:

1. avoiding nuclear devices, such as the nuclear density gage, and;
2. using a parameter more directly related to limiting deformations, which is the design criterion.

As a result, several tools have been developed to measure a modulus in the field. They are the GeoGauge (Briaud, et. al. 2004, ASTM D6758), the Seismic Pavement Analyzer or SPA (Nazarian, et. al. 1993), the Dynamic Cone Penetrometer or DCP (ASTM D6951), the Clegg Impact Soil Tester or CIST (ASTM D5874-02), the Falling Weight Deflectometer or FWD (ASTM D4694-96) and its portable version the PFWD (Livneh, et. al. 1997).

The Briaud Compaction Device or BCD is a new instrument to measure a soil modulus in the field and in the lab. It has two main advantages compared to the above devices. It is a much faster test (approximately 5 seconds) than even the fastest of the above listed tests and it can be used both in the lab to obtain the target modulus and in the field to verify that the target modulus has been achieved. This is critical as it is important to establish a modulus compaction curve in the lab first, much like the dry density compaction curve, establish a target modulus value from that curve, include a modulus value in the specifications, and verify that the target modulus value has been achieved in the field. Considering how many factors can influence a modulus (Briaud, 2001), it is much preferable to measure the modulus in the lab and in the field with the same instrument.

1.2. Dry density or modulus?

Should one use the dry density or the modulus as a basic parameter to control and accept compaction work? Due to high suction at low water contents, it is possible to have a high modulus without having particles which are close together (high dry density). This apparent stiffness is destroyed as soon as the soil gets wet again. In this case, controlling compaction on the basis of dry density appears to be preferable. On the other hand, uniform sand with well rounded particles may reach its maximum dry density but still have a relatively low modulus. In this case, compaction control on the basis of a target modulus seems preferable.

The dry density gives the compactness of the soil because it is directly related to how many particles are within a given volume; a modulus gives the stiffness of the soil under specific conditions. The two parameters are not directly related in a clear fashion (e.g.: Rhee, 2004). The influence of the water content on the dry density is well known. The amount of information on the influence of the water content on the modulus is much more limited (Turnbull, McRae, 1950, Turnbull, Foster, 1956, Seed, Chan, 1959, Lenke et al., 2003). Considering the three parameters - dry density, modulus, and water content - it appears that one must have two of the three parameters to determine whether a soil is well compacted or not.

1.3. Soil modulus

The modulus of a soil depends on many factors (Briaud, 1992, 2001) and needs to be precisely defined when quoted. Referring to Fig. 1.1, the secant modulus E_s corresponds to the slope from O to A. One would use E_s for predicting the movement of a spread footing under the first load application. The tangent modulus E_t is obtained from the tangent to the point considered on the stress strain curve. One would use E_t to calculate the incremental movement due to one more story in a high-rise building. The unloading modulus E_u corresponds to the slope from A and B on Fig. 1.1. One would use E_u when calculating the rebound of a pavement after the loading by a truck tire (resilient modulus). The reload modulus E_r corresponds to the slope from B to D on Fig. 1.1. One would use E_r to calculate the movement of the pavement under reloading by the same truck tire. The cyclic modulus E_c corresponds to the slope from B to C on Fig. 1.1. One would use E_c and its evolution as a function of the number of cycles for the movement of a foundation subjected to repeated wave loading.

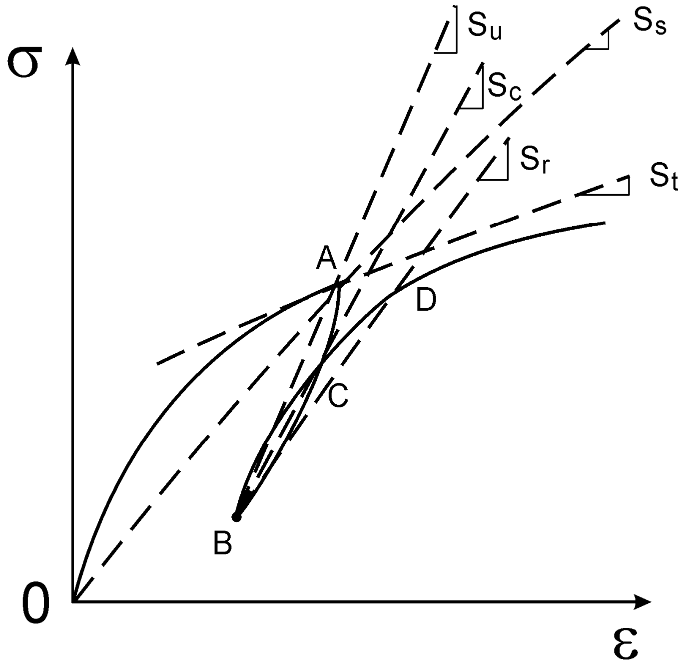


Fig. 1.1 – Various Modulus Definitions

A soil modulus is influenced by soil state factors and by loading factors. Among the soil state factors are the porosity or dry density, the soil structure, the water content, the stress history, and the cementation. Among the loading factors are the stress level, the strain level, the rate of loading, and the number of cycles. As a result of all these influencing factors, soil moduli vary significantly (1 MPa to 1000 MPa). Other approximate values of moduli are given for comparison purposes: steel 200,000 MPa; concrete 20,000 MPa; wood and plastic ~ 13,000 MPa, and; rock 2,000 MPa to 30,000 MPa.

The modulus obtained with the BCD corresponds to a reload modulus, at a mean stress level averaging about 50 kPa within the zone of influence, a strain level averaging 10^{-3} within the zone of influence, and a time of loading averaging about 2 seconds. The modulus measured by the BCD on the surface of soil deposits used for roadway base, retaining wall backfills, embankment fills seems to fall in the range of 3 MPa to 300 MPa and mostly between 5 MPa and 100 MPa..

What percentage of the maximum soil modulus E_{max}, should be included in the specifications and accepted in the field. Using 95% of E_{max} seems too high as the modulus varies more than the dry density. If one accepts that a settlement precision of the order of +/-33% is reasonably achievable and if one further assumes that the modulus is directly related to the settlement, then a value of 75% (1/1.33) may be a reasonable target. However establishing such a target will require much more thought and discussion, probably through the work of a national committee.

CHAPTER 2 - THE IDEA OF THE BCD

The idea of the BCD, shown in Figure 2.1 as a conceptual diagram, is to load a plate in contact with the ground surface, measure the bending strain of the plate (Figure 2.2) and relate that strain to the modulus of the soil below the plate. If the soil is hard, the plate does not bend very much (low bending strains), if the soil is soft the plate bends more (high bending strains). The relationship between the strains in the plate and the modulus of the soil below has been established by numerical simulation. If the soil is very soft the plate does not bend much and simply punches through the very soft soil. Therefore there is a range of soil moduli over which the BCD can be used. Based on numerical simulations, this range can be estimated to be 5 MPa to 150 MPa.

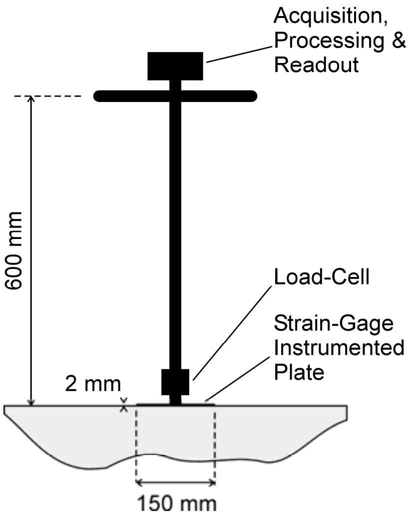


Fig. 2.1 - Conceptual Sketch of a BCD

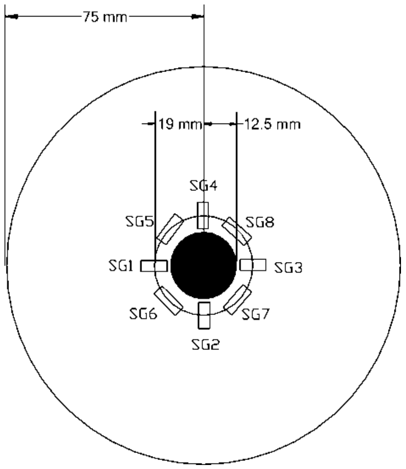


Fig. 2.2 - Plan View of BCD Plate with Strain Gages

The potential of the BCD is in the field of soil compaction. This includes compaction of soil layers for highway and airport pavements, compaction of soil layers for embankments, compaction of backfills for retaining walls. At present, it is difficult to test large areas of compacted soils because the tests are quite time consuming. As a result, un-compacted or poorly compacted areas can go unnoticed during construction and become a problem after the pavement is finished and open to traffic. The cost of maintenance then becomes very significant.

Replacing the density approach by the modulus approach requires a reliable modulus measurement device like the BCD. The BCD, through its speed of testing, through its completeness of approach (lab test, target value, field verification), through its simplicity of operation, can have a significant impact on the ability of the engineer to control the quality of the finished pavement, embankment, and retaining wall backfill.

This study advances the knowledge on the BCD as follows:

1. A new BCD model 4 was developed with significant improvements over previous models as described in sections 3.1 to 3.4.
2. A new series of calibration tests were performed by comparing the BCD modulus with plate tests modulus. A very good correlation was found.
3. A series of comparison tests were performed to compare the BCD modulus with the resilient modulus. An excellent correlation was found for a given soil.
4. A series of comparison test were performed to compare the modulus "compaction curve" with the Proctor compaction curve. They show that the BCD modulus is much more sensitive to the water content than the dry density and therefore a much better parameter to check a compaction job.
5. Recommendations were developed to use a sand cushion solution and alleviate the variations induced by uneven surfaces.

CHAPTER 3 - BCD DESIGN

3.1 First Version: BCD-1

BCD-1 was the first version of the BCD built. It was built at Texas A&M University in 2003 and consisted of a simple plate at the end of a rod. The plate was strain-gauged and the readings were taken by using a separate strain gage indicator (Figure 3.1)

Fig. 3.1 - The first version of the BCD - BCD-1

Because BCD-1 depended on a conventional electric power source and consisted of several independent modules, it was difficult to use it in the field. But the conceptual idea of the BCD was verified and developed into BCD-2 with many design considerations.

3.2 Second version: BCD-2

BCD-2 was the second version of the BCD. It was built at Texas A&M University in 2004 and consisted of a completely independent and self sufficient unit (Figure 3.2(a)) including the read-out device (Figure 3.2(b)). The readings were recorded by hand and the modulus calculated by hand for each test. The BCD-2 was tested in the field and in the lab with many different soil types. During the BCD-2 tests several BCD design changes were discussed and implemented in BCD-3.


(a) BCD-2 **(b) BCD-2 Read-out Unit**

Fig 3.2 - The second version of the BCD - BCD-2

3.3 Third version: BCD-3

At this point in the evolution of the BCD, Roctest was chosen as the manufacturer of the BCD. Therefore the BCD-3 was built by Roctest in 2006 after signing a license agreement with Texas A&M University. Roctest evaluated the BCD internally over a period of 8 months and worked on many aspects developed from the observation made on BCD-2.

BCD-3 reads the modulus directly and automatically. It records the data internally; this data can be dumped on a computer at the end of a day. A swivel was introduced between the bottom of the rod and the plate to prevent the user from introducing any parasite moment. A guard plate was also built to prevent excessive bending of the plate. Furthermore, BCD-3 included general commercial esthetic improvement (Figure 3.3).

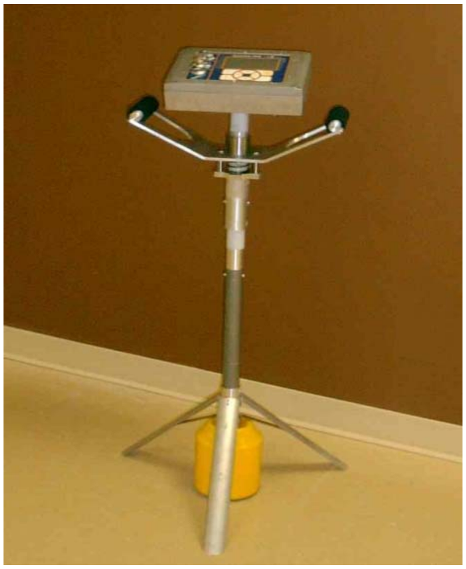


Fig. 3.3 - Third version of the BCD - BCD-3

3.4 Fourth version: BCD-4.

BCD-4 was built by Roctest in 2007 and incorporated another set of improvements including a lower height for ease of use, a simplification of the stand mechanism, a better steel plate, a more appropriate location of the swivel, a new bell rather than a guard plate to protect against excessive bending, and a decrease in the overall weight of the instrument. BCD-4 has the same recording unit as BCD-3. BCD-4 is shown in Figure 3.4. This unit is much simpler than any of the previous units including BCD-3 shown in Figure 3.3. The improvements are described in more details in the following section.

Fig 3.4 - Fourth version: BCD-4

3.4.1 Modification of BCD-4 Design.

After testing the BCD-3, the following issues were identified.

- Problem of permanent deformation of the plate over time and easily damaged plate by accidental impact.
- Narrow reading range on stiff material.
- Different range of values for the BCD modulus compared to the modulus from other modulus measuring devices.
- Difficulty to guarantee good repeatability between different BCD units.
- Inconsistent modulus reading on rough soil surfaces in the field.

As a result, the following measures were taken.

- First, the design of the BCD plate was improved to reduce the permanent bending and extend the measuring range for stiff soils. The plate was allowed to “float” by using a universal joint. This allowed the plate to move freely around the joint instead of being fixed rigidly to the rod. Hard steel pins were also added to prevent the plate from rotating during long term testing and disconnecting the wires of the strain gages. Efforts were made to redesign all electrical and mechanical connections in such a way that the plate could be disconnected and replaced with more ease. This solution was not achieved but remains an issue to be solved. Such an option would make it easier on the user who would not have to send the BCD back to Roctest every time the plate gets damaged.
- Second, the strain gages were protected against tough field conditions.
- Third, the rubber bell which protects the top of the plate and the instrumentation was modified. the plate was reduced from 31.75mm to 25.4mm. This change helped extend the measuring range of the BCD reading to higher modulus (Figure 3.5(a)).
- Fourth, water and dust proof silicon coating was applied on the top of the BCD plate (Figure 3.5(b)).

(a) Modified plate connection **(b) New rubber bell on top of plate**

Fig. 3.5 - Changing the plate design and connection

3.4.2 Improving the BCD modulus repeatability and BCD calibration.

The modulus displayed on the BCD read out unit has been changed. Previous versions of the BCD were displaying the modulus as p/7ε (p= 12.6 kPa, average pressure on the plate for a downward load of 223 N, and ε the average hoop strain in microstrains measured by the four strain gages at their location in the plate). Now the BCD modulus is the modulus obtained from an equation derived by calibrating the BCD against rubber blocks of known modulus. The modulus of the rubber blocks are determined by performing unconfined compression tests on the rubber blocks (Figure 3.6). Each BCD plate does not have the exact same mechanical properties. This is due to the fact that the BCD modulus is very sensitive to the location of the stain gages and other factors occurring during the manufacturing process. Therefore each BCD plate should be calibrated against the standard rubber blocks and calibration factors specific to that BCD must be developed before assembly. There may still be some variations in the strain readings from one unit to another but the variation is now within tolerable limits and the modulus readings shall be more repeatable. With this procedure, the range of the BCD modulus has been established. The BCD-4 unit has a range of 5 to 150 MPa. With this new calibration procedure, the range of the BCD and the accuracy of each unit over that range can be established.

Also the software in the BCD display unit was change to specify the new calibration factors. The modifications included: 1) enabling a polynomial relationship between p/ε and the reference rubber blocks to be uploaded, and 2) warning the user when the reading is over or under the ideal specified range.

The calibrations consisted of performing two sets of tests: unconfined compression tests on rubber blocks and BCD tests on the same rubber blocks. Four different rubber blocks made of polyurethane and having hardness varying from 40A to 95A Duro were used. A PVC block was added to complete the very high modulus range. By combining two rubber blocks of different Duro, it was possible to create intermediate values of the modulus. For example, the combination 60/85 in Table 1 means that the upper pad was rated 60A Duro and the lower pad 85A Duro.

Unconfined compression tests were performed by loading the rubber blocks up to 223 N with a rigid piston head. Two 0.30m x 0.30m x 0.038m rubber blocks were stacked for a total thickness of 0.076m. The PVC block was a 0.30m high, 0.23 m diameter cylinder. Each combination of reference blocks was tested as shown in Table 1 and Figure 3.6. The average modulus E of the two rubber blocks was taken as the ratio between the vertical stress imposed by the rigid piston head (Figure 3.6) and the vertical strain measured as a result of that stress.

The BCD tests were then performed by placing the BCD plate on top of the same block (Figure 3.7) and applying a 223N weight on the BCD plate much like it would be done in a true BCD test. The reading of the BCD (mean pressure p over the measured average hoop strain ε in the strain gages on the back of the BCD plate) was obtained for each test.

The modulus E of the rubber blocks was plotted against the BCD reading p/ε. By repeating this operation for several different blocks, an equation relating the BCD reading to the rubber block modulus was developed. This is the proposed calibration process for the BCD. Once calibrated, the equation is uploaded in the software of the BCD. As explained in this section, the process of calibration should be done for each BCD plate.

Table 1: Modulus of the reference blocks

Combination of reference block	Modulus from Unconfined Compression Test
45/45	6.11 MPa
60/60	10.03 MPa
60/85	17.72 MPa
85/60	29.54 MPa
85/85	37.98 MPa
95/95	75.96 MPa
PVC	232.79 MPa

Fig. 3.6 – Obtaining the block modulus **Fig. 3.7 - Calibration test of BCD plate**

The BCD plate is made of stainless steel 316 for high corrosion resistance. The thickness of the plate is 1.85mm inside the limit specified by the manufacturer (1.980mm+/- 0.178mm). As explained above, each plate is calibrated individually with a load up to 223N by increment of 44.5N. Then, each plate is first calibrated by itself to obtain the slope in microstrain by pound (ε/lb). Then it is recalibrated after connecting the readout unit to obtain this time the slope in pound by millivolt (lb/mv). The multiplication of these two factors leads to a calibration factor in microstrain by millivolt (ε/mV) for each plate. This calibration factor is then transferred in the readout memory. Figure 3.7 shows the calibration test setup; one of the test results is shown in Figure 3.8.

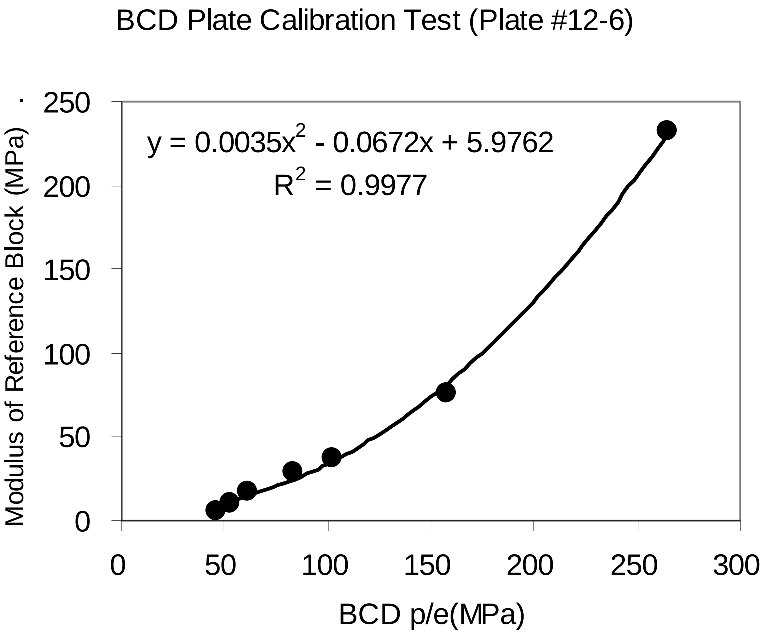


Fig.3.8 - BCD Plate Calibration Test

Figure 3.8 shows the relationship between the unconfined compression modulus of the reference blocks and the pressure / hoop strain (p/ε) from the BCD test on top of the same rubber block. A second order polynomial regression is performed and fits the calibration data very well. The polynomial equation obtained from the calibration test is embedded in the calculation processor of the BCD display and is called upon by the BCD to transform the pressure/hoop strain (p/ε) value to the BCD modulus. This BCD modulus is displayed on the unit.

3.4.3 Technical specifications of the BCD

The technical specifications of BCD-4 are shown in Table 2.

Table 2: Technical specification of the BCD

Measuring Range	BCD soil modulus from 5MPa to 150MPa
Depth of measurement	240mm at E of 10MPa 150mm at E of 100MPa 121mm at E of 300MPa
Time required for a test	Approx. 5sec
Display	240x128 Pixels, LCD CCFL, Backlit
Function Keys	Six function keys to navigate within interactive menus
Memory	1MB RAM with lithium battery backup
Data Output	Format ASCII and Spreadsheet compatible format
Interfacing	Communication port: RS-232,9600 Baud
Power supply	Six Rechargeable 2 Volt, 8Ah, batteries External battery charger input External power supply input
Connectors	4-pin female connector for battery charger 6-pin connector for download data port and hand switch
Readout Housing	Waterproof, Shock resistant aluminum casting
Dimensions	Overall height : 855mm Plate diameter: 150mm
Weight	9.6kg

CHAPTER 4- NUMERICAL SIMULATION

4.1 Depth of influence of the BCD.

Numerical simulations were used to study the behavior of the BCD plate. The general finite-element program ABAQUS V6.2 was used together with a linear elastic model to study the depth of influence of the BCD test. An axysimmetric mesh was used.

The simulation results gave the vertical stresses distribution in the soil as a function of depth below the center of the plate (Figure 4.1) under a load of 223 N. This figure gives an idea of the depth of influence of the BCD test. A common definition of the depth of influence is the depth at which the vertical stress has decreased to one tenth of the stress at the surface. With this definition, the depth of influence is the one shown in the legend of Figure 4.1. It can be stated that for moduli between 5 and 100 MPa, the depth of influence of the BCD is at least 150 mm.

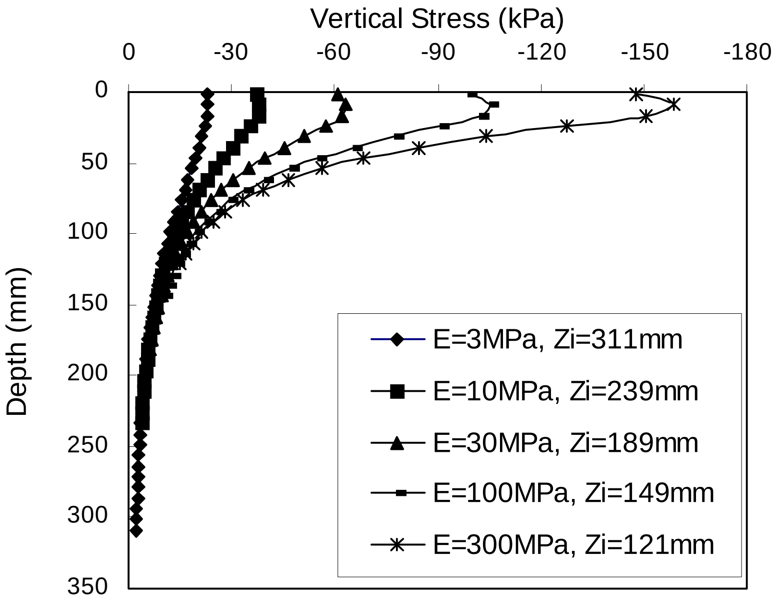


Fig. 4.1 - Vertical Stress Distributions with Depth below the BCD Plate.

The depth of influence can also be considered in terms of displacement. In this case the depth of influence may be defined as the depth at which the vertical displacement under the center of the plate has decreased to one tenth of the displacement at the surface. With this definition, the depth of influence is the one shown in the legend of Figure 4.2. It can be stated that for moduli between 5 and 100 MPa, the depth of influence is at least 120 mm.

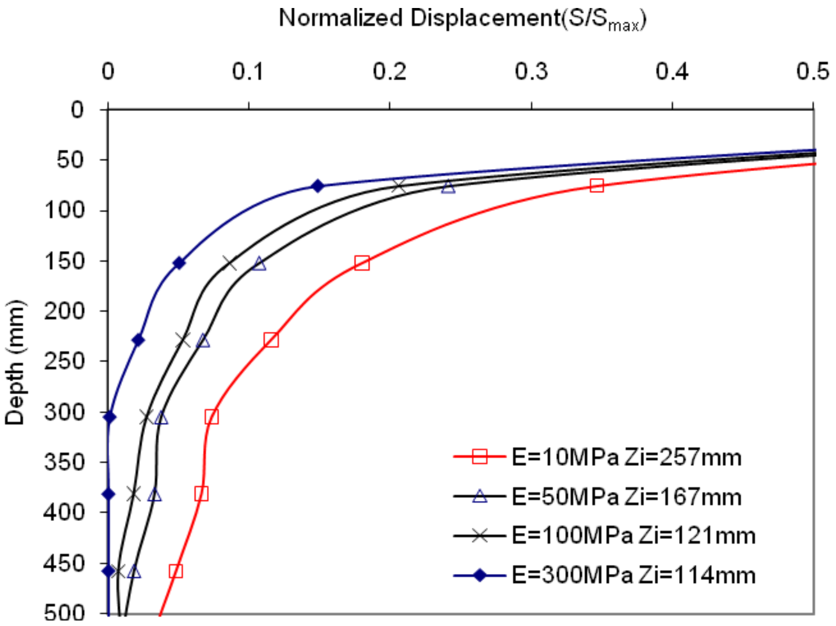


Fig. 4.2 - Normalized Vertical Displacement with Depth below the BCD Plate

The stress distribution under the BCD plate was obtained from the simulations. The average pressure under the BCD for a load of 223 N is 12.6 kPa. The simulations indicated that the pressure under the center of the plate is much higher than the average pressure and increases with the soil modulus. An example of pressure distributions is shown on Figure 4.3. This figure shows that for very low soil moduli the plate applies a relatively uniform pressure on the soil while at very high soil moduli the pressure is more concentrated towards the center of the plate and that the edges of the plate are not in contact with the soil. The edge lift-off occurs for a soil modulus equal to 30 MPa. The loss of contact is due to the fact that the plate is not flexible enough to stay in contact with the soil. This means that the loaded area is reduced and the average pressure on the soil increases. These changes are absorbed in the calibration process (Section 3.4.2) where the same phenomenon takes places. The calibration takes this phenomenon into account and corrects it automatically.

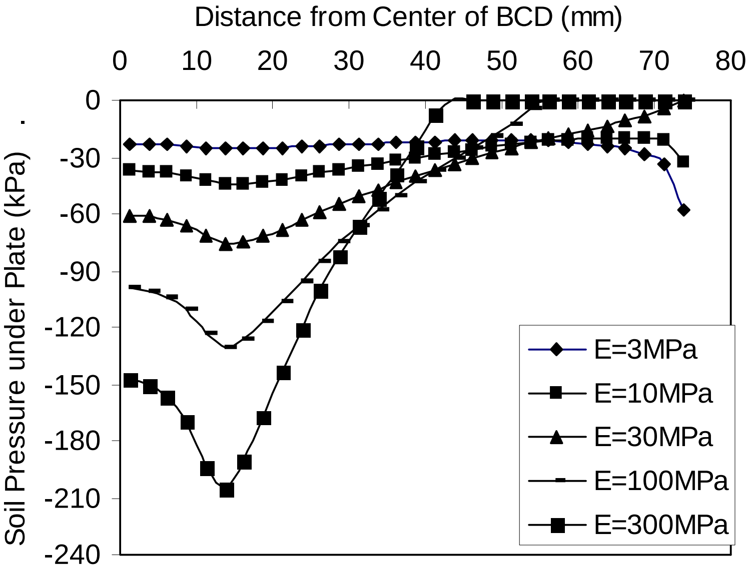


Fig. 4.3 - Pressure Distributions on the Bottom of the BCD Plate.

4.2 Simulation of BCD: lab and field test.

The elastic equation for the deflection of a rigid plate on an elastic half space is

$$s = I\,pB / E$$

where s is the plate settlement, I an influence factor typically a function of Poisson's ratio, p the mean pressure under the plate, B the diameter of the plate, and E the modulus of the half space. By analogy the formula for the BCD was taken to be of the same form but I had to be determined.

Numerical simulations were performed to investigate the influence of the Poisson's ratio on the influence factor I for the BCD. Figure 4.4 shows that the Poisson's ratio does not have a significant influence on I whether it is performed in the field (BCD on top of an elastic half space) or in the lab on top of the Proctor mold (BCD on top of a confined elastic cylinder). This indicates that the modulus using the BCD on top of the Proctor mold and the modulus using the BCD in field can be compared directly.

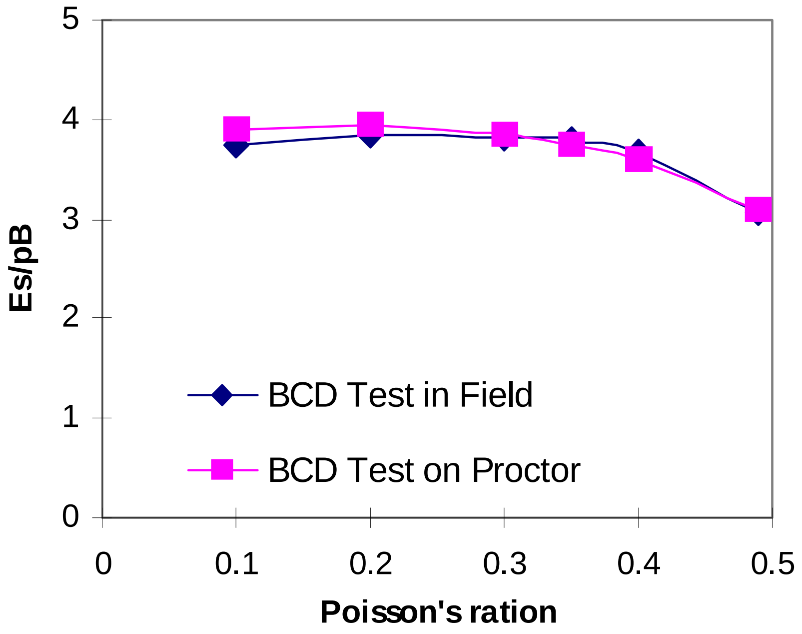


Fig. 4.4 - Influence Factor as a Function of Poisson's Ratio for the BCD Test

Figure 4.5 shows additional results from the same simulations. The vertical axis represents the values of the elastic modulus input into the numerical simulations while the horizontal axis represents the BCD modulus calculated from the output of the numerical simulations. The BCD modulus was calculated as the ratio of the mean pressure under the BCD over the hoop strain in the BCD steel plate at the location of the strain gages. Figure 4.5 indicates that there is practically no difference between the curve for the field simulation (BCD on an elastic half space) and the curve for the lab simulation (BCD on top of an elastic sample confined in the Proctor mold). This interesting and unexpected result allows the BCD software in the BCD display to have only one equation for obtaining the modulus from the field test and from the lab test.

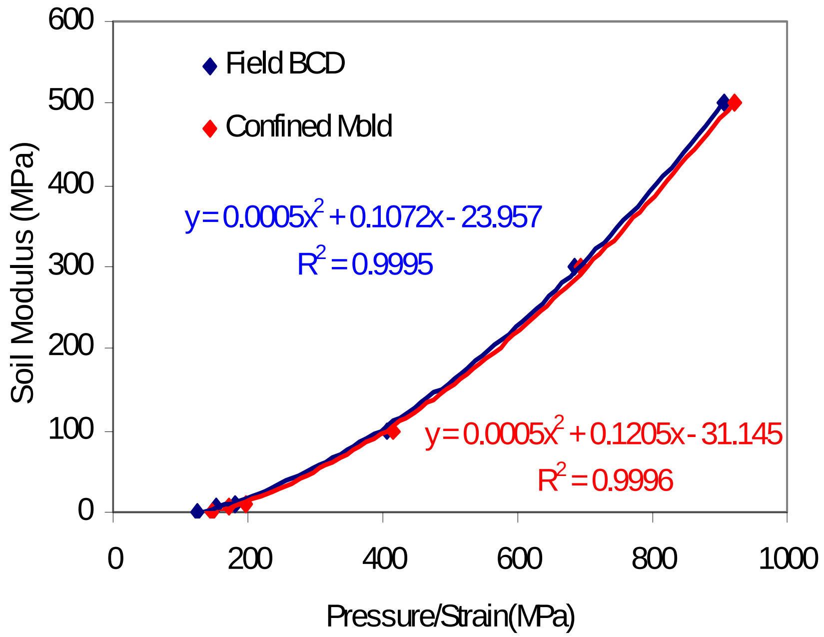


Fig. 4.5 - Elastic soil modulus input in the simulation versus the BCD modulus.

CHAPTER 5- BCD TEST

5.1 Repeatability of the BCD test

The BCD test was performed on the same rubber block by repeating the test 8 times. The rubber block was 304 mm square and 76.2mm thick. The tensile strength of the rubber was 11.72 MPa, the durometer hardness was “shore A: 70”. At each test the same load, 223N was applied then the strain output from the read-out unit was recorded. The Coefficient of Variation (COV) of the strain output which was obtained in that fashion was 0.5 % as shown in Figure 5.1. This repeatability is considered to be excellent.

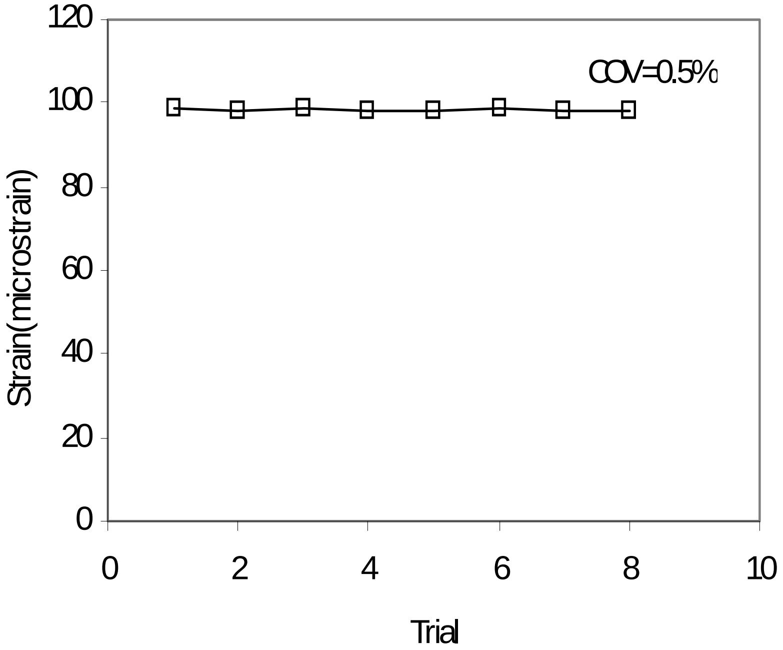


Fig. 5.1 - Repeatability of the BCD test

5.2 Linearity of the BCD test.

The linearity test was performed on the same rubber block used for the repeatability test. The load on the BCD was increased in equal steps and for each step the hoop strain in the plate was recorded. Figure 5.2 shows an excellent linearity between the load applied and the hoop strain measured in the BCD plate.

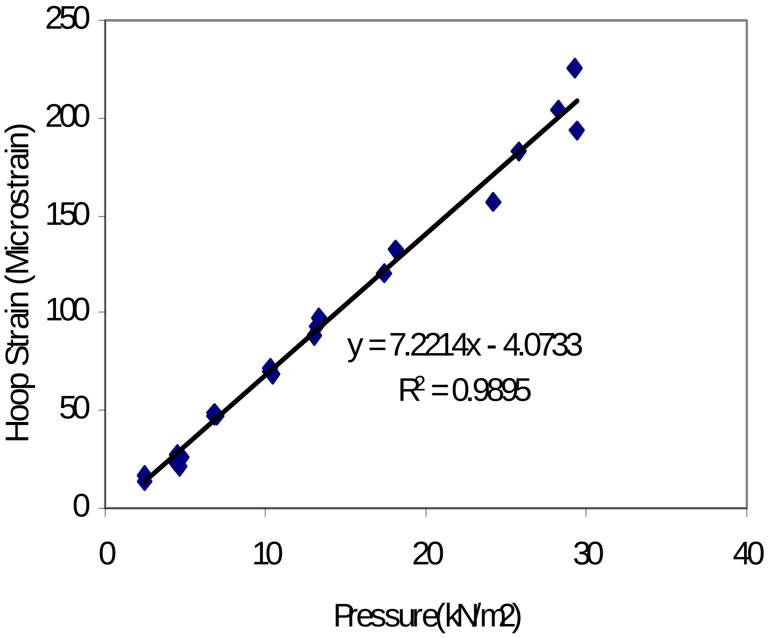


Fig. 5.2 - Linearity test for the BCD

5.3 The BCD field test

5.3.1 Sand Cushion

The use of a sand cushion was investigated to improve the contact between the soil to be tested in the field and the BCD steel plate. The sand cushion was built as follows: one handful of wet uniform fine sand (water content between 10 to 12%) is placed on the ground surface and flattened by hand. The sand cushion is 2 to 4 mm thick. Tests were performed with and without a sand cushion at two filed sites: the Texas A&M University Memorial Student Center parking lot and Texas Highway 49 near College Station. Figure 5.3 shows that the sand cushion decreased significantly the coefficient of variation of the test results (15% to 2.8% in the MSC parking lot and 8.7% to 3.9% on Texas highway 49). The sand cushion had a minimal impact on the modulus values although a slight increase was noted. Since the results showed clear evidence of the benefit of using a sand cushion, it was decided that all future BCD field tests would be done with a sand cushion.

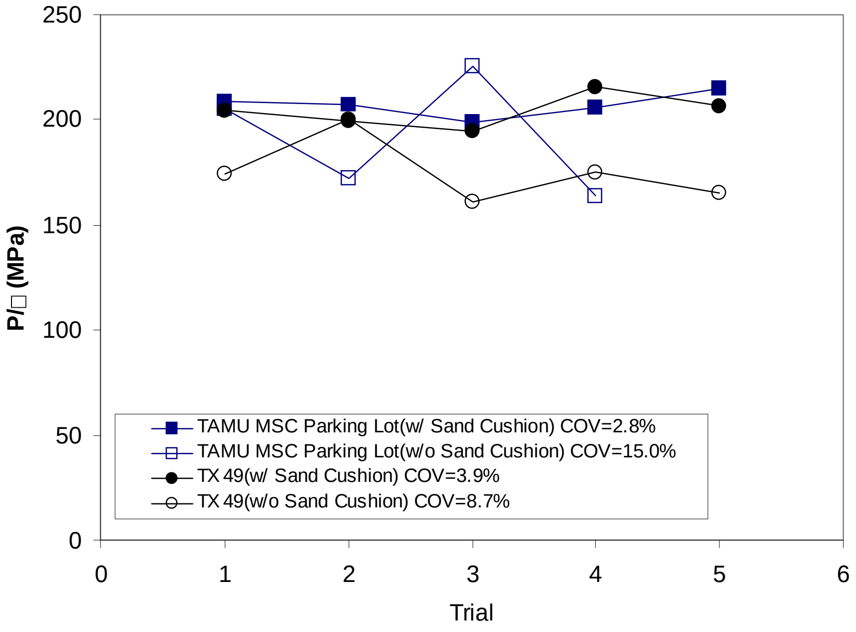


Fig. 5.3 - Sand cushion tests on uneven surface

5.3.2 Field Test Procedure

Before the BCD test is performed in the field, it is strongly recommended that a sand cushion (Figure 5.4(a)) be placed to improve the reliability of the results. The sand cushion should be clean uniform fine sand at a water content of approximately 10%. The sand ensures a good contact between the BCD plate and the uneven soil surface by filling the voids (Figure 5.4 (b)). The sand is prepared at about 10% water content in a bucket before testing. It is important to use a fine, uniform, and wet sand. Dry sand or other cohesionless materials are not recommended.

The following steps should be followed for the BCD field test:

Step 1: Prepare the wet sand to use as a cushion and ensure good seating. Place a handful of wet sand on the test location and pat it down firmly and evenly into a 4-5 mm thick sand layer (like Figure 5.4 (a)). The diameter of the sand cushion should be at least equal to the diameter of the BCD bending plate (Figure 5.4 (b)). A separate rigid steel plate can be used to help achieve a proper sand cushion.

(a) Sand Cushion **(b) The BCD on Sand Cushion**

Fig. 5.4 - The BCD field test with sand cushion

Step 2: Place the BCD device perpendicularly to the prepared sand cushion surface (vertically if the ground surface is horizontal) and set up the BCD to be ready to test. Ensure that a good contact exists between the sand cushion and the BCD plate. One clue is to see if the BCD plate leaves an imprint in the sand cushion.

Fig. 5.5 - The BCD field test

Step 3: Keep the device approximately perpendicular to the ground surface without applying any load; the test can start. The BCD should be kept approximately perpendicular to the soil surface throughout the test (Figure 5.5).

Step 4: Load the BCD by leaning on it until you hear a beep sound. This is the first loading test which is not used. The beep sound indicates that correct load is reached 50lb (223N). It is important that the time elapsed between the time where the operator starts leaning on the BCD and the time where the beep is heard be at least 5 seconds. Faster loading may lead to loads significantly different form 223 N. Unload the BCD back to zero load until another beep sounds.

Step 5: Load the BCD by leaning on it a second time until the beep sounds (follow the 5 second rule again). This is the reload test and is the one used for obtaining the BCD modulus. Again it is critically important that the BCD be loaded very slowly (0 to 223 N in more than 5 seconds) to obtain reliable results.

Step 6: If the displayed load is very different from 50lb (223N), carefully do the BCD test again.

Step 7: It is recommended to repeat the BCD tests 4 times at the same location by rotating the BCD 90 degrees each time. Using the average of the 4 readings gives a better accuracy of the readings.

Step 8: The average of the 4 BCD test readings is the BCD field modulus.

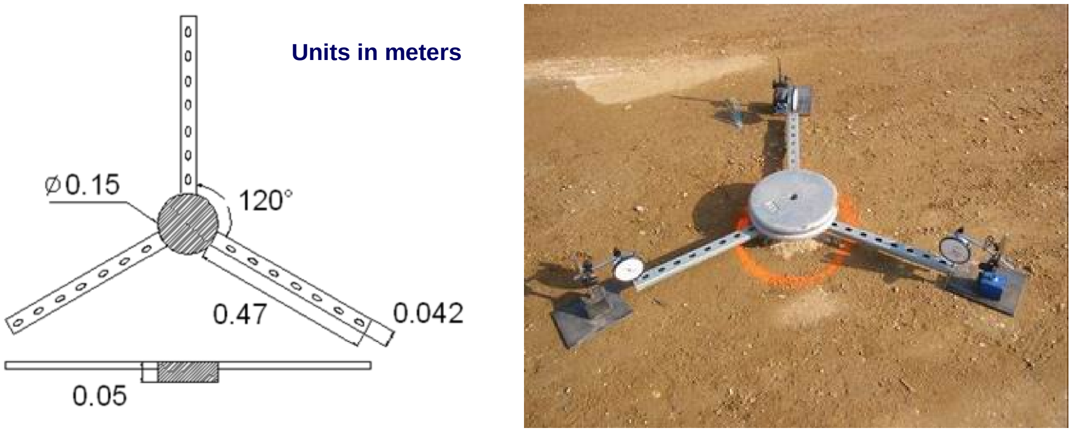
5.3.3 The Rigid Plate Test

In order to prove that the BCD can measure a soil modulus in the field, a simple plate test (Figure 5.6(a)) was devised and performed in parallel with the BCD test in the field .The plate is a steel disk 150 mm in diameter and 50 mm thick with three 0.47 m long arms spaced around the circumference of the plate at 120 degrees from each other. The weight of the plate and its arms is about 90 N which is similar to the dead weight of the BCD; the dead weight provides the seating load for the test. Dial gages precise to 0.0025 mm are placed at the end of the three arms and a zero reading is taken on the dial gages. The plate is loaded with 223 N of dead weight and the dial gages are read again; this process is repeated a second time to obtain the reload modulus of the soil. All dial gage readings are taken after stabilization of the plate movement (Figure 5.6(b)).

The data reduction steps are: (1) plot the load (Q) versus settlement (S) curve, (2) obtain the slope of the first loading and the slope of the second loading, and (3) use the formula below to obtain the soil modulus E.

$$E = I(\nu)\frac{Q}{BS} = 0.89\frac{(1-\nu^2)\,Q}{B\,S} \qquad (1)$$

Where E is the modulus of the material below the plate, I(ν) is a factor depending on the Poisson's ratio ν, Q is the vertical load applied on the plate, B is the plate diameter, and S is the settlement of the plate. Equation 1 is based on numerical simulations performed with PLAXIS for a 50 mm thick, 150 mm diameter steel plate resting on an elastic soil cylinder 6 m in diameter and 3 m deep. The results of the numerical simulations for the relationship between I and ν is shown on Figure 5.7. The expression I(ν) = 0.89 $(1-\nu^2)$ was selected as it describes well the curve in Figure 5.7. For more details see Briaud et al. (2006).



(a) The Rigid Plate Tester **(b) The Rigid Plate Test in Field**

Fig. 5.6 - The Rigid Plate Test

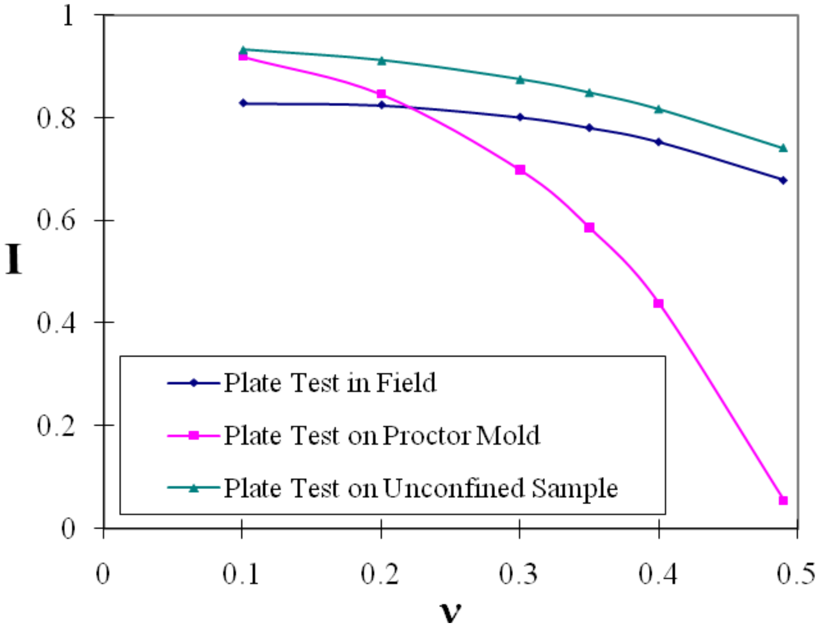


Fig. 5.7 - Influence Factor vs. Poisson's Ratio for the Plate Test (Briaud et al. 2006)

5.3.4 Comparison with Plate Test.

Field BCD tests and field plate tests were performed in parallel to verify the BCD-4. Construction-like field situations were sought. A total of 10 plate tests and 10 BCD tests were conducted in the field on 10 different types of soils and pavement bases (Table 3). Before the tests, the soil surface was trimmed with a steel scraper to make the surface more even. This procedure was used to minimize the number of extraneous variables that could influence the comparison. At each location, the BCD test was performed twice and the second test was recorded.

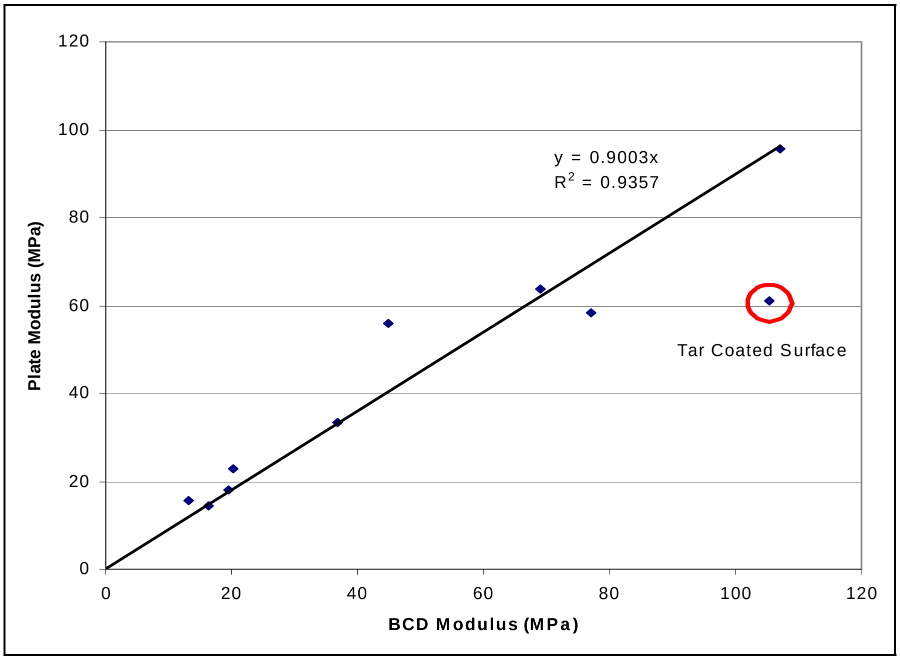


Fig. 5.8 - Correlation between Plate Test and BCD Test

Immediately after removing the BCD from the location, the plate tester was placed directly on the BCD imprint and loaded. From the test results, a plot comparing the reload modulus E from the plate test and the modulus E of the BCD (reload as well) was produced (Figure 5.8).

Table 3: BCD and Plate Test Sites

Test Site	Soil Description	Modulus (Mpa)	
		Plate Test	BCD
Texas A&M River Side Campus Runway #1	Crushed lime compacted ground	55.96	45
Texas A&M River Side Campus Runway #2	Crushed lime compacted ground	63.67	69.14
NGES Sand Site #1	Sand Surface	17.95	19.5
NGES Sand Site #2	Sand Surface near various footings	22.96	20.15
NGES Sand Site #3	Compacted road base	33.25	36.78
NGES Sand Site #4	Sand Surface near drilled shaft	14.51	16.31
NGES Sand Site #5	Sand Surface near drilled shaft	15.51	13.26
TX-47 Construction Site #1	Lime stabilized subgrade	95.5	106.96
TX-47 Construction Site #2	Tar coated lime stabilized subgrade	61.02	105.4
Energy Transfer Station	Crushed lime compacted ground	58.2	77.08

One outlier, circled in red on Figure 5.8, was eliminated from the comparison as the two tests were performed on a tar coated surface. Indeed in this case the tar, which is a very viscous material, could have squeezed from under the loaded surface or deformed excessively. Since the plate test is a much slower test than the BCD test, it is the reason why the plate test gave a much lower modulus.

The coefficient of determination (R^2) without this outlier is 0.936 which indicates a reasonable correlation between the two parameters. Therefore, the BCD can predict the plate reload modulus of the soil with reasonable accuracy.

5.4 The BCD Lab Test

5.4.1 BCD Lab Test Procedure

The lab BCD test consists of placing the BCD plate on top of the sample in the Proctor mold and running a BCD test on the soil within the mold. By performing lab BCD tests in parallel with dry density tests, one can obtain the modulus versus water content curve as well as the dry density versus water content curve.

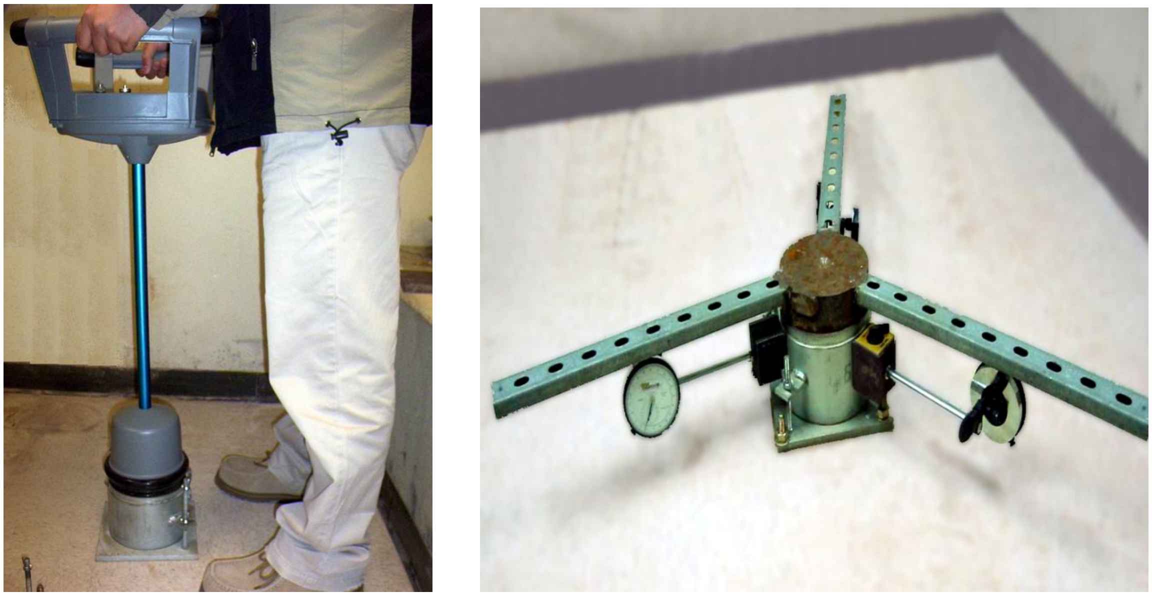
To prepare the compaction sample (Standard Proctor Test, ASTM D698 or Modified Proctor Test, ASTM D1557), a 150mm (6 inches) diameter Proctor mold was used. The BCD test was performed on top of the compacted sample as shown on Figure 5.9 (a).

Step 1: Set the Proctor mold on a hard surface, and then sit the BCD on top of the sample in the proctor mold. Keep the BCD as perpendicular to the sample surface (vertical) as possible throughout the test (Figure 5.9 (b)).

Step 2: Ensure that the edge of the BCD plate does not touch the wall of the mold. Check all around the BCD plate and set up the BCD to be ready to test.

Step 3: Keep the device vertical on the soil surface without applying any load, the BCD should be maintained as perpendicular as possible to the soil surface during the test.

Step 4: Follow the same procedure as the field BCD test procedure to obtain the BCD modulus



(a) BCD Test on Compaction Mold **(b) The Plate Test Compaction Mold**

Fig. 5.9 - Lab BCD and Plate test

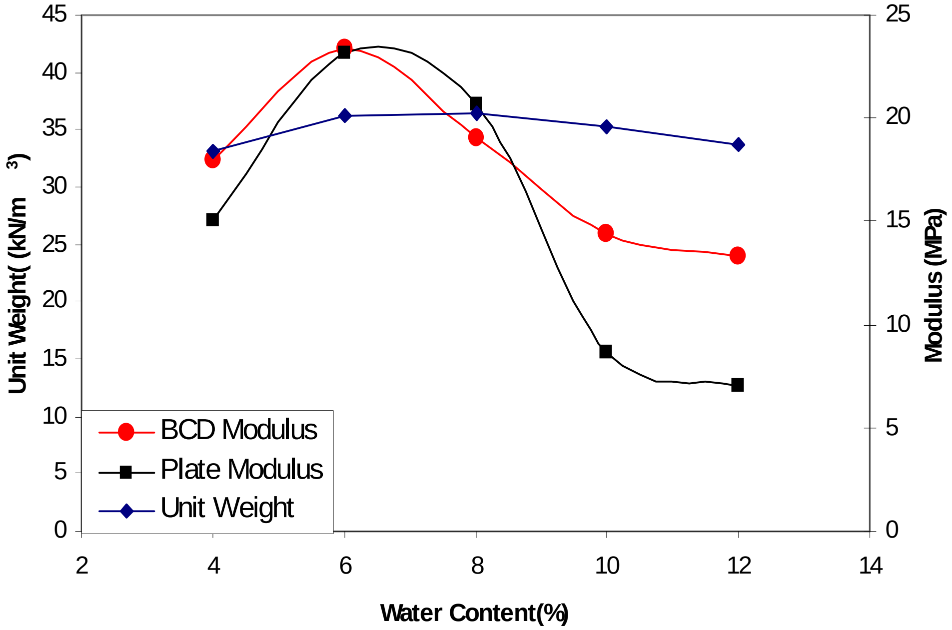
5.4.2 Comparison with Compaction Curve

The comparison included the BCD modulus, the plate modulus, and the dry density all plotted as a function of water content. The BCD test was performed first according to the step by step procedure described in 5.4.1. The BCD modulus was obtained by using the same equation as the one used in the field. Indeed recall that according to Figure 4.5 the same equation applies to the field and to the lab for the BCD. The thick steel plate test was performed next by placing the plate directly on the compaction sample and loading it (Figure 5.9(b)). The plate modulus was obtained by using the following formula:

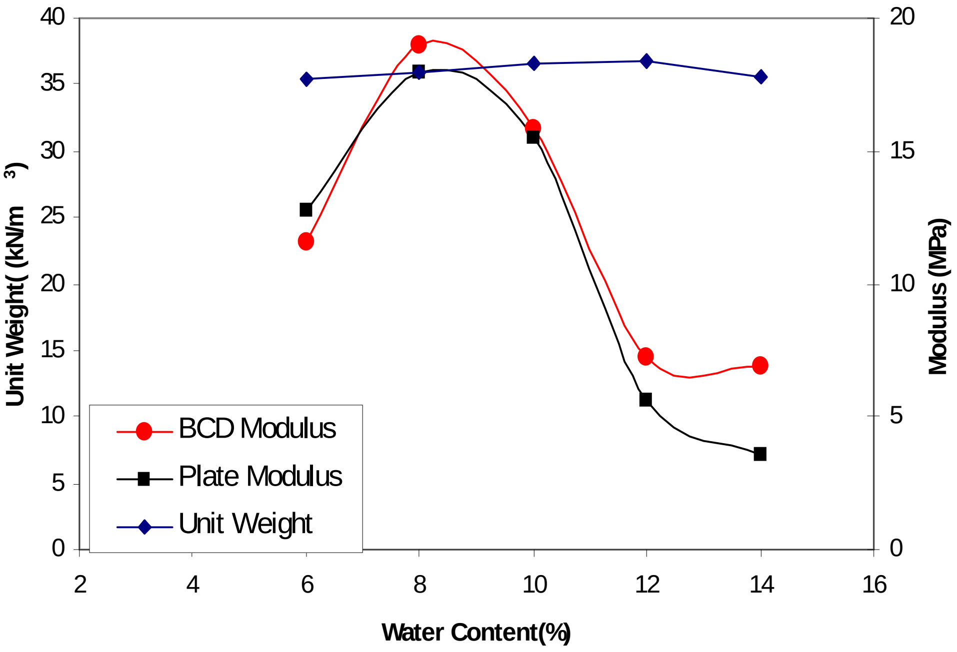
$$E = I(\nu)\frac{Q}{BS} = 0.67\frac{(1-\nu^2)\,Q}{B\,S} \tag{2}$$

Where: E is the modulus of the material below the plate; I(ν) is a factor depending on the Poisson's ratio ν; Q is the vertical load applied on the plate; B is the plate diameter, and; S is the settlement of the plate. Equation 2 for the plate test in the lab was obtained from a numerical simulation. It was performed using a cylindrical mesh with a diameter equal to 150 mm and with a depth equal to 112.5 mm and a distributed load of 12.2 kPa applied to the top of the rigid plate. In the simulations, three different side boundaries, fixed nodes, sliding nodes, and free nodes (unconfined compression) were investigated. The output results gave the following I(ν) values: I = 0.154 for fixed side nodes, I = 0.585 for sliding side nodes, and I = 0.850 for free side nodes (unconfined). Parallel testing with the plate on top of the soil in a real Proctor mold indicated that I = 0.585 was very close to the measurements. Therefore the sliding nodes best represented the behavior of the soil in the mold. The value of I = 0.585 was selected and transformed into: $I = 0.67(1-\nu^2)$ to incorporate the influence of Poisson's ratio. For more details see Briaud et al. (2006) and Li (2005).

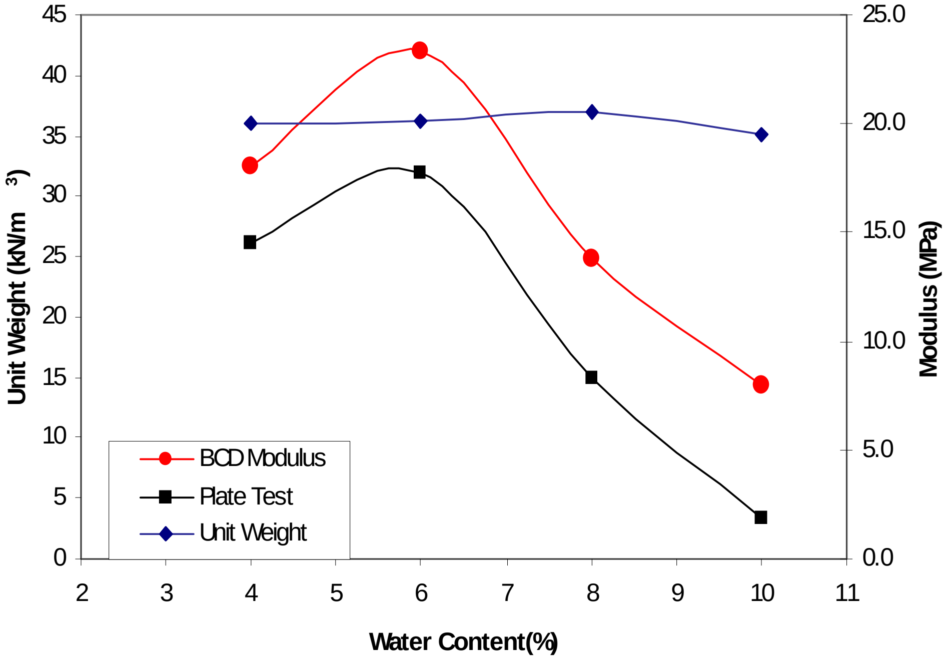
The test results are presented in Figure 5.10 (a,b,c) which is a plot of the reload modulus E from the plate test, the BCD modulus, and the dry unit weight all as a function of the water content. The optimum water contents for the maximum modulus do not correspond directly to the optimum water contents for the maximum dry unit weight (Figure 5.10 (a,b,c)). But the BCD and the plate modulus show a maximum modulus for each soil at almost the same water content. This confirms the ability of the BCD to measure a soil modulus. The validity of the rigid plate modulus becomes more doubtful as the soil becomes wetter and approaches saturation. Indeed in this case the voids in the soil become full of water and therefore the soil becomes incompressible. As a result the rigid plate modulus can rapidly approach infinity (constrained modulus of an incompressible material). This limitation does not apply to the BCD as the BCD plate is flexible and allows the soil to deform in shear around it even though the soil is close to being infinitely stiff in hydrostatic compression.



(a) SH 290 Mixed Soil with Modified Compaction



(b) SH 290 Mixed Soil with Standard Compaction



(c) NGES Sand Clay Mixed Soil with Modified Compaction

Fig. 5.10 - The Modulus curve from the BCD and the plate test versus Unit weight Curve.

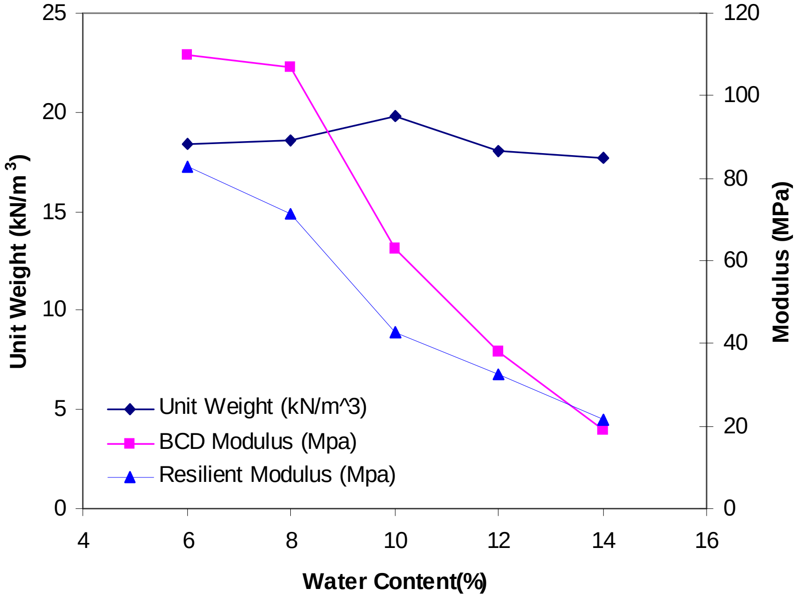
5.4.3 Comparison with Resilient Modulus

Because the resilient modulus is increasingly used in pavement design, a comparison was performed between the BCD modulus and the resilient modulus. Resilient modulus tests were performed in the TAMU lab with 150 mm (6 inches) diameter and 203mm (8 inch) high silty clay samples at various water contents. BCD tests were performed on the compacted soil sample in the mold. Then the split mold was removed from around the soil sample and the sample was transferred to the resilient modulus test machine. Once the sample was set up, two LVDT were attached on the side of the rubber membrane covering the soil sample and the test followed the procedure recommended in AASHTO T 307-99. The test set up is shown in Figure 5.11.

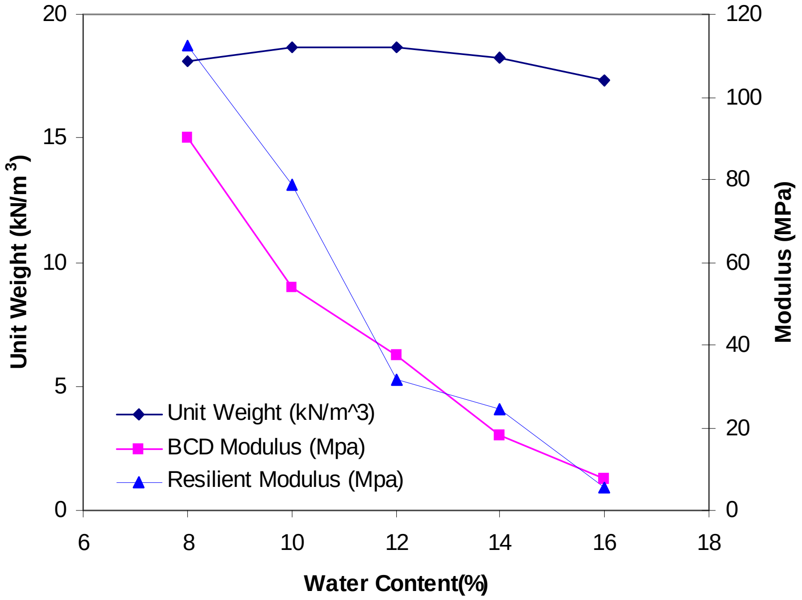
(a) Sample preparation **(b) Resilient modulus testing**

Fig. 5.11- Set up for the resilient modulus test

The resilient modulus and the BCD tests were performed on soil from two locations: State Highway 290 construction site and State Highway 130 construction site. In each case five samples were prepared at five different water contents. The comparisons between the dry density, the BCD modulus, and the resilient modulus vs. water content are shown in Figure 5.12 (a,b). The soil modulus from the resilient modulus test and the BCD test show a rapid drop beyond 8.5% water content while the dry density shows a lack of sensitivity by comparison. Even though the stress state and the strain level are likely somewhat different between the BCD test and the resilient modulus test, the BCD and the resilient modulus parallel each other quite well in both cases.



(a) The BCD and the resilient modulus test results for SH 290 mixed soil



(b) The BCD and the resilient modulus test results of SH 130 soil

Fig. 5.12 - Unit weight vs. the BCD modulus and resilient modulus curve

Figures 5.13 and 5.14 show the correlations between the BCD modulus E $_{(BCD)}$ and the Resilient modulus E$_{(res)}$. For a given soil the R^2 are well above 0.9 and the relationship is very strong. This means that a site specific correlation would allow the engineer to extent the value of a few resilient modulus tests by using the less expensive BCD test. Indeed, a few E$_{(res)}$ could be obtained in parallel with E$_{(BCD)}$ to establish a local correlation; then the BCD tests could be used extensively to obtain E$_{(res)}$ from that point on.

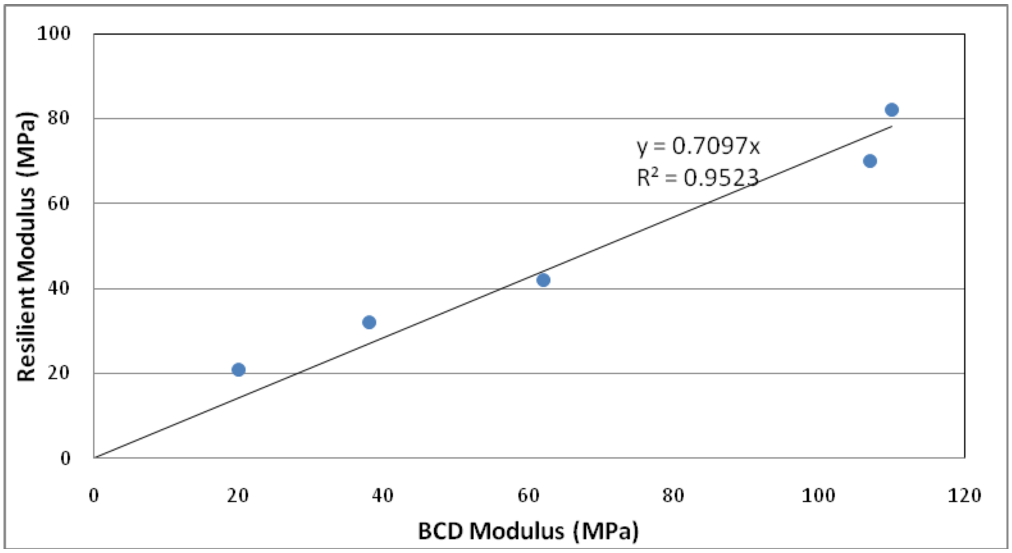


Fig. 5.13 - Correlation between the Resilient Modulus and the BCD Modulus (SH 290 mixed soil)

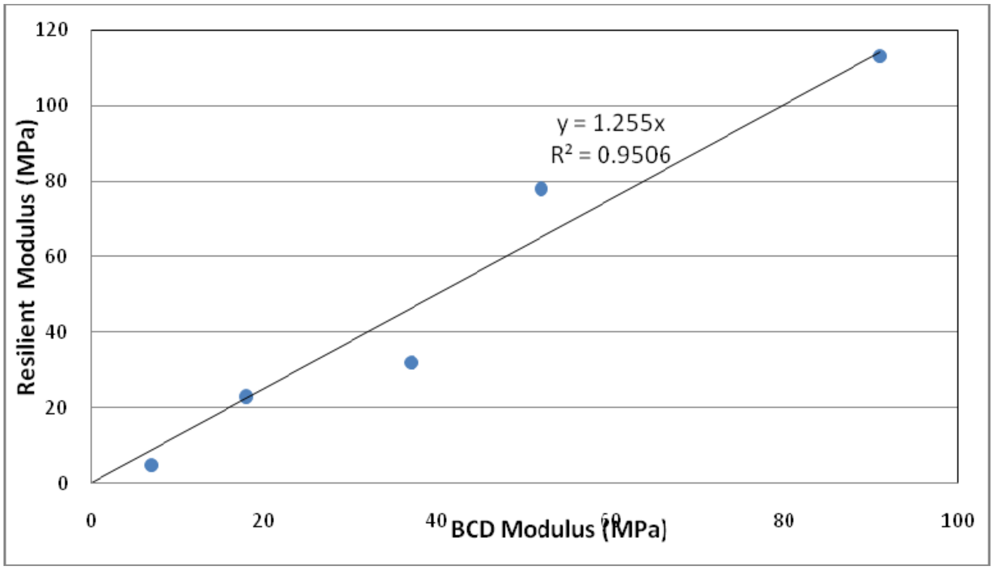


Fig. 5.14 - Correlation between the Resilient Modulus and the BCD Modulus (SH 130 soil)

CHAPTER 6- POSSIBLE USE OF THE BCD FOR COMPACTION CONTROL.

6.1. Current Practice

A typical sequence for current practice in compaction control is as follows. After selecting the fill material, the compaction criterion to be achieved in the field is established through lab tests. Modified Proctor or Standard Proctor tests are performed and the optimum moisture content as well as the maximum dry density are determined from the compaction curves. These lab results are used to define target values of moisture content and maximum dry density which are written in the specifications and must be achieved in the field. The range of typical dry density values is from 95% to 100% of maximum dry density. On the job site, the target values of dry density and water content are verified through field testing (Figure 6.1).

Fig. 6.1 – Current compaction control practice

6.2. Proposed Practice

A typical sequence for the proposed practice for using the BCD for compaction control is as follows (Figure 6.2). After selecting the fill material, the compaction modulus criterion to be achieved in the field is established through lab tests. Modified Proctor or Standard Proctor tests are performed and the optimum moisture content as well as the maximum dry density is determined from the compaction curves. At the same time and for each Proctor test, BCD tests are performed on top of the sample in the Proctor mold to obtain the BCD modulus. The result of these Proctor tests is a BCD modulus vs. water content curve as well as a dry density vs. water content curve. The modulus curve is used to define the maximum BCD modulus and the corresponding optimum moisture content (Figure 6.3). Then the target BCD modulus and the target water content are selected and written in the specifications; they must be achieved in the field. The suggested target modulus value is 75% of the maximum modulus value. On the job site, the target value of BCD modulus is verified by BCD tests (Figure 6.2) and the water content is verified independently through field testing (e.g.: the new suitcase field oven).

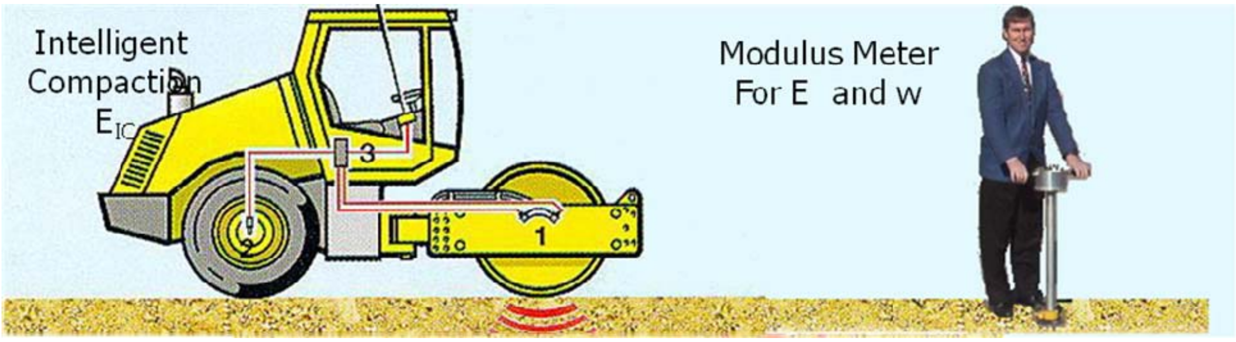


Fig. 6.2 – Proposed compaction control practice

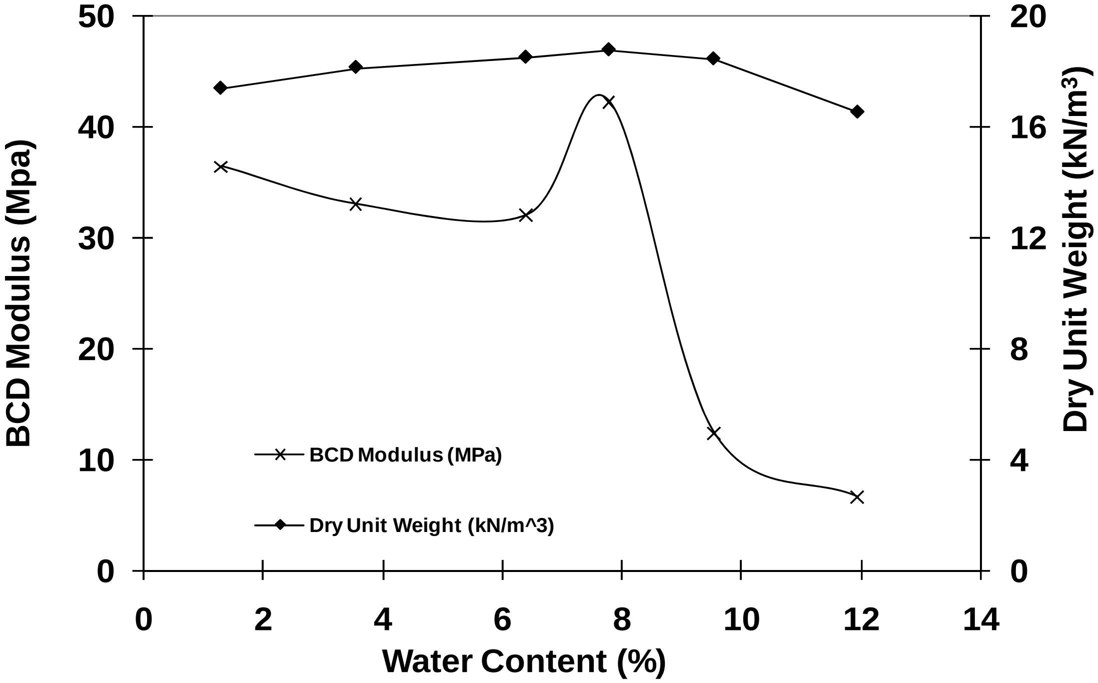


Fig. 6.3 – BCD modulus vs. water content curve

CHAPTER 7 - CONCLUSIONS

The idea of the BCD is to use the bending of a flexible steel plate resting on the ground surface (field test) or the soil surface at the top of the Proctor mold (lab test) to obtain the modulus of the soil below. A load of 223 N or 50 lbs is applied by the operator leaning over the BCD rod and the bending strains in the plate are measured by strain gages glued to the top of the plate. The recorded strains are transformed into a soil modulus according to an equation. This equation is demonstrated to exist by numerical simulations but is obtained by calibration against rubber blocks of known modulus for each BCD plate. The repeatability and linearity of the BCD results were demonstrated by performing tests on a rubber block in the lab. After running tests with and without a sand cushion it is recommended that such a sand cushion be used to significantly decrease seating problems; the sand should be wet fine uniform sand. The modulus measurement range of the BCD is estimated to be 5 MPa to 150 MPa based on numerical simulations. The BCD modulus shows a good relationship with the plate modulus and the resilient modulus (R^2 much higher than 0.9) but no strong correlation to the dry density. The depth of influence of the BCD is shown from numerical simulations to be at least 150 mm for soils with modulus ranging from 5 to 100 MPa. A series of improvements and the construction of four prototypes led to the latest BCD, BCD-4, which is now manufactured by Roctest under license with Texas A&M University.

The proposed new practice based on the BCD modulus consists of performing the same steps as the current practice but adding the BCD test on top of the Proctor mold sample to obtain the BCD modulus vs. water content curve, choosing a target BCD modulus and water content value to write in the specifications, and checking that such a modulus has been achieved in the field with the BCD as well as the water content. Note that it is critical to use the same tool to obtain the modulus in the lab and in the field as the modulus depends on many factors.

The BCD modulus was found to correlate very well with the resilient modulus for a given soil. This means that a site specific correlation would allow the engineer to extend the value of a few resilient modulus tests by using the less expensive BCD test. Indeed, a few $E_{(res)}$ could be obtained in parallel with E(BCD) to establish a local correlation; then the BCD tests could be used extensively to obtain $E_{(res)}$ from that point on.

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