
Use of Best Fit Line of Optimums (BFLO) for Recompacted Soil Liner Construction

PURPOSE

This educational guideline outlines a procedure for using site-specific maximum dry density and optimum moisture content points (MDD/OM) from standard and modified proctor tests to develop a best fit line of optimums (BFLO). The BFLO is one option that can be used to determine if there is a significant change in soil material properties. It can also be used as the pass/fail criteria for compacted density and compacted moisture content during construction of recompacted soil liners as well as separatory liner/leachate collection systems and cap system soil barrier layers.

APPLICABLE RULES/STATUTES

MSW: OAC 3745-27-08
ISW: OAC 3745-29-08
RSW: OAC 3745-30-07
Tires: OAC 3745-27-72

APPLICABILITY

This procedure can be used by owners and operators of municipal (MSW), industrial (ISW), and residual (RSW) solid waste disposal landfills, and scrap tire monocells and monofill disposal facilities who will be constructing recompacted soil liner, separatory liner/leachate collection system, or cap system soil barrier layer at their facilities.

DETAILED DISCUSSION

The line of optimums is defined as a line or curve connecting MDD/OM points from proctor curves created at different compactive energies for a given soil. For example, if a modified proctor density curve, a standard proctor density curve, and a reduced energy proctor density curve, for the same soil, are plotted on the same proctor graph, a curve drawn through the three MDD/OM points is the "line of optimums" for that soil (see Figure 1).

Numerous studies over the last 10 years by Benson, Daniel, Boutwell, and others have demonstrated repeatedly that compaction of most cohesive soils above the line of optimums has a high probability of resulting in a recompacted soil with a field permeability (K_f) less than 1×10^{-7} cm/sec. Conversely, compacting below the line of optimums is much more likely to result in a recompacted soil with K_f greater than 1×10^{-7} cm/sec.

An example of this can be found in a 1999 study of 85 liners and test pads from all regions of the United States and Canada. The liners and test pads incorporated standard construction procedures and QA/QC measures, as well as a wide variety of CL and CH soil materials. The soils ranged in liquid limit (LL) from 21 to 101, fines content varied from 48 to 99 percent, and 2 μ m clay content varied from 16 to 57 percent. Twenty-six (26) percent of the test pads and liners exceeded the maximum K_f requirement of 1×10^{-7} cm/sec.¹ A comparison of the field density and moisture content measurements obtained during construction to the line of optimums was available for 16 of the failed test pads and liners. 14 of 16 (88%) of the failing test pads and liners were compacted below the line of optimums. In comparison, 18 of 18 (100%) of test pads compacted above the line of optimums passed the field hydraulic conductivity requirements.

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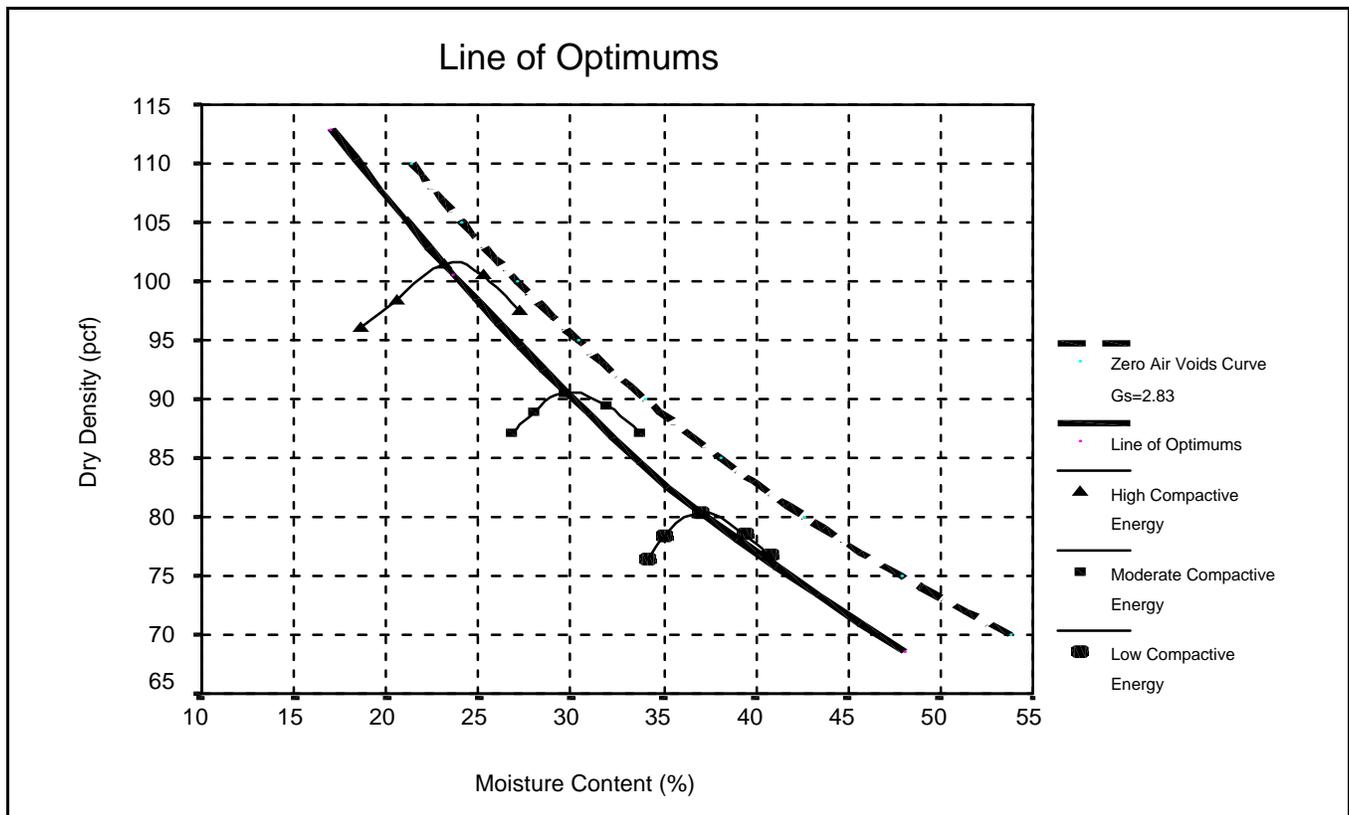


Figure 1. Line of Optimums Based on Different Levels of Compactive Energy for One Soil Sample

Compacting soils to a density and moisture that plots above the line of optimums produces a low K_F liner because the soils are wet enough to allow the macrostructures in the soils to be eliminated during compaction. This remolding eliminates clod boundaries, reduces the size of pore spaces, reduces the number of connected pore spaces and decreases the amount of air in the soil. As a result, movement of water through the recompacted soil is slowed. Conversely, compacting below the line of optimums leaves macrostructures in existence and leaves the soil with a larger number of connected pore spaces and air, resulting in a higher K_F . However, moisture content is not the sole factor affecting RSL permeability. Other factors include hydration time, lift thickness and the type of compactive energy. The test pad is used to assess the effect these factors have on the K_F .

The use of the BFLO is applicable to those soils that are inorganic, plastic, and fine grained as determined using the Universal Soil Classification System. Unsuitable soils are non-plastic (a 1/8 inch thread cannot be rolled at any water content), coarse grained (contain < 50% fines passing #200 sieve), or organic.

For existing facilities, authorization to use the BFLO is through an alteration. For new facilities, the use of the BFLO can be included in the permit-to-install application. Alterations or permit applications that propose deviations from the procedure outlined below may be subject to increased review time while the deviations are being considered.

DSIWM recommends that each BFLO be submitted to the appropriate district office for review before it is used for construction, and include the soil characterization data and a graph showing the BFLO. Any new BFLOs (e.g. developing a BFLO for outliers to the right of the approved BFLO, should also show the approved BFLO on the graph.

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1. Characterizing Soil when Using the BFLO Method.

Soils are characterized to determine if they are suitable for use in RSL construction, and to provide data for developing the BFLO. Soil characterization is also used to identify unsuitable soils so they can be segregated during borrow excavation.

The BFLO can be developed either by using (1) data that characterize all the suitable soils in the entire borrow area, or by using (2) data that characterize all the suitable soils that will be used during a construction project.

Preliminary characterization of soils needs to be completed to identify potentially suitable and unsuitable soils. When using the BFLO method, *suitable soils* are inorganic, plastic, fine grained soils as determined using the Universal Soil Classification System (USCS). The USCS defines a fine grained soil as a soil having greater than 50 percent of particles passing #200 sieve. Suitable soils will also have a lab permeability (K_L) $< 1 \times 10^{-7}$ cm/sec when compacted to a moisture and density that is on the BFLO. *Unsuitable soils*¹ fall under the USCS as non-plastic soils, coarse grained soils, or organic soils. Soils that do not have a $K_L < 1 \times 10^{-7}$ cm/sec when compacted to a moisture and density that is on the BFLO are also unsuitable. Some soils manufactured from crushed shale respond appropriately to this method. However, this has not yet been established for all crushed rock materials.

Increasing the number of proctor points increases the accuracy of the BFLO. Selecting soil samples from a wide range of potentially suitable soils (e.g. by collecting soil samples from varying depths and lateral locations in the borrow area) increases the diversity of soils represented by the BFLO. Once the specifications are defined for qualified suitable soils, procedures need to be put in place to make sure only qualified suitable soils are delivered to the phase for use in liner construction.

Below is a description of necessary testing if using the BFLO method. Other testing required by rule or authorizing documents should also be completed as required by those documents, unless changed in an approval authorizing the use of the BFLO method.

Standard and modified proctor curves. A proctor curve should be generated at a frequency of at least one per 1,500 cubic yards (cy) of soil to be used (this is the same frequency required by rule). Because proctor curves using different compactive energies are needed to establish the BFLO, modified proctor and standard proctor tests should be alternated so that there are approximately equal numbers of each proctor test. In addition, at least once for every 12,000 cy of soil to be used, both modified and standard proctor tests should be run on subsamples of the same soil. Soils from different test pits or different depths should not be composited to produce soil samples.

Specific gravity (G_s). G_s should be tested at a frequency of at least one set of tests per 1,500 cy of soil to be used. Although this is not required by rule, G_s is needed to accurately determine percent saturation, which is used for data validation when using the BFLO method. If the soils are relatively uniform, the frequency can be reduced; however, it is recommended that at a minimum, G_s should be determined from the same soil sample used for the combined modified and standard proctor tests mentioned above (i.e. every 12,000 cy).

Remolded laboratory permeability (K_L) at construction specifications. K_L should be tested at a frequency at least once per 10,000 cy of soil to be used. Construction specifications for the purposes of this document are any combination of density and moisture that results in the soil sample being compacted as near the BFLO as possible. The soil samples should not be composited. Any soil represented by a sample that has a $K_L > 1 \times 10^{-7}$ cm/sec when tested in this manner should be deemed to be unsuitable.

¹ Coarse grained soils with fines, and non-plastic fine grained soils may be used for liner construction if hydraulic conductivity less than 1×10^{-7} cm/sec is demonstrated through a test pad and other applicable rule requirements are met. However, the BFLO method may not be appropriate for coarse grained or non-plastic soils.

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Using the BFLO and Test Pads

When a BFLO is not used, the test pad establishes the construction details (equipment, number of passes) as well as refines the minimum moisture content and density. When the test pad is constructed, it is usually constructed in the 'dry corner' getting as close to the allowed minimums for moisture content and density as possible and still result in the required maximum permeability.

When a BFLO is used, the BFLO sets the minimum moisture content and density. If the test pad is constructed with the same pass/fail criteria as explained in Section 5., it is possible that the test pad could be constructed better than the recompacted soil liner, thus defeating the purpose of modeling the construction to meet the permeability requirement. DSIWM recommends instead that the test pad be constructed so that the moisture content and density of the test pad lifts plot a little below (to the left of) the BFLO. If the test pad passes, then constructing the liner with moisture content and density above the BFLO will assure that the recompacted liner permeability meets the required maximum.

If a test pad is constructed before the owner or operator decides to use a BFLO, the test pad results can still be used as a model of recompacted soil liner construction if the moisture content and density in the test pad straddle, or fall below (to the left) of the BFLO (see figure 6A). If the moisture content and density plots consistently above (to the right of) the BFLO, then the moisture content and density limits established by the BFLO may be too low to assure the required maximum permeability will be met. Thus, the BFLO should not be used (see Figure 6B).

If, at a later date, a new BFLO is developed, it will need to be compared with the BFLO approved by the test pad to verify that the two BFLOs are similar enough to conclude that the test pad is applicable to the new BFLO.

2. Data Validation

Before the soil characterization data is used to develop the BFLO, at a minimum, the following should be done to validate the data.

Validating proctor curves - All of the screening techniques below can be used to help determine if each proctor value is valid. There may be other data validations that could also be helpful for this purpose.

Using saturation to validate proctor density tests.

If G_s for a soil is known, calculate the percent saturation of the MDD/OM point (Equation 1).

$$\text{Equation 1} \quad S = \frac{M}{\frac{g_w}{g_s} - \frac{1}{G_s}}$$

Where:

M = Moisture content of the soil being tested.
 Y_w = Density of water.
 Y_s = Dry density of the soil being tested.
 G_s = Specific gravity of the soil being tested.
 S = Percent saturation.

The calculated percent saturation typically falls between 82 percent and 88 percent for a properly conducted proctor test on a fine grained soil.

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Using MDD vs Liquid Limit (LL) and OM vs LL to validate proctor tests. Another check that can be done is to plot on one graph the MDD (y-axis) vs. LL (x-axis) for both modified and standard proctor test results. The trend should be that MDD decreases as LL increases (See Figure 2). By developing a best fit line through the modified proctor test results and another best fit line through the standard proctor test results, outliers can be identified. A similar plot of the OM in percent moisture content vs LL can also be used to identify outliers (See Figure 3).

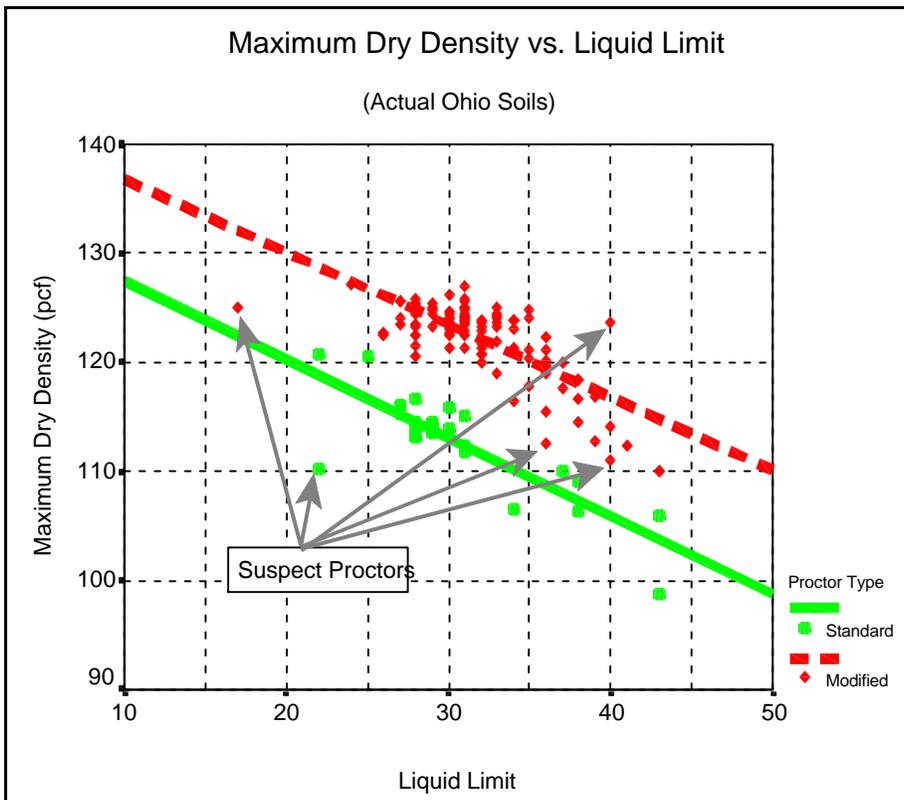


Figure 2. Plot of Maximum Dry Density vs. Liquid Limit for Actual Ohio Soils

Typically, any given outlier may exist because the proctor test was run incorrectly, the soil is very different from the others being tested, or the test was labeled as a modified proctor test when in reality it was a standard proctor test, or visa versa.

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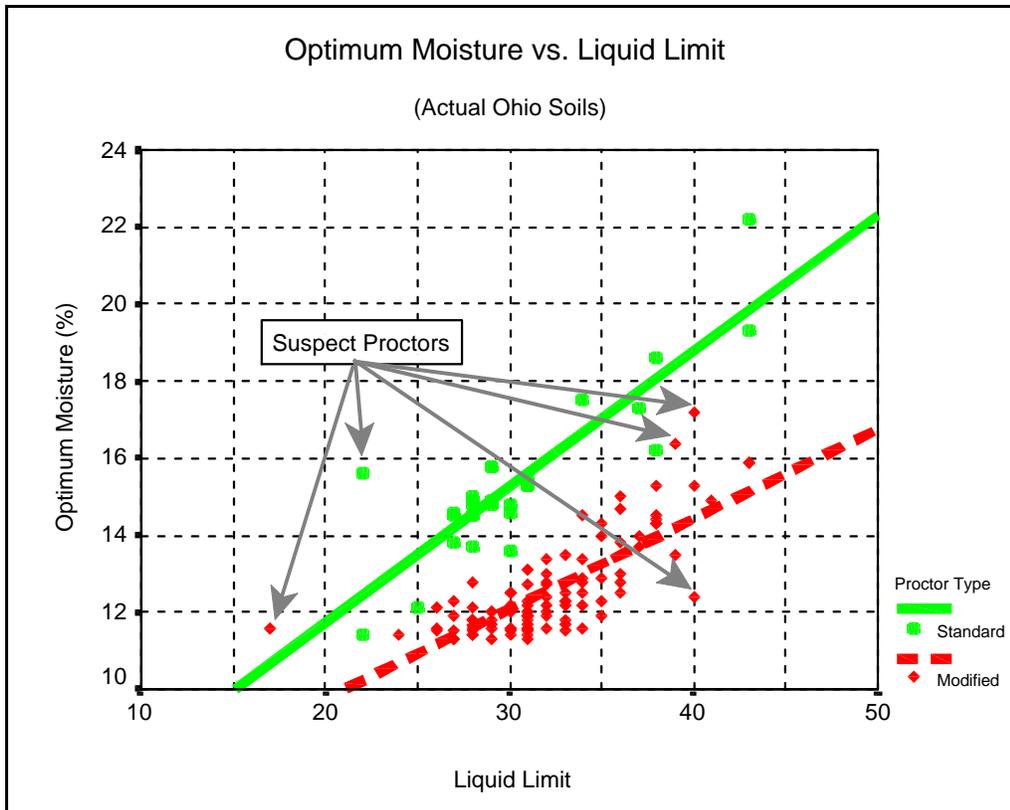


Figure 3. Plot of Optimum Moisture vs. Liquid Limit for Actual Ohio Soils

Visual inspection of curves to validate proctor tests.

By looking critically at the proctor curves, unusual curves can be identified for further evaluation. Examples of curves that may cause the MDD/OM values to be suspect are proctor plots that have two peaks, have only one point on either side of optimum moisture, plot nearly flat between adjacent dry and wet side points, or have an extremely narrow range of moisture content causing the plot to be very peaked.

Validating specific gravity (G_s) and laboratory permeability testing - The location of the zero air voids curve (100 percent saturation curve) on a graph of density vs. moisture content is dependent upon G_s . If G_s of a soil is known and if the lab permeability test was run properly, the dry unit weight and percent moisture after a lab permeability test is run, should represent 100 percent saturation for that soil.

As a result, the dry density and percent moisture of a sample of soil after the lab permeability test is completed, should plot on or near the zero air voids curve for the G_s of the soil being tested. If it does not, then either the G_s testing for the soil is suspect, or the lab permeability test is suspect.

3. Developing the BFLO to be used for RSL construction

Before the BFLO can be developed, the soil to be used needs to be characterized (see Section 1.) and the testing data need to be validated (see Section 2.). Use only validated site-specific proctor data from suitable soils when developing a BFLO.

Follow the steps below to develop the BFLO for the characterized suitable soils.

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Step 1. Plot all the validated MDD/OM points (both standard and modified proctor) obtained from suitable soils together on one proctor graph. The zero air voids curve for the maximum and minimum G_s of the suitable soils should also be plotted on this graph. The two zero air voids curves give an idea of the variability of the soils in the borrow area. It is expected that the MDD/OM points will plot in a cluster that will follow the general trend of the zero air voids curve (See Figure 4).

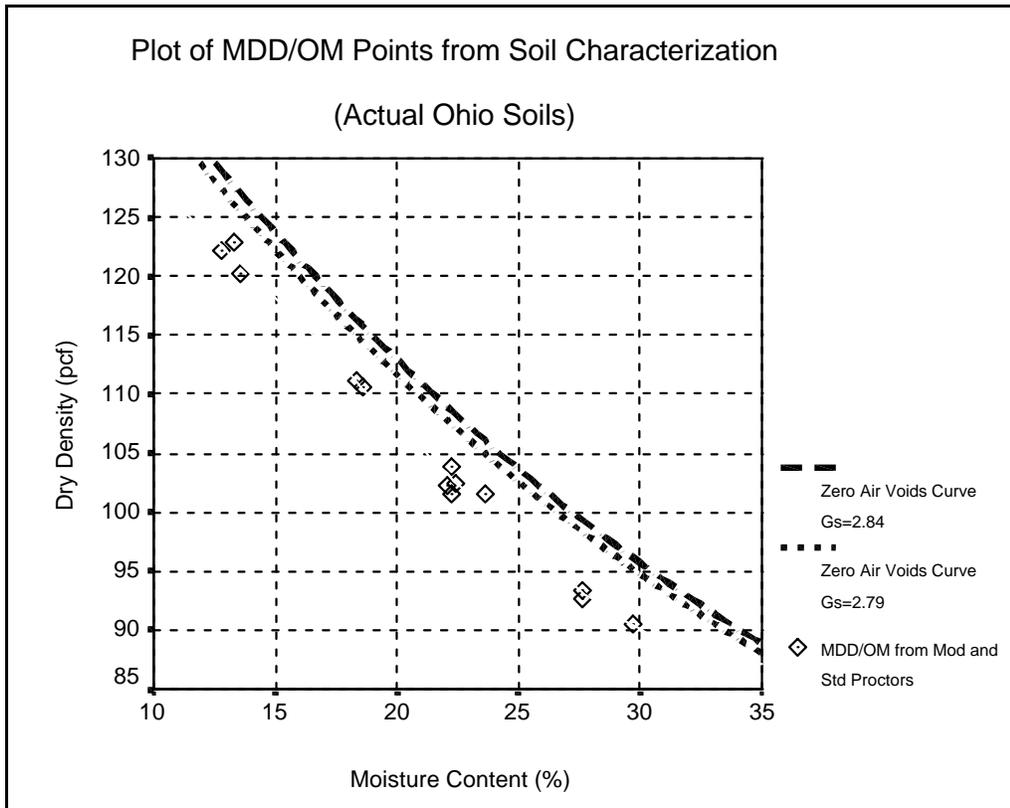


Figure 4. Plot of MDD/OM Points from Modified and Standard Proctor Tests for Soils from the Same Borrow Area

Step 2. Once the validated MDD/OM points are plotted, a BFLO can be developed using quadratic regression analysis. This will calculate the best fit curve for the data. The regression analysis will also produce a formula that defines the BFLO. A plot of a BFLO for actual data from a site in Ohio is shown in Figure 5.

Step 3. Once the points are plotted outliers can be identified if they exist. Outliers are defined as MDD/OM points that plot more than one (1) percentage point of moisture content (parallel to the x-axis) in either direction away from the BFLO (see Figure 5). In most cases it is expected that less than 10 percent of the MDD/OM points that are plotted on the graph will be outliers. Any suitable soils that have a validated MDD/OM point that falls within ± 1 percentage point of moisture content from the BFLO can be considered soils of similar soil material properties for the purposes of construction. Soils exhibiting a significant change in soil material properties are represented by MDD/OM points that are more than ± 1 percentage point of moisture content away from the BFLO, and the BFLO developed does not apply.

The high moisture content end of the BFLO will be limited by the shear strength that is needed for the RSL to provide for a stable facility. Soils to be used for RSL should be tested at a variety of moisture contents for internal and interface shear strength to determine the maximum water content that can be used during

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compaction and still have the composite liner system exceed the minimum factor of safety required in the authorizing documents.

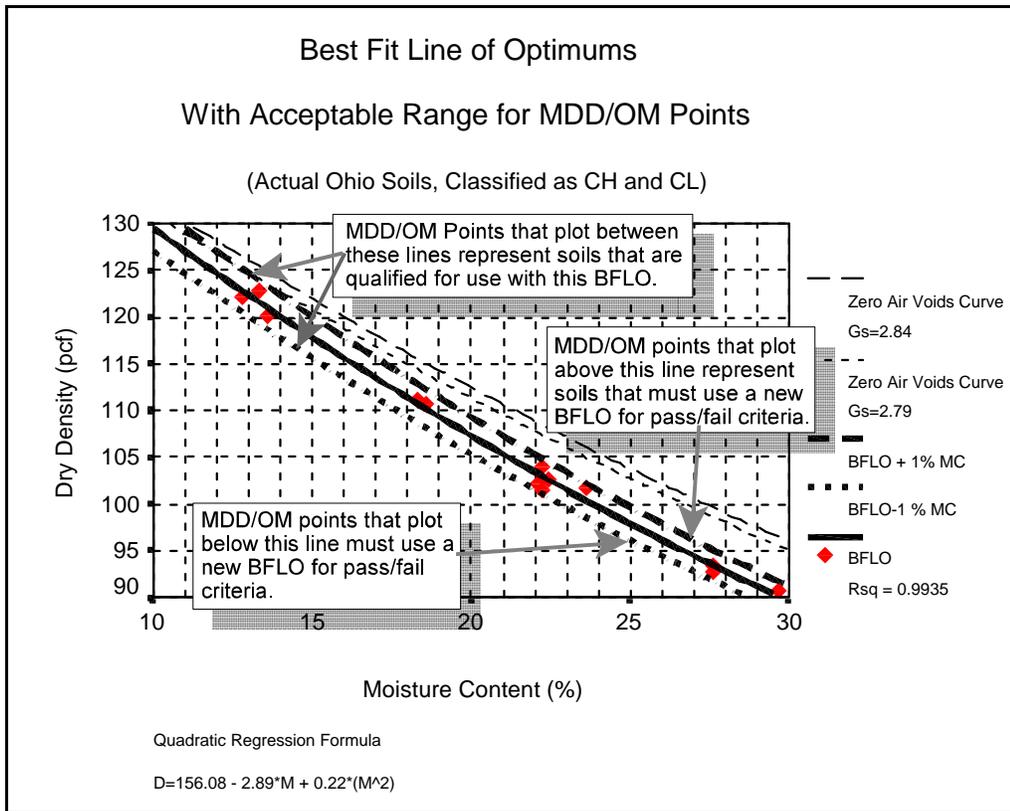


Figure 5. BFLO Showing Acceptable Ranges for MDD/OM Points of Soils Proposed for Use in Construction of RSL

Step 4. Express the BFLO as an equation, as depicted at the bottom of Figure 5.

4. Using Best Fit Line of Optimums to Qualify Soils During Construction.

Once the soil testing has been validated (see Section 2.) and the BFLO developed (see Section 3.), it is important to continuously evaluate the MDD/OM points for any newly characterized soils to make sure the approved BFLO is applicable. Discussed below are four possible outcomes (Figures 6A to 6D) when comparing an MDD/OM point to the BFLO (See Figure 5).

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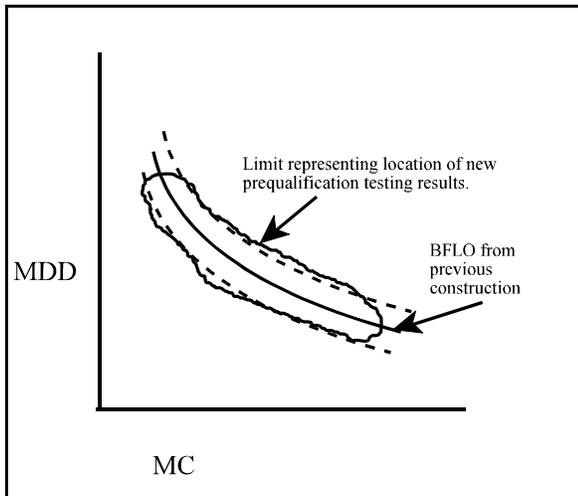


Figure 6A. New Data Points Compared with the BFLO from Previous Construction. This distribution of new data points indicates BFLO from previous construction is appropriate to use with soils represented by MDD/OM points > 1% moisture content from the BFLO being excluded.

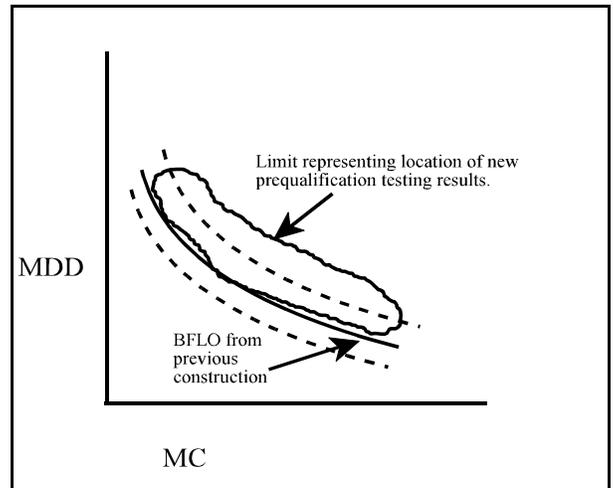


Figure 6B. New Data Points Compared with the BFLO from Previous Construction. Because the BFLO represents the average of the MDD/OM points, this shift in the distribution of new data points indicates the OM of the population has shifted. Compaction using the BFLO would result in compaction that is too dry. A new BFLO is needed.

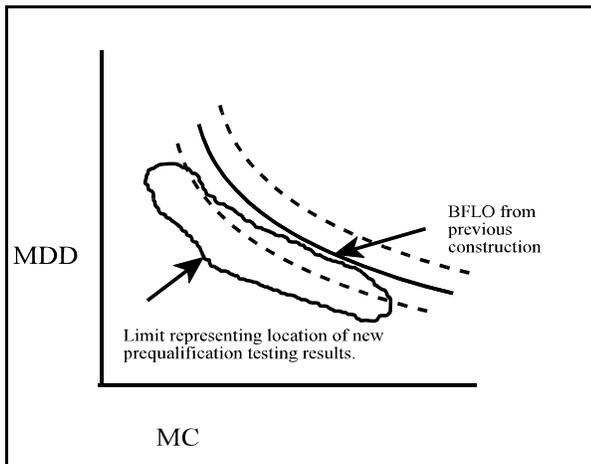


Figure 6C. New Data Points Compared with the BFLO from Previous Construction. This shift in the distribution of new data points indicates a new BFLO would probably be easier to use for construction, but the owner could elect to try and use the BFLO from previous construction. However, due to increased moisture needed to pass, construction may be difficult and the shear strength of the RSL may be weaker than required. Note: This shift may take the BFLO for the new data below the density and moisture contents recorded during construction of the test pad. If that happens, and because the moisture content requirement is decreasing, a new test pad would be required.

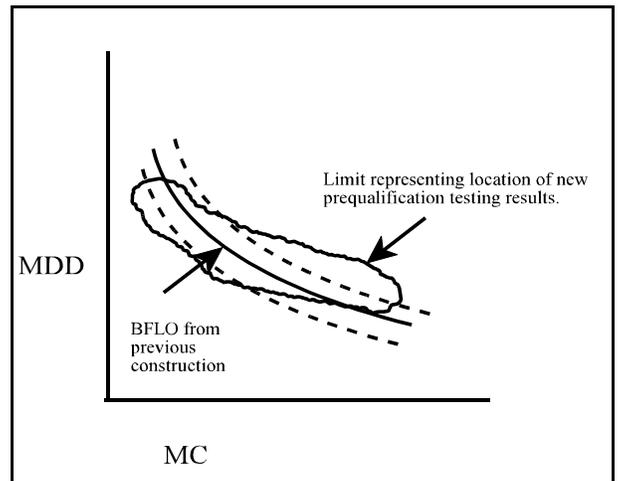


Figure 6D. New Data Points Compared with the BFLO from Previous Construction. The new data could also start from above the line and cross below it. This pattern has been observed with manufactured soils (crushed siltstone, mudstone, etc.). This shift in the distribution of new data points indicates there may be something wrong with the proctor data results. If the data were validated properly, and samples were collected and tested in the suggested alternating pattern of a modified, then a standard proctor through the borrow area, then a new BFLO would be indicated.

Use of BFLO for Recompact Soil Liner Construction

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