CRITICAL UNSATURATED SOIL PROPERTIES FOR SOIL COVERS[1]

R. B. Valceschini, and S.A. Morrow.[2]

Abstract. Monolithic soil covers are becoming more widely accepted as viable alternatives to standard resistive barriers for covers at mining facilities in arid and semi-arid regions. Design procedures and available models have been documented as have the results of monitoring data from soil covers that have been in operation for a number of years. The primary soil response associated with the design and performance of a soil cover is the Soil Water Characteristic Curve (SWCC). The SWCC test is a relatively expensive and time consuming test to perform. The next logical step in advancing the state-of-practice of soil covers from the conceptual stage to implementation on a routine basis is to develop a detailed understanding of the unsaturated soil properties, specifically the aspects of the SWCC that are critical to the performance of a soil cover; i.e. air entry pressure, storage function etc. Ideally, these properties can be reliably correlated to simple index tests; grain-size-distribution and Atterberg limits, in-place density in such a manner that a few SWCC tests can be performed for a site and the index tests used to delineate acceptable soils. The results can also be used to develop construction quality assurance and construction quality control (CQA/CQC) procedures.

This paper presents the results of a parametric modeling study performed on typical cover soils. Variations in SWCC properties are utilized in the model and their impact on cover performance assessed. Changes to the SWCC as a result of changes in index properties are estimated based on trends published in the literature. Conclusions are drawn with respect to correlating index properties, cover performance and SWCC results.

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Introduction

Alternative soil covers (soil covers) are being proposed more frequently as cover systems over mine waste components. Regulatory acceptance of alternative covers is also increasing. This increased popularity is based, in the writers' opinion, on several factors including:

- Advances in computer technology which allow sophisticated unsaturated flow computer models to be efficiently ran from personal computers,
- Numerous instrumented covers have been constructed and sufficient time has elapsed for data to be analyzed and performance evaluated,
- The US Environmental Protection Agency's (USEPA) Alternative Cover Assessment Project (ACAP) success in installing lysimeters in numerous different climates across the United States, and,
- Industry professionals have done an effective job of communicating with and educating the regulatory community.

General Concepts of CQA/CQC

The intent of a construction quality assurance/construction quality control (CQA/CQC) program is to provide a means of verifying, with some degree of certainty, that during construction the soil parameters utilized in arriving at the final design are achieved in the field in such a manner that the intent of the design is met or exceeded. The activities performed while implementing a CQA/CQC plan are developed around the projects material and performance specifications. The material specifications delineate soils that are acceptable for use in the project and the performance specifications delineate acceptable procedures and conditions for placing and compacting the soil. Conditions attached to the permit may also specify CQA/CQC requirements on a project specific basis.

Typically, the exact soil property of concern cannot be measured efficiently in the field or laboratory during construction. For example, in engineered fills beneath buildings, compressibility of the fill is a concern. During construction, however, the in-place dry density is measured, not the soil's compressibility. The reason for this is that consolidation tests to measure the soil's compressibility are time consuming and expensive. Construction would be unreasonably delayed and costs would be considerably higher if the contractor had to wait for consolidation test results before the next lift of fill could be placed. The same can be said for shear strength during embankment construction.

The confidence that allows for dry density to be used as the primary means for controlling fill placement during implementation of a CQA/CQC plan has its basis in the design phase for the project. During design level laboratory testing, index testing (grain-size-distribution and Atterberg limits) is performed on numerous samples. The results of the index tests are reviewed and the site soils grouped based on their suitability for their intended use and similar index properties. The more sophisticated tests, consolidation and shear strength, are then performed on a limited number of soils. At a minimum the more conservative (worst case) soils are tested. In order to have confidence that the worst case soils were selected for additional testing, the engineer needs to have a thorough understanding of how variations in index properties impact the critical soil properties and more importantly, the overall performance of the design.

In terms of the CQA/CQC plan, the plan is prepared to support the material and performance aspects of the specifications. Material specifications are typically developed based on the results of index testing, the results of the more sophisticated laboratory testing and design analysis. Typically, acceptable bandwidths for grain-size-distribution and plasticity are specified. Again, this requires detailed knowledge of the impact of variations in index properties on performance. Performance specifications typically involve minimum compaction criteria, bandwidth of moisture content during compaction and oftentimes the type of compaction equipment. Over the years enough engineered fills have been constructed, tested for in-place dry density and documented that there is a high degree of confidence that for a soil of known index properties, compacted to a certain minimum relative density, within a certain moisture content range, the fill's performance can be reasonably well predicted.

In waste containment, traditional soil CQA/CQC evolved around compacted low hydraulic conductivity soil liners (LHCSL). The primary property of a LHCSL is the saturated hydraulic conductivity of the in-place liner. Considerable research and intensive field testing during construction of test pads and production LHCSLs was performed during the early years of their implementation. The result of that effort is an existing comfort level for experienced engineers as to what material properties have a significant effect on a in-place soil liner's hydraulic conductivity and overall performance of the liner system. For example, the following are generally accepted trends for LHCSL performance:

- The moisture content at compaction is critical for remolding clods and minimizing soil liner macro-permeability affects. Generally, the wetter the soil at compaction (to a point) the better for hydraulic conductivity. Shear strength (stability) and desiccation can be criteria for limiting the upper bound moisture content at compaction,
- The denser the soil the better for both limiting hydraulic conductivity and providing adequate shear strength,
- Generally, finer grained soil limits hydraulic conductivity but reduces the shear strength. Therefore, hydraulic conductivity generally governs the coarse side of the grain-size-distribution specification band and shear strength generally governs the fine side of the grain-size-distribution specification band.
- With respect to the soils plasticity, the more plastic the soil the better it is from a hydraulic conductivity stand point and the worse it is from a shear strength and desiccation stand-point. Therefore, hydraulic conductivity generally dictates the lower plasticity specification and shear strength and desiccation generally dictate the upper plasticity specification.

This detailed understanding has developed over a number of years and has resulted in standard specifications for LHCSLs that consist of requirements for:

- Grain-size-distribution as an acceptable band width,
- Minimum Atterberg limits, if desiccation or shear strength are critical, an upper limit will usually then be specified,
- Minimum compaction limits,
- Moisture content during compaction, usually as a defined range above and below the soil's optimum moisture content. There is also typically a requirement that the moisture content be uniformly distributed throughout the soil,
- Maximum lift thickness, is often a regulatory requirement,
- Appropriate compaction equipment, (typically a sheep's foot compactor with fully penetrating pads).
- Maximum saturated hydraulic conductivity.

CQA/CQC Concepts for Alternative Soil Covers

The primary parameter for alternative soil covers is the soil water characteristics curve (SWCC), Figure 1. It can be considered analogous to the saturated hydraulic conductivity for LHCSLs. The same concepts presented above for LHCSL will most likely have to be applied to soil covers. However, the SWCC test is extremely time consuming to perform. Additionally, Zapata et. al. (2000) indicate that there can be significant variability in the laboratory determination of the SWCC. The present variability, coupled with the long time to perform the test, makes the SWCC test an unlikely candidate as a CQA/CQC test at this time. The unsaturated hydraulic conductivity is another primary soil property controlling water movement in a soil cover. Laboratory testing to determine the unsaturated hydraulic conductivity is even more costly and time consuming than SWCC testing. Typically, the SWCC is used to estimate the unsaturated hydraulic conductivity as a function of unsaturated moisture content. Developing a CQA/CQC plan will naturally focus on the proposed cover soils laboratory characterization results and soil input parameters used in the modeling that was instrumental in arriving at the final design. Therefore, it will be advantageous to understand the effect of variations in grain-size-distribution, Atterberg limits, in-place density and moisture content during compaction on the SWCC and in turn what affect the variations will have on a cover's performance.

Parameters that describe the SWCC are the saturated moisture content, the residual moisture content and the air entry pressure (AEP). Moisture contents are typically reported as volumetric moisture contents, which is calculated as the volume of water to the total volume of soil. The AEP is actually the suction at which the soil begins to desaturate during soil drying. Also of interest is the slope of the curve between the AEP and the residual moisture content. Together with the saturated hydraulic conductivity, the The effect of soil index properties such as grain-size-distribution and Atterberg limits (plasticity) as well as soil density on the SWCC are beginning to be understood. However, what is of particular interest is what deviations from the "design" material can be tolerated without impacting cover performance. Currently these relationships are not as well understood. This paper begins to investigate these relationships to assist in developing a CQA/CQC plan for alternative soil cover construction.

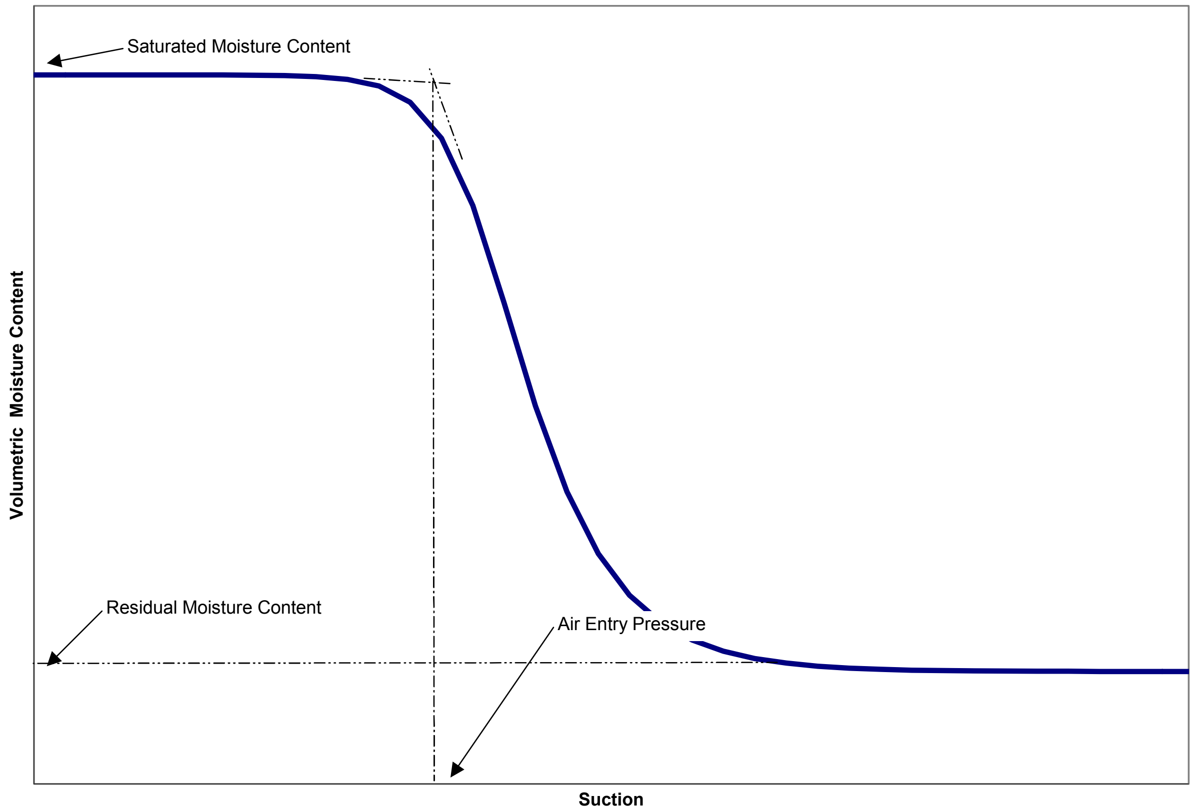

Figure 1. Typical Soil Water Characteristics Curve

Work to Date

Numerous studies have been performed with respect to soil cover performance. Most of these studies, however, were performed for a specific site utilizing a specific soil and performance type construction criteria. Therefore, there was not an extensive amount of laboratory index testing performed on the soils and very little in-place testing was performed. The exception to this is the work performed in the ACAP project. ACAP data is currently being reviewed by the writers.

Tinjum, et al., (1998) and Miller (2002) performed studies relating the impact of compactive effort, moisture content at compaction and plasticity index for compacted clays. These studies provide very useful information, however, clayey soils are not typically used for alternative soil covers. Soils more typically used for alternative soil covers are silty to clayey well graded sands with gravel.

Grain-Size-Distribution

Zapata et al., (2000) provides very useful information with respect to variations to the SWCC measured in the laboratory as well as providing an estimation technique based on the soil's Atterberg limits or the soil's D_{60} if non-plastic (Figure 2). A soil's D_{60} is the particle size of the soil for which 60-percent of the soil is finer by dry weight.

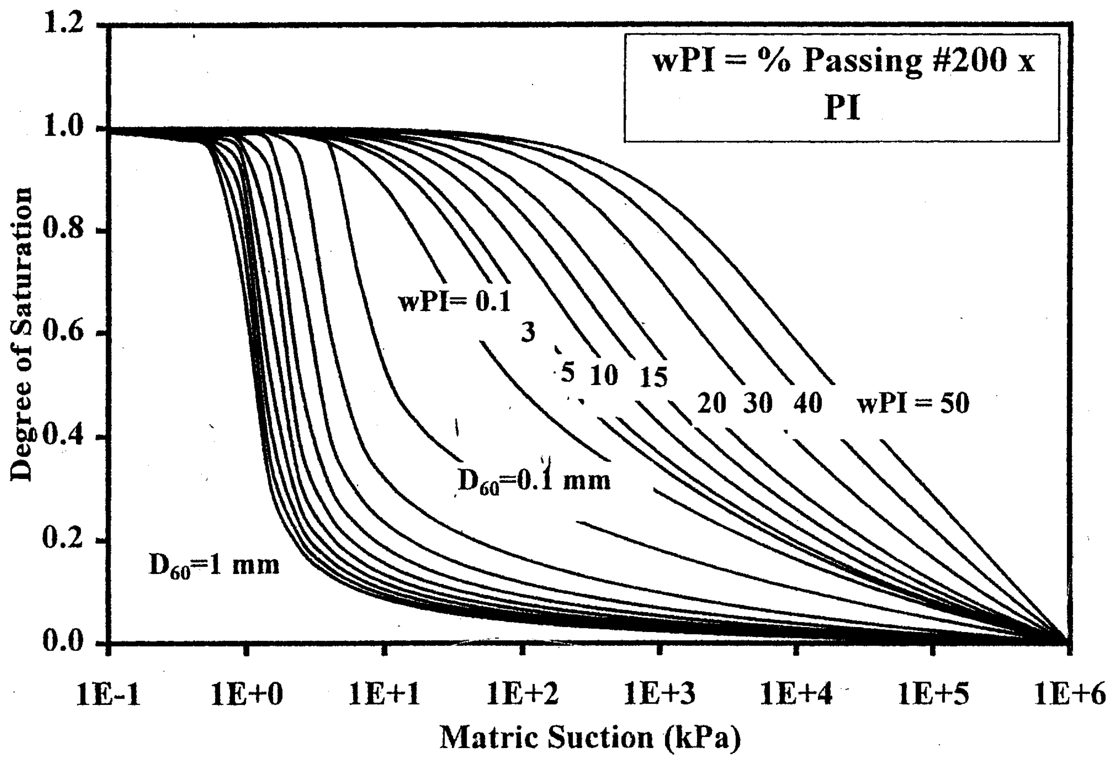

Figure 2. Predicted SWCC based on D_{60} and wPI, Zapata et al., (2000)

Newman et al., (1997) classified soils during a mine waste rock study based on the percentage of the soil passing the No. 4 sieve size. Figures 3 and 4 present the results of the grain-size-distribution and SWCC results from this study.

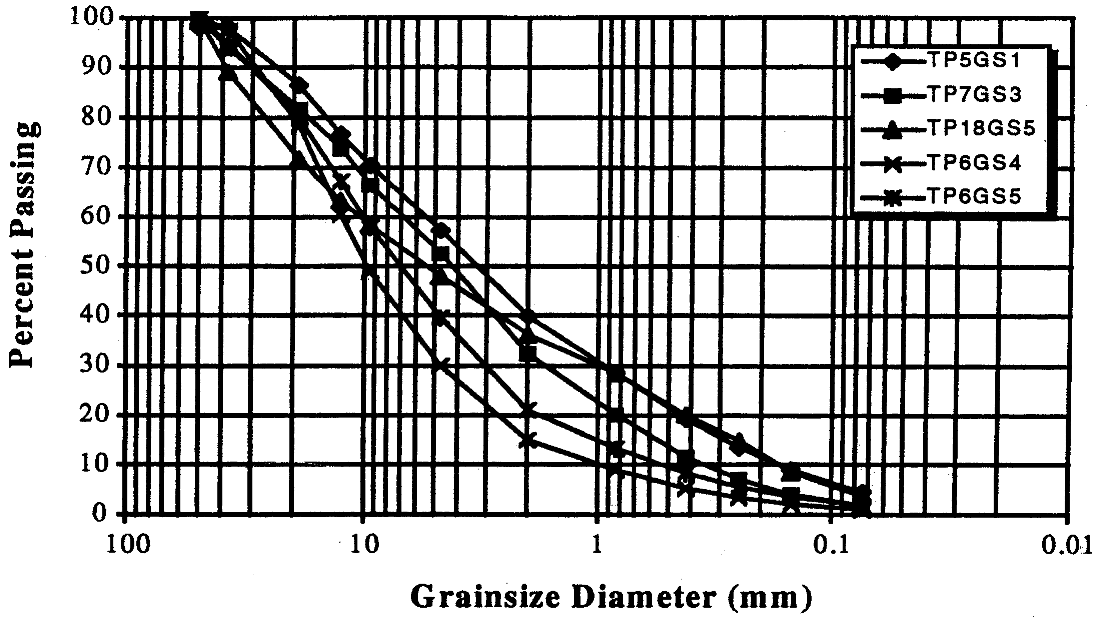

Figure 3. Grain-Size-Distribution curves for samples from Newman et al. (1997).

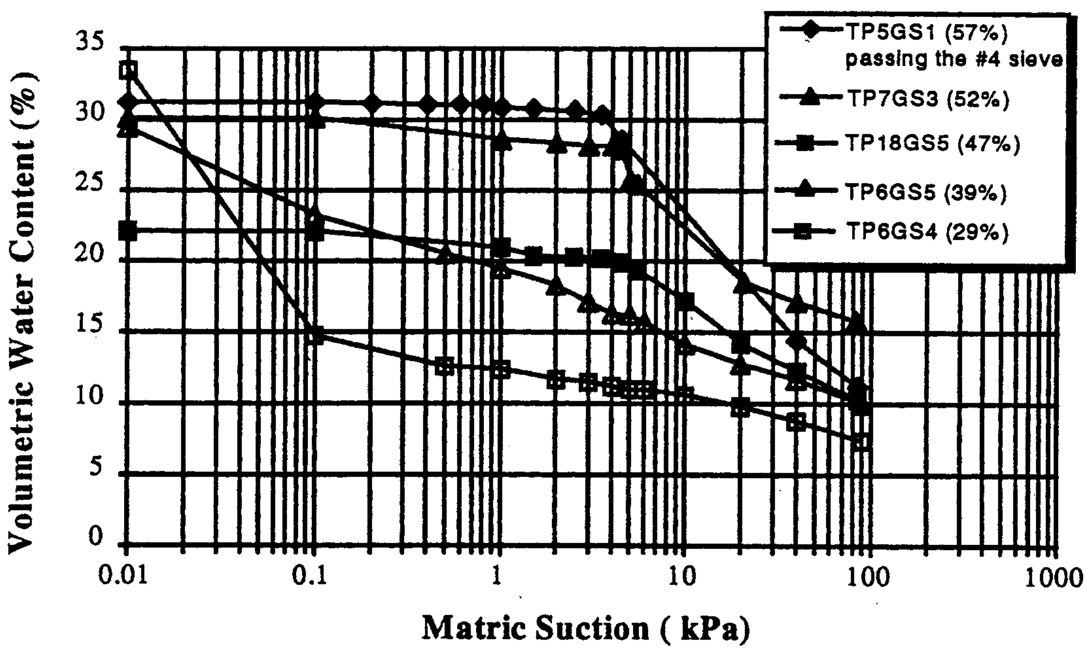

Figure 4. SWCC for soils in figure 3, Newman et al. (1997).

Their results indicate a change in material behavior between soils that had greater than or less than 40-percent passing the No. 4 sieve. Soils that had greater than 40-percent passing the No. 4

sieve were capable of retaining water under negative pressures before they drained, that is they exhibited relatively more water storage capacity. The two soils with less than 40-percent passing the No, 4 sieve exhibited little water storage capacity. The difference in water storage capacity between the two classifications is demonstrated by the AEP, approximately 5 kPa versus 0.1 kPa and the slopes of the curves at suctions greater than the AEP.

Yazdani et al., advanced a theoretical framework to estimate the AEP based in particle size and packing. The results of the study indicated the following

- Particles greater than the No. 4 sieve size exhibit little capilarity.
- Particles greater than the No. 4 sieve size had approximately the same AEP, very small.
- For particles smaller than the No. 10 sieve size, the AEP is significantly affected by both particle size and packing.

This also implies that for soils with significant amounts of material passing the No. 10 and possibly even the No. 4 sieve, the density of the soil will have an affect on the AEP. For soils without significant amounts of material passing the No. 4 sieve, the AEP will be independent of the soils density. Figures 5 and 6 present grain-size-distribution curves and laboratory SWCC's from Yazdani et al.

It can be seen that increasing the coarse fraction of the soil changed the saturated volumetric moisture content (porosity), the slope of the SWCC between the AEP and residual moisture content and the storage capacity of the soil. This indicates that as the coarse fraction increases in a soil, the water storage capacity of the soil decreases making it less effective as an alternative soil cover material. These results are generally consistent with Newman (1997).

<u>Atterberg Limits</u>

Detailed review of data presented in Tinjum et al., (2000), Zapata et al., (2000) and Miller et al., (2002) indicates the following trends (Figure 7):

- There is an increase in AEP with increasing plastic index however, it does not appear to be dramatic.
- The slope of the SWCC between the AEP and residual moisture content increases with increasing plastic index, and;

The actual relationships between soils are very dependant on the saturated volumetric moisture content (porosity).

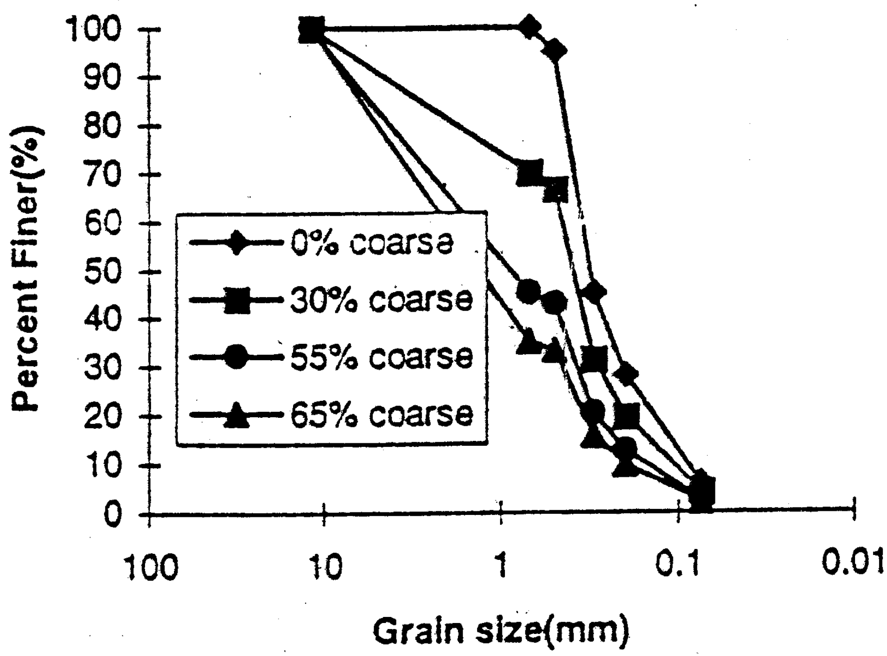

Figure 5. Grain-Size-Distribution of soils tested for SWCC by Yazdani, et al. Coarse is defined as particles retained on the No. 4 sieve.

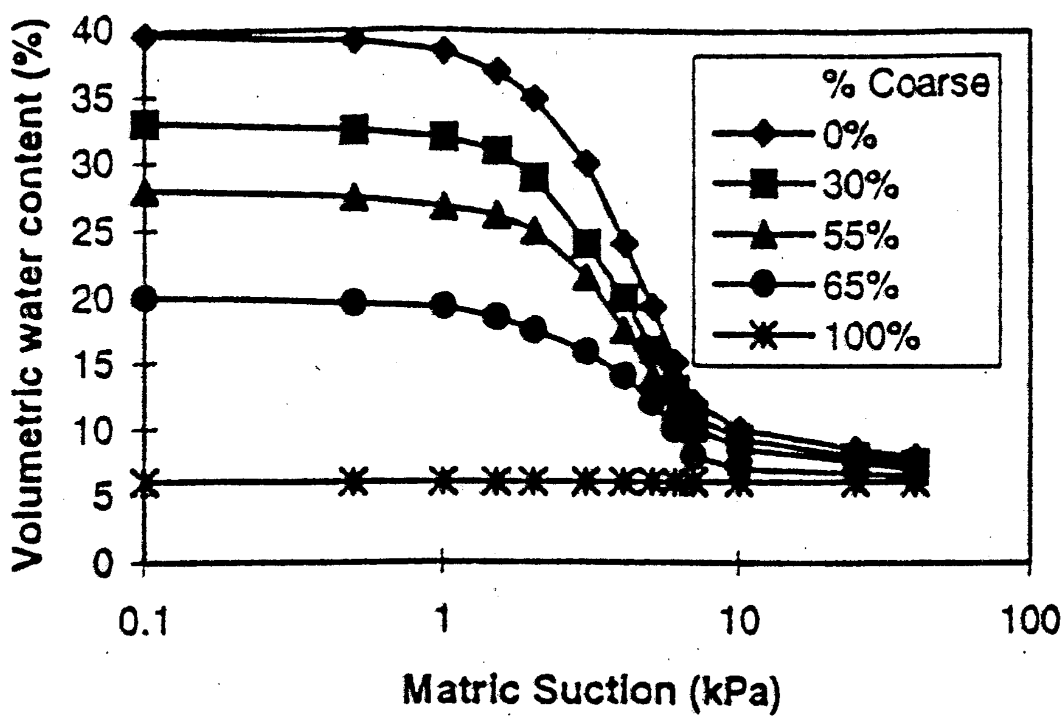

Figure 6. SWCC results for soils in Figure 5, Yazdani, et al.

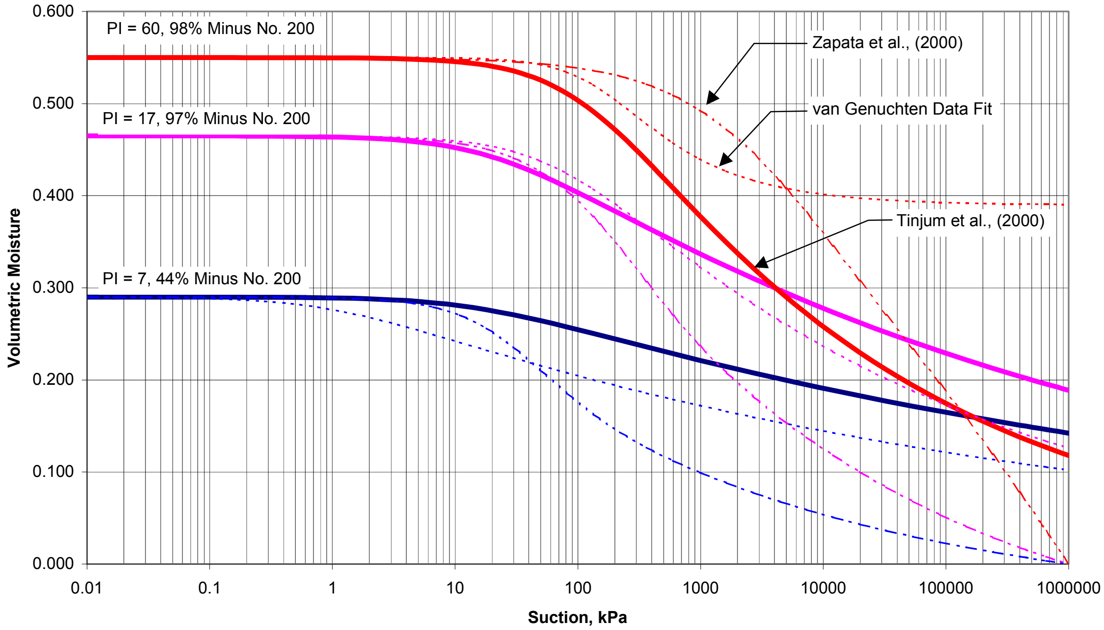

Figure 7. Effect of Plasticity on SWCC for three soils. Soil data from Miller et al., (2002) Standard Compaction Effort, Plus 2-percent Moisture. Calculations after Zapata et al., (2000) and Tinjum et al., (2000).

At lower suctions it appears that with increasing plastic index, the higher the volumetric moisture content at the same soil suction, Miller et at., (2002), Tinjum et al., (1997) and Zapata et al., (2000). However, observation of Figure 7 indicates that at higher suctions the relationships are more complicated when initial porosity and percent passing the No. 200 sieve are taken into account. Figure 2 presents Zapata et al's. (2000) estimation of SWCC variation with plasticity which are presented as a function of the amount passing the No. 200 sieve multiplied by the plastic index.

It should be noted that Miller et al., (2002) interpreted their data for relatively low suctions, less than 1,400 kPa. Cover soils in arid regions can reach suctions over an order of magnitude greater. Detailed review of their data indicates that some of the trends actually reverse at higher suctions.

It is seen that the impact of plasticity for fine-grained soils is complex, however, it appears that the saturated hydraulic conductivity dominates the performance of theses soils making the SWCC relationships more a curiosity than a critical parameter.

Compaction

In general, increasing compaction decreases the porosity which decreases the saturated volumetric moisture content. Other trends that are reasonably consistent based on a review of the literature are:

- An increase in AEP with increase in density, and;
- An increase in the slope of the SWCC between the AEP and residual moisture content with decreasing density.

Typical results are presented in Figure 8.

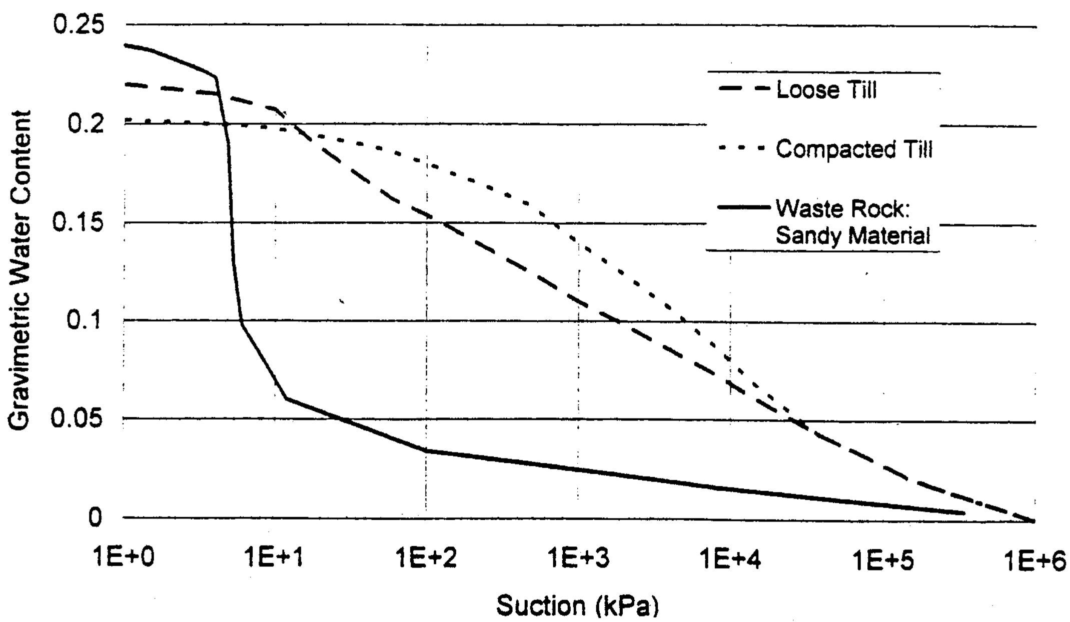

Figure 8. Typical effect of compaction in SWCC curves. From Wilson et al., (1995).

Moisture Content at Compaction

Miller et al., (2002) stated that variations on moisture content at compaction for fine grained soils resulted in "…insignificant and unsystematic changes…" in the SWCC curve for moisture content variations of plus and minus two-percent of the soil's optimum moisture content.

Tinjum et al., (2000) however indicate that variations in moisture content at compaction for fine grained soils results in smaller pore sizes and therefore a higher AEP and generally higher suctions at the same moisture content. The slope of the SWCC between the AEP and the residual moisture content was steeper for soils compacted with increasing moisture content.

Parametric Study

A parametric modeling study was performed to investigate the impact that reasonably expected variations in SWCC and related properties might have on cover performance. The SoilCover Version 5, 2000 was used to model the various scenarios. The study was performed using laboratory soil properties from Zapata et al., (2000) as a basis for initial SWCCs. The index properties for the soils used in the parametric study are presented in the Table 1.

Table 1. Index properties of soils used in parametric study (Zapata et al., 2000).

Property	El Paso Sand	Price Club Silt	Fountain Hills Clay
Grain-Size-Distribution			
Percent Sand	92	46	6
Percent Silt[1]	7	48	35
Percent Clay[1]	1	6	59
Atterber Limits			
Liquid Limit	Non Plastic	22	70
Plastic Index	---	4	41
USCS Classification	SP	ML	CH

1 There were no particle size criteria given in the reference. The information is included to provide relative comparisons of materials.

The SWCC's used in the study were obtained from the Best-Estimate figures in Zapata et al. (2000). Systematic adjustments in accordance with the discussions presented above were made to the best-fit curves to account for what would be reasonable variations in material properties and in-place density during construction. The scenarios modeled are presented in Table 2.

Table 2. Modeled scenarios.

Soil	Scenario	-----------Soil Property-----------	
		Ksat, cm/sec	Porosity
El Paso Sand	Scenario 1 – Best Fit	1.0×10^{-4}	0.47
	Scenario 2 – Coarser Material	1.0×10^{-4}	0.42
	Scenario 3 – Lower Compaction	5.0×10^{-4}	0.53
Price Club Silt	Scenario 1 – Best Fit	1.0×10^{-5}	0.47
	Scenario 2 – Finer Material	1.0×10^{-5}	0.52
	Scenario 3 – Lower Compaction	1.0×10^{-4}	0.52
Fountain Hills Clay	Scenario 1 – Best Fit	1.0×10^{-6}	0.59
	Scenario 2 – Lower Compaction	5.0×10^{-6}	0.63

The SWCC's for each soil are presented in Figures 9, 10 and 11 for El Paso Sand, Price Club Silt and Fountain Hills Clay respectively.

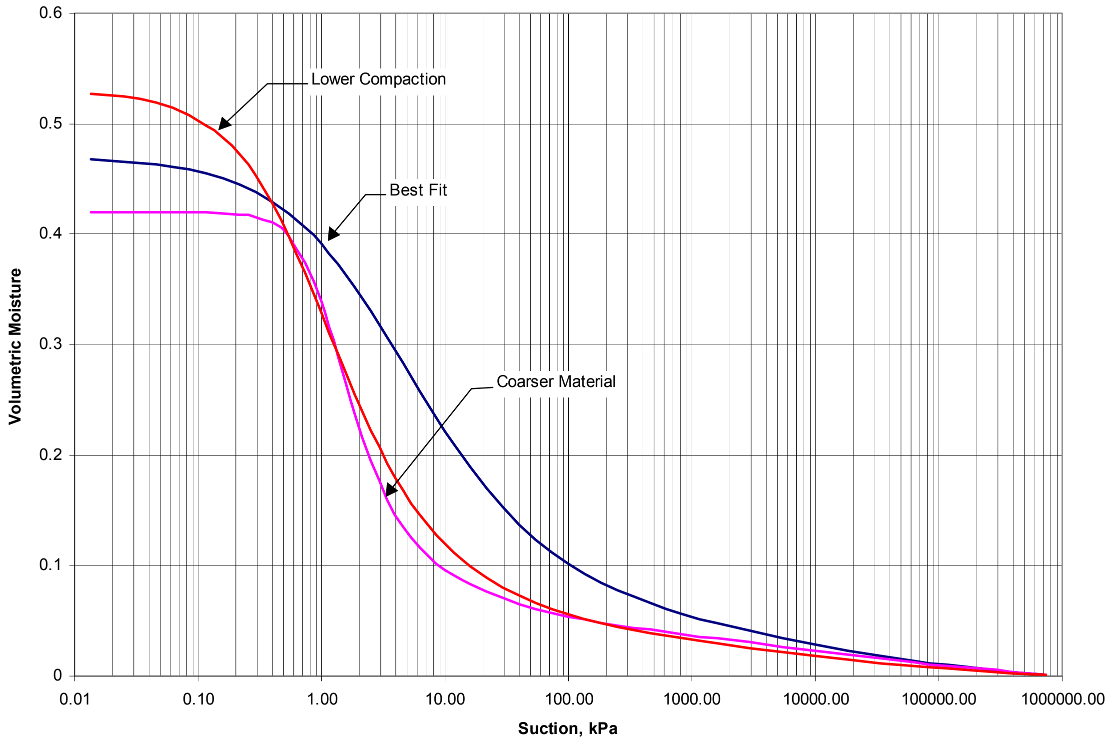

Figure 9. El Paso Sand SWCCs used in parametric study.

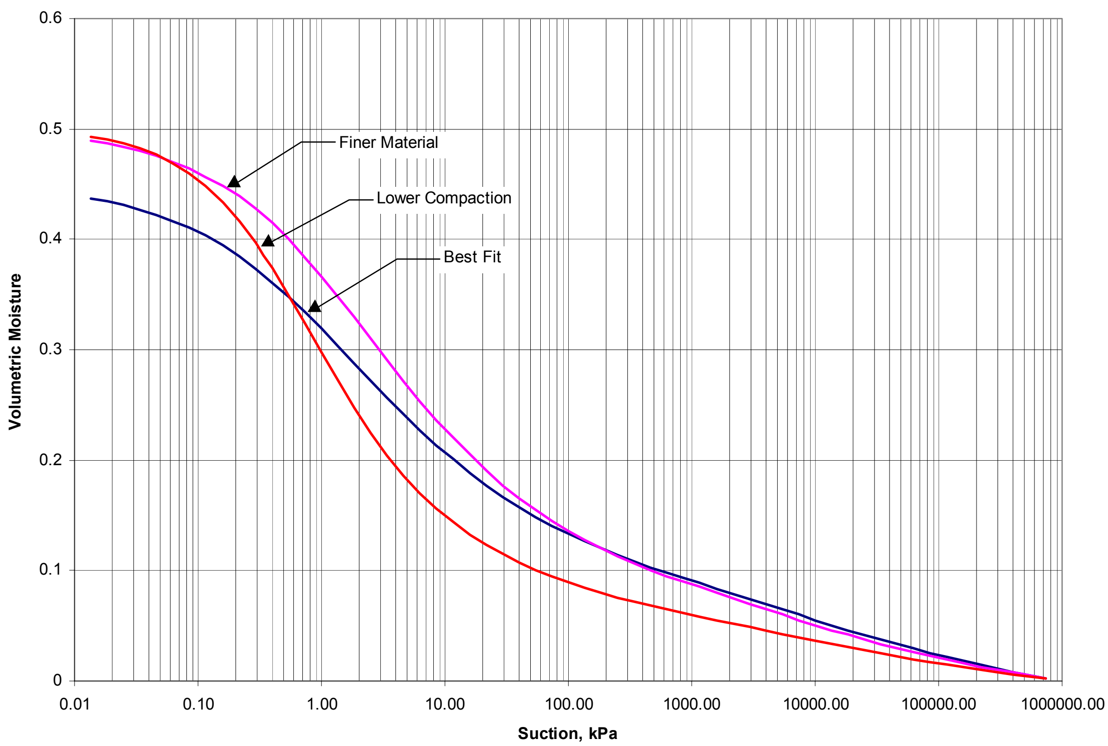

Figure 10. Price Club Silt SWCCs used in parametric study.

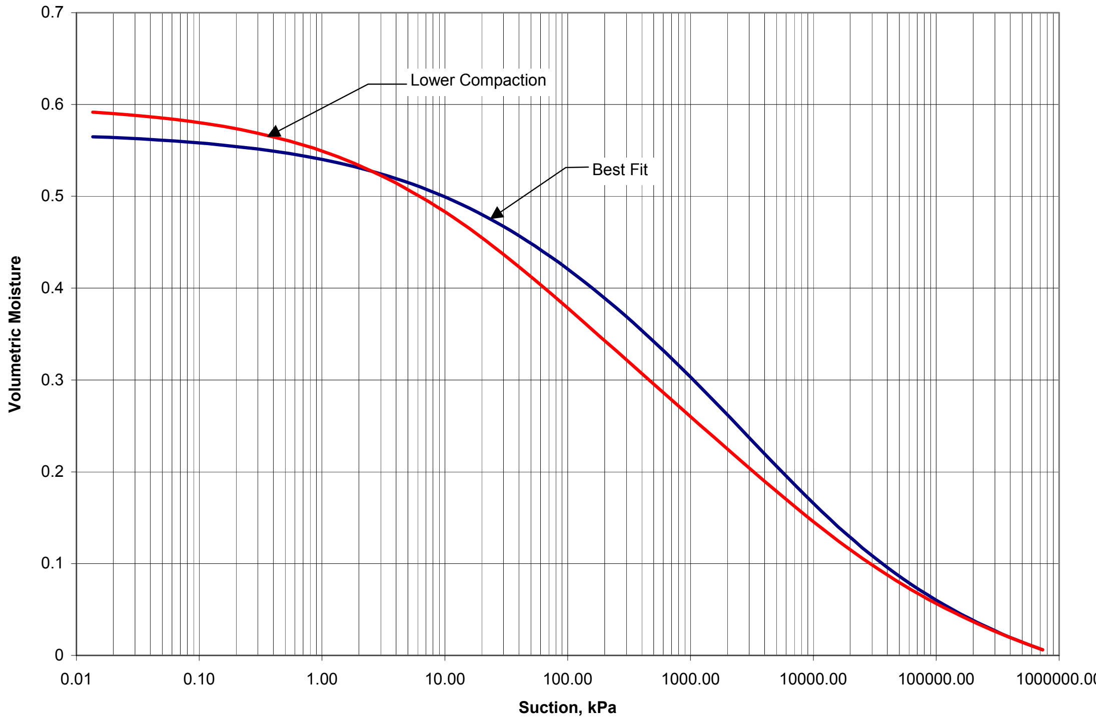

Figure 11. Fountain Hills Clay SWCCs used in parametric study.

All scenarios considered a 3-feet thick cover, no vegetation and no snowmelt. The precipitation pattern used is presented in Figure 12.

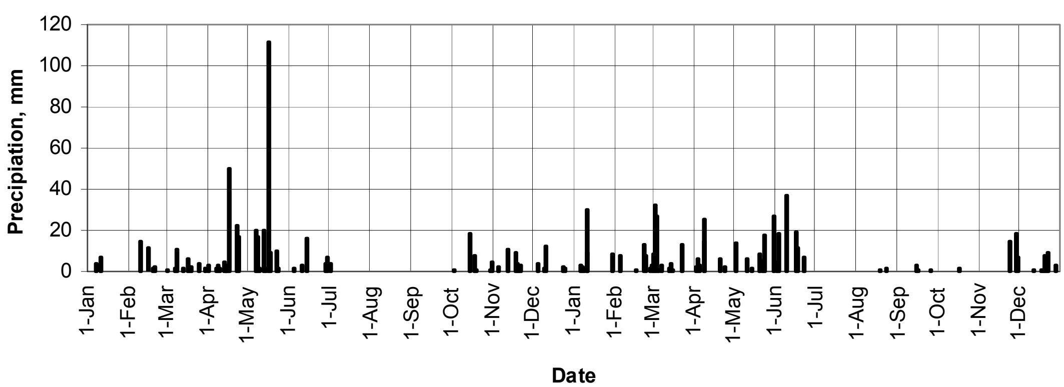

Figure 12. Precipitation pattern used in parametric study.

The total precipitation used in the study, 495 mm (19.5 inches) in the first year and 497 mm (19.6 inches) in the second year are approximately twice that of a typical semi-arid climate and were used to stress the covers in order to magnify the differences between scenarios. The precipitation pattern used is typical of a semi-arid climate.

Results and Conclusions

The results of the parametric study are presented in Figures 13 through 18 which present cumulative flux (water flow across a unit area) at the bottom of the cover and the change in water storage in the cover with time. Also presented in the cumulative flux plots is the precipitation so that the impact of major precipitation events on cover performance can be easily determined.

With respect to the cumulative flux plots, it should be noted that a positive slope indicates upward flow and a negative flux indicates downward flow across the bottom of the cover. It should be noted that in interpreting the flux plots, even though there may be a net cumulative upward flux, any downward flux component should be considered as having broken through the cover and will enter the waste.

El Paso Sand

The results of the El Paso Sand parametric study are presented in Figures 13 and 14. The best fit soil has a slight downward flux component for approximately 1 ½ years. Both the coarser and lower compaction soils had a larger downward flux but responded quicker to evaporation and achieved a net upward flux in approximately one year. All of the soils exhibit a delayed flux response at the bottom of the cover from the time of major precipitation events.

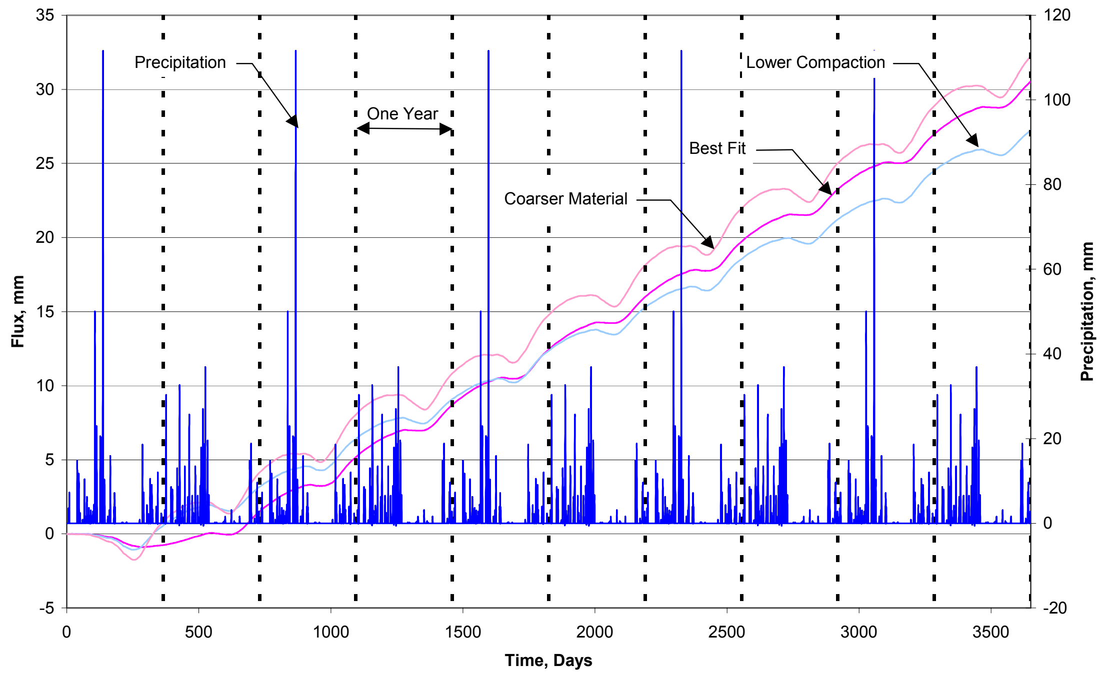

Figure 13. El Paso Sand cumulative flux and precipitation.

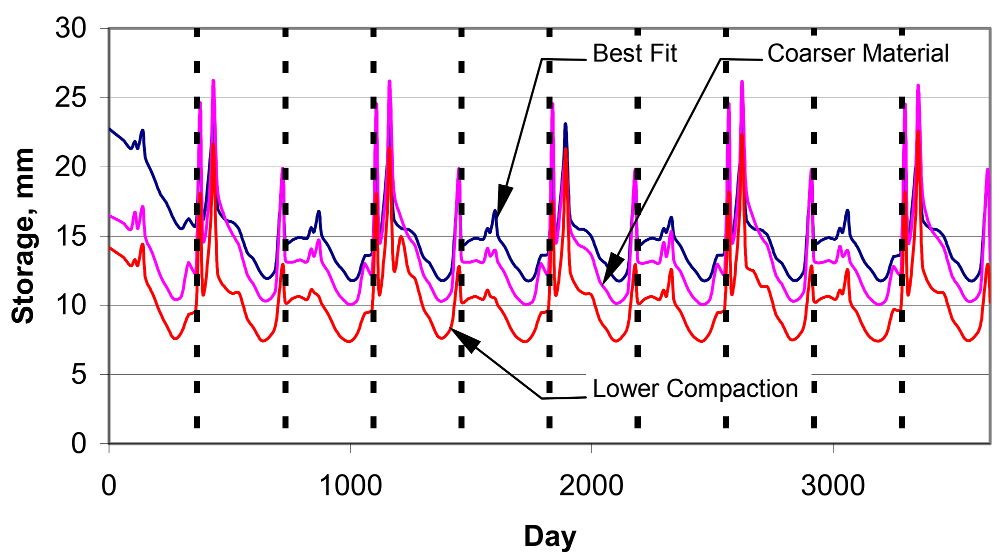

Figure 14. El Paso Sand, cover storage curves.

The most striking comparison of the different soils is in the magnitude of the response to major precipitation. The response magnitude is indicated in the amplitude of the variations in the flux plots and in the storage plots. It can be seen that the coarser material had the largest variations in both the flux and storage plots followed by the lower compaction soil and then the best fit soil. The reason for the larger variation is due to the steeper slope between the AEP and the residual portion of the SWCC curve shown in Figure 9. Therefore, for sandy soils, coarser soils may have more of a detrimental impact on cover performance than lower compaction. This is consistent with previous discussion regarding coarse soil SWCC insensitivity to compaction. These results are dependant of course on the slight increase in saturated hydraulic conductivity attributed to lower compaction.

Price Club Silt

The results of the Price Club silt parametric study are presented in Figures 15 and 16. The results indicate that there is an extreme difference in performance between the lower compaction soil and the best fit and finer soils. The lower compaction material demonstrated a downward flux for approximately three years and it took approximately five years to achieve a net upward flux. The best fit and finer soils had a downward flux for less than one year and achieved net upward flux in less than two years. The lower compaction soil exhibited a much more cyclic response than the other two soils as indicated by both the flux and storage plots. It should also be noted that after approximated 1 ¾ years both the best fit and finer soils had constant upward flux. The lower compaction soil, however, continued to have a downward flux component after each wet cycle. This indicates a critical response to the one order of magnitude increase in saturated hydraulic conductivity input for the lower compaction soil. Similar to the El Paso sand, the Price Club silt response appears to related to the slope of the SWCC curve between the AEP and residual moisture content

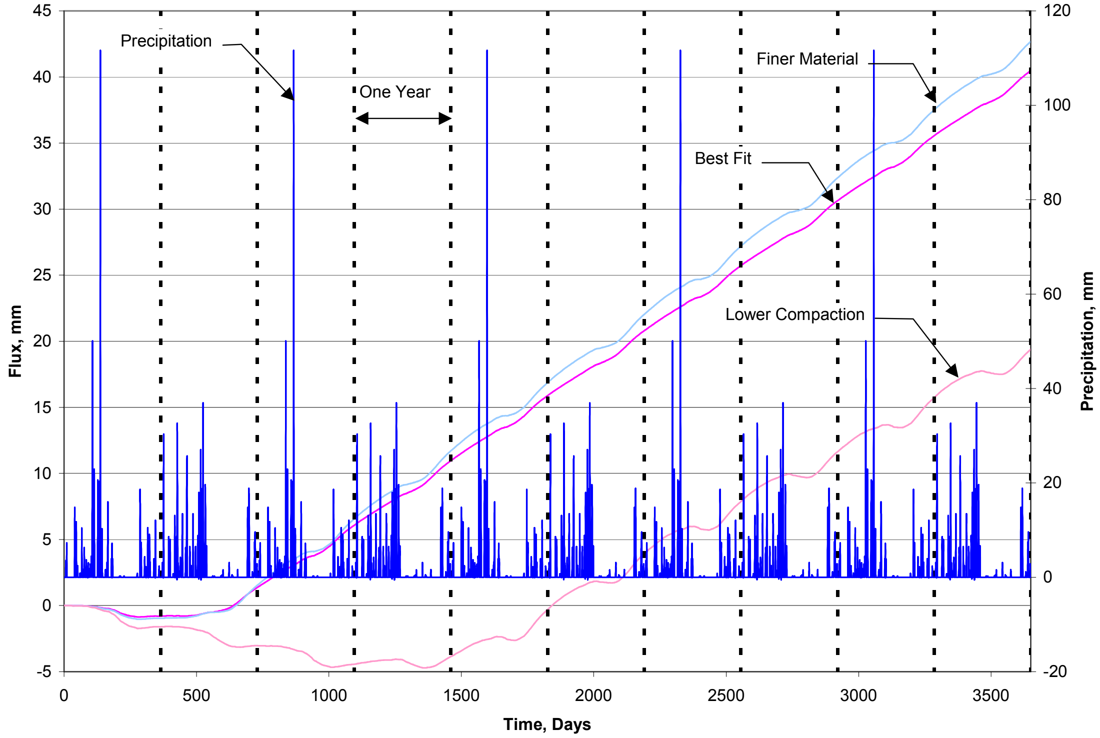

Figure 15. Price Club silt cumulative flux and precipitation.

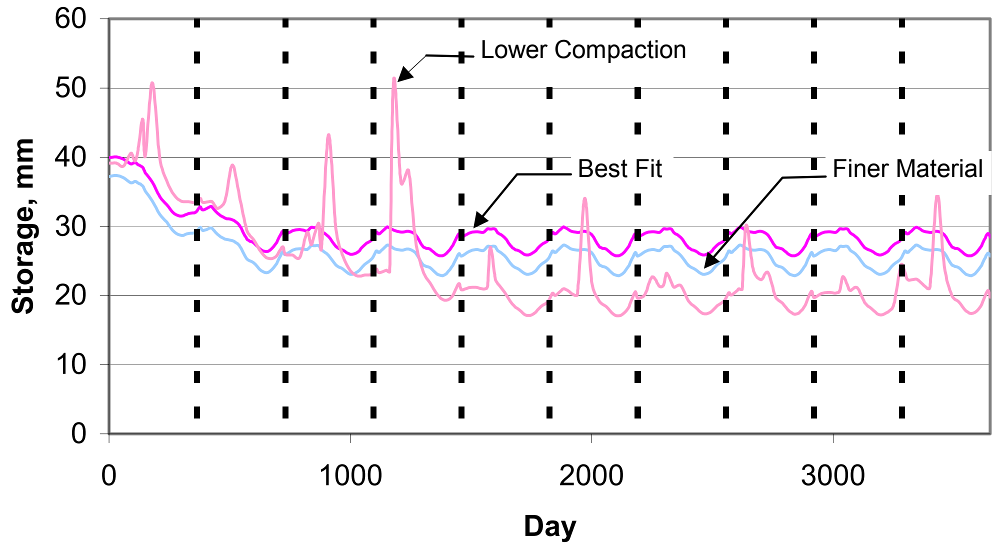

Figure 16. Price Club silt, cover storage curves.

Fountain Hills Clay

The results of the parametric study for the Fountain Hills clay are presented in Figures 17 and 18. There was very little difference between the best fit soil and the lower compaction soil cumulative flux response. The storage responses were essentially the same being off-set by the difference in porosity associated with the differences in compaction. The similar responses can be attributed to the fact that the saturated hydraulic conductivities for both soils are low compared to the applied precipitation.

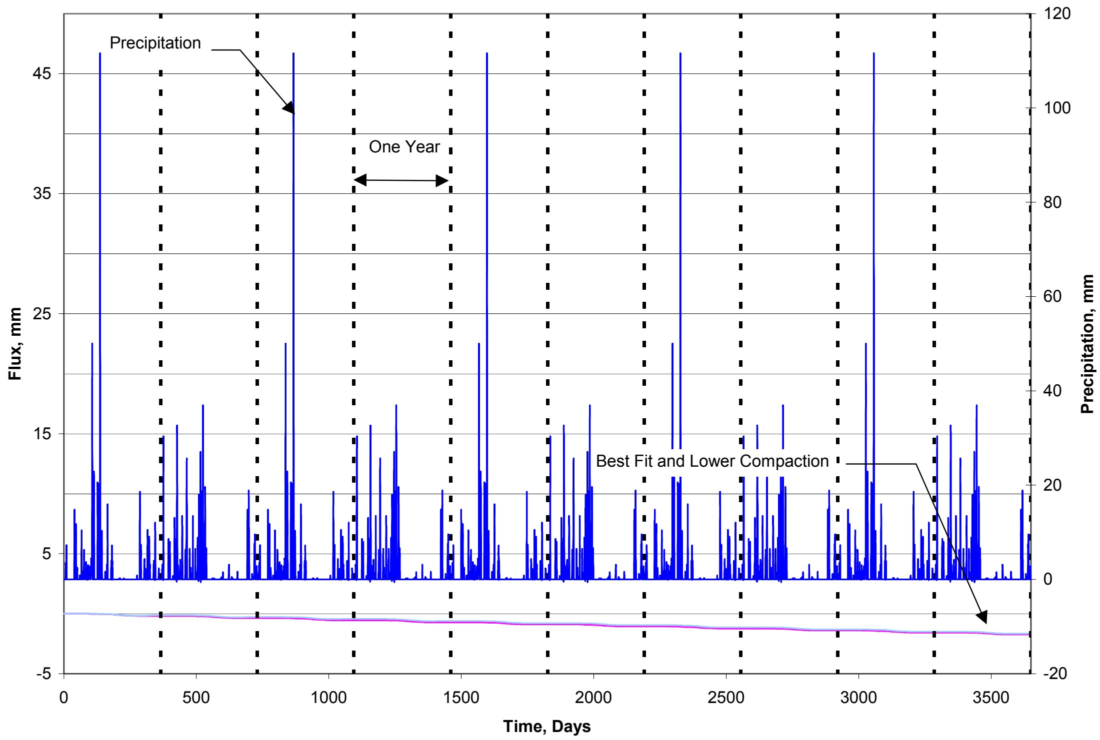

Figure 17. Fountain Hills clay cumulative flux and precipitation.

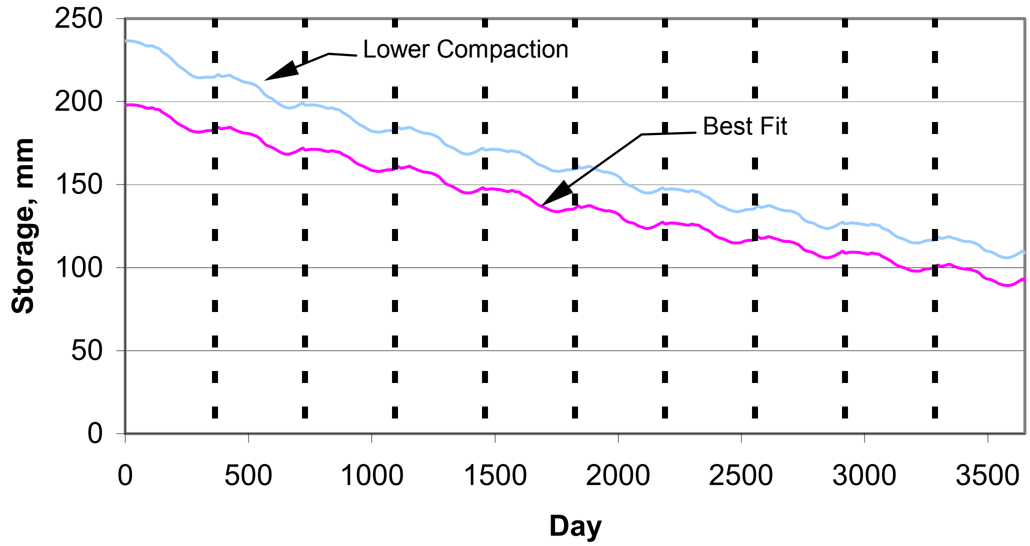

Figure 18. Fountain Hills clay, cover storage curves.

Of interest is the fact that the clay soils demonstrated continued downward flux through the cover over the ten year simulation period. The total flux is small, approximately 2 mm, 0.04-percent of the total applied precipitation. It is assumed that the clay stayed sufficiently moist to maintain a relatively high unsaturated hydraulic conductivity, or that there is gravity drainage out of the bottom of the liner.

For clay soils, based on the writer's experience with compacted soil liners and the results of this study, it is our opinion that the most critical aspect during construction are moisture content at compaction, degree of compaction and the resulting saturated hydraulic conductivity.

Conclusions

In general, based in the work presented above, the performance of the cover is most strongly impacted by the slope of the SWCC curve between the AEP and the residual moisture content and on the saturated hydraulic conductivity. There appears to be slightly different sensitivities of the SWCC slope for different soil types.

For sands, grain-size-distribution is critical particularly with respect to the No. 4 and No. 10 standard sieve sizes. If laboratory testing of a broad range of soils during design is not practical, it would be prudent to error on the fine side when developing the grain-size-distribution band.

Compaction in the field is not too critical unless there is a significant amount passing the No. 10 sieve size and there are no significant increases in saturated hydraulic conductivity.

For silts, provided the material does not get too coarse, compaction and saturated hydraulic conductivity are the most critical parameters. At the present time, it may be acceptable to develop the specification and CQA/CQC plan in the same manner as would be used for compacted soil liner, however, it should be noted that the criteria would not be as stringent as for a low hydraulic conductivity soil liner.

For clays, the low saturated hydraulic conductivity in relation to typical arid precipitation dominates the performance. Therefore, CQA/CQC procedures consistent with achieving a low hydraulic conductivity soil liner would be appropriate. Two important issues that will need to be addressed when developing specifications include maximum clod size and desiccation. Soil processing and construction procedures typically used to minimize clod size, ensure uniform moisture content and to inhibit desiccation are costly and may prove to negate the cost benefits of installing a soil cover if not properly considered in design. For example, if it is not cost effective to reduce clod size below a certain level, then the design should consider macro porosity associated with an appropriate clod size.

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