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Liner-Leachate Interaction Curve Models for Clayey Soils from Landfills around the City of Johannesburg

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ABSTRACT

The study presented herein links to a regression analysis that ties into three mathematical models from the Brutsaert, Mualem and Burdine equations respectively. The paper describes a series of experimental investigations on the characteristic permeation and interaction of three clayey soil types as barrier liners with landfill leachate from around the City of Johannesburg (CoJ), South Africa. From the outcomes therefrom, sequence of logarithmic relationships were projected towards proposing rational approximations of the best curve-fitting bounds using the Grain Size Distribution (GSD) and Atterberg Limits (AL) of the respective soils as selected classification properties. The outcomes which generally revealed reasonable indicative values were expressed using the weighted Plasticity Indices (PI) of the respective soils in conformance to Sitarenios et al. The two curve-fitting parameters *x* and z incorporated to simulate the Liner-Leachate Interaction Curve (LLIC) of the three clayey soils sampled from respective landfills around the CoJ, South Africa yielded 118, 0.6; 1211, 0.6; 1058, 0.6 in the Brutsaert model, 0.1, 1.2; 0.0, 1.5; 0.0, 1.5 in the Mualem model and 0.1, 2.4; 0.0, 2.6; 0.0, 2.7 in the Burdine model for samples A, B and C respectively, with a general R^2 value of 0.904.

Keywords: *Atterberg Limits, Clayey Soils, Landfill, Leachate, Liner, Regression Analysis.*

1 INTRODUCTION

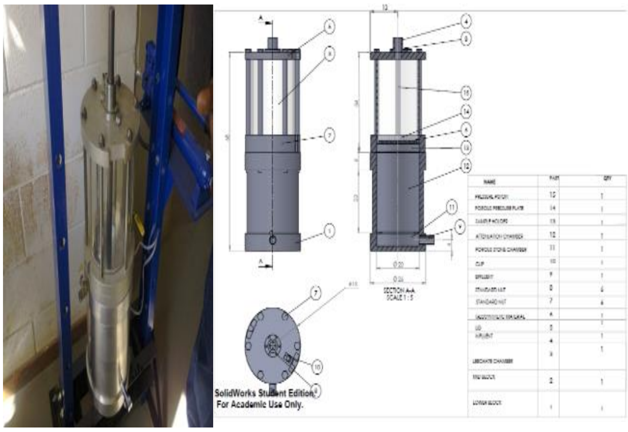
Conventionally, the disposal of waste involves the use of land and this has remained the trend from decades past. As recorded by Rowe (2011) disposal of waste in landfills generates gases and leachates/contaminants whose break away from engineered containment facilities must be constantly monitored and controlled to prevent or eliminate severe impact on the surrounding environment. Hence, to ensure that soil and groundwater resources are protected from landfill leachates, geo-composite barrier systems are mostly employed. Geomembrane/mineral composite barriers are often utilized in engineered waste containment sites and will progressively gain grounds as significant components of landfill lining systems. It is well known however, that in-situ and ex-situ geomembrane failures can at best be minimized but cannot be prevented (Agbenyeku and Akinseye, 2015). In this light, geomembrane forming part of a geo-composite liner may fail due to defects on or out of site from fabrication, installation or aging (Agbenyeku et al. 2014a; 2014b). Therefore, ascertaining the leachate seepage through mineral/soil liners is vital for the designs of waste containment systems. The construction of such systems around valuable water sources are in some cases inevitable. In such cases, effective separation of the waste body and ground water need be properly executed as recorded by the Department of Water and Sanitation-DWS (2005). This can be made possible when compacted clay liners (CCLs) are utilized as part of the composite barrier system to control migrating leachate that may infiltrate the defected liner i.e., geomembrane (GM) or geosynthetic clay liner (GCL).

In a fast growing and developing country like South Africa, Gauteng province and the City of Johannesburg (CoJ) alone generates approximately half of the nation's daily waste with dumping space (landfills) drastically decreasing for reasons of land shortages. As recorded by the Environmental Impact Assessment Regulation- EIAR (2005), the vast and increasing tonnages of disposed waste each day are attracting concerns with waste dumping often leading to health, environmental and aesthetic problems. The pollution of vital subsurface and groundwater resources is often of major interest. There are several predictive equations proposed for similar problems of seepages through defected landfill barriers however, Touze-Foltz and Giroud (2003), Foose et al. (2001) stated that predicted values differ by wide margins for different scenarios and applied conditions.

The Liner-Leachate Interaction Curve (LLIC) plays a major role in describing the nature, mechanical and hydraulic behaviour of unsaturated soils and it is often initiated as a constitutive equation integrated in various constitutive models and in finite element method applications for predicting leachate seepage/flow, pressure and deformation characteristics. The LLIC/Soil-Water Characteristic Curve (SWCC) may be expressed as any relation between water content or degree of saturation, gravimetric or volumetric water content and soil suction. As such, various empirical, closed-form, mathematical equations have been proposed using a reverse sigmoidal curve to describe the relationship between leachate/water content with respect to degree of saturation, gravimetric or volumetric water content and suction. Nevertheless, series of physico-empirical models have been proposed to estimate the LLIC in the form of SWCC primarily from grain size distribution curve, yet they possess limited reliability especially when applied to structured and clayey soils as reported by Fredlund (2006). In such instances, conducting laboratory investigations to determine the LLIC and subsequently carrying out a regression analysis to define the curve-fitting parameters associated with LLIC/SWCC models is a pertinent alternative. However, in recent times, conducting extensive laboratory LLIC measurements is cost and time demanding often revealing a series of separate data points limited over insignificant portions of the whole suction range or several portions with significant gaps in between, depending on the number and type of methods initiated. Hence, the need for empirical equations correlating the curve-fitting parameters with soil liner index properties remains highly needed. This paper therefore, is in line with efforts made to correlate the curve-fitting parameters of distinct two-parameter LLIC/SWCC models with the index properties of three distinct clayey soils harvested from respective landfills around the City of Johannesburg (CoJ). A regression analysis suitable for nonlinear equations, has been performed to determine the optimum curve–fitting parameters for the LLIC of the respective soils.

2 METHODOLOGY

For the purpose of this study, a soil liner layer-24 mm thick having a 225 mm thick buffering profile (BP) made up the bespoke test setup used in the investigation. The bespoke device- is a column hybrid of 160 mm diameter with Figure 1 showing a view of the device consisting of three sections: (i) The bottom part called the buffering bucket; which contained the respective natural parent clayey soils serving as the natural earth/subsoil below the clayey liner as shown in Figure 2. (ii) The mid-section called the sample holder; which contained the designed liner (respective parent clayey soils) placed over the buffering bucket as shown in Figure 3. (iii) The upper section above the liner system; which served as the leachate basin/pond as shown in Figure 4 used to initially saturate the BP.



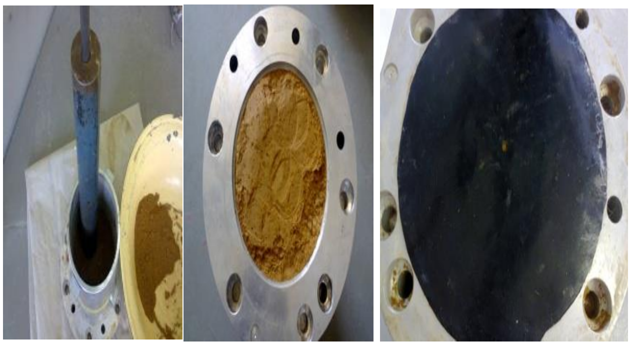
a) Pictorial view b) Schematic view

Figure 1: Bespoke column permeameter device

(a) (b)

Figure 2: (a) Moist geotextile on porous stone to prevent outlet clogging (b) Lightly rammed BP to simulate loosed subsoil

The leachate basin held a constant head of 250 mm through the span of the permeation tests. Layers of soil were compacted in the bottom and mid sections of the device. A moistened geotextile on a porous stone served as filter to prevent moving fines from clogging the outlet of the device at breakthrough. After the components were assembled, O-rings, gasket corks and silicon sealants were used to prevent leakages and maintain tight seals between the top, mid and bottom sections of the device.



a) (b)

Figure 3: (a) Soil compacted in layers (as CCL) in liner holder (b) Failed polyethylene with 5mm centered puncture overlain the CCL

The respective parent clayey soils prepared as liner and BP were sampled from distinct landfills around the CoJ, South Africa for this investigation as shown in Figure 5. The parent materials were taken from points sufficiently remote from the actual dump ground to guarantee a certain degree of purity and the soils were labeled A, B and C respectively. Extra tests were conducted with soil sample-A mixed with 50% coarse sand (equal proportion of particles passing 4.75 mm, 3.35 mm, 2.36 mm and 2.00 mm sieves). Inclusion of coarse sand was primarily to increase permeability of the barrier layer and shorten the test duration. Gravelly back-fill material mixed with coarse sand (equal proportion of particles passing 4.75 mm and 3.35 mm) was used as BP, however, the outcomes of the extra tests were not reported in this study. More to this, two methods were employed for suction control; the axis translation approach as applied in a soil moisture pressure extractor with 1500 kPa air-entry value porous ceramic disks for matric suction control and the salt solutions method for total suction control. Table 1 presents the saturated solutions of the salts used in the study with the saturation molarities experimentally measured. The process involved gradually introducing salt, increasing the concentration by 1 M at a time until salt appeared as sediment at the bottom of the testing vessel holding the solution. This appearance of sediment is not the definite factor as sediment may appear during and after stirring but finally dissolve over time. The solution prepared at each concentration was therefore left for the time necessary for chemical equilibrium, usually 48 hrs and if the sediment at the bottom of the vessel was not dissolved a record was made that this particular concentration led to the appearance of sediment.

(a) (b)

Figure 4: (a) Simulated leachate basin (b) Test setup of the bespoke device

Figure 5: Soil sampling vicinity

TABLE 1: CHARACTERISTICS OF SALT SOLUTIONS INITIATED IN THE TOTAL SUCTION CONTROL TEST

Salt	Salt saturation molarity	Total suction measured (kPa)
K_2SO_4	1	3.11
$BaCl_2$	2	7.98
KCl	3	11.3
NaCl	5	31.2
$Mg(NO_3)_2$	7	63.8
$MgCl_2$	12	115.2

Molarities of the solutions prepared for actual use for total suction control were increased by 1 M relative to the threshold values that sediment appeared for the first time, in order to ensure the ability of the solutions to remain saturated after applying the required suction value to the soil samples. Total weight of the solution was monitored and the required amount of salt was added in order to maintain the concentration. This was necessary as the samples placed in the solution chambers were saturated slurries. Water vapour from their drying therefore adds to the amount of water in the solution as with any sample, but in this case much more as substantial water evaporates from the slurries, given their very high initial water content. Therefore by knowing the initial amounts of water and salt in the solution and monitoring the weight of the samples in the chambers one could add the salt necessary to keep the solution saturated as drying of the slurries continued. Also presented in Table 1 are the total suction corresponding to the equilibrium relative humidity of the salt solutions measured in a chilled-mirror hygrometer. Similarly, rather than depending on temperature measurements and Kelvin's law, the total weight of the soil samples placed in solution chambers were monitored until stabilization and then the samples were taken and sectioned into three; one for total suction measurement using the chilled-mirror hygrometer, one for water content measurement and one for immersion in molten paraffin wax for total volume measurement and calculation of void ratio in conformance to Bardanis and Grifiza (2011).

All slurries were prepared at an initial water content using de-aired, de-ionized water, left for hydration for two days in a humidity chamber with occasional stirring in order to avoid sedimentation of coarser particles in the slurry and then placed for at least half an hour under vacuum for air removal. Samples were placed in lubricated plastic tubes taped on the porous stone of the pressure extractor or tin holders for placement in the salt solutions chambers. Given that samples were slurries in their initial condition, volume decrease during their drying was large. Careful lubrication of the inner surfaces of the tubes was crucial so as to avoid cracking of the samples during shrinkage as any inhibition of the diameter decrease by adhesion to the inner surface of the tubes resulted in cracking. The chemical constituents of the parent soils were determined by X–ray diffraction analysis. The standard proctor compaction test was done by a light rammer with self-weight of about 0.0244 kN and striking effort of about 595 kN-m/m^3.

The parent soils were prepared at the desired water content and lightly compacted to simulate in-situ conditions of natural soils. Leachate used as permeant for the test program was manually scooped from a landfill leachate pond as shown in Figure 6 designed to retain generated leachate (due to infiltration of storm water and/or interception of the subsurface water with the buried waste). The permeant was taken from a number of points within the leachate pond and pooled together to ensure a proper leachate mixture. The chemical ions were measured by full spectral analysis method on the influent and effluent and were compared to South African standard of drinking water in conformance to Water Services Act No 108 of 1997 and ASTM (2010). The fine gravels passing the 19.0 mm (3/4 in.) but retained on the 9.5 mm (3/8 in.) sieve openings were specifically selected, washed, oven dried and used as porous stone to serve as filter to the drainage path in the experimental setup of this study.


Figure 6: Permeate scooped from leachate pond

The measure of the particle size range of the collected soil samples using the Uniformity Coefficients (C_u) showed that the C_u values were greater than the range value of 5 i.e., $C_u > 5$ for all samples, which implies that the respective soils were non-uniform having very limited range of particles. From the Coefficient of Gradation (C_z) used to measure the shape of particle size curves, values obtained for the different soil types were below the range for a well graded soil i.e., $C_z < 1$ for all soil types, signifying that the respective soil samples are poorly graded. The various mechanical characterizations of the sampled natural soils are presented in Table 2.

TABLE 2: SOIL INDEX PROPERTIES USED IN THE STUDY

Properties	ASTM Test desig.	Soil A	Soil B	Soil C
Liquid Limit	D 4318	47	61	55
Plastic Limit	D 4318	25	36	31
USCS**	D 2487	CL	MH	CH
Natural Water Content (%)	D 2216	20	32	27
Specific Gravity	D 854	2.77	2.79	2.62
Dry Unit Weight (kN/m^3)	D 698	15.2	16.4	17.3
Wet Unit Weight (kN/m^3)	D 698	17.7	18.9	20.1
Void Ratio	-	0.79	0.67	0.48
Porosity	-	0.44	0.40	0.32
Perm Coeff. (D.Water as permeant soln)(m/s×10^{-8})	D 2434	1.25	1.41	1.21

***Unified Soil Classification System*

For the mechanical index tests, Unified Soil Classification System (USCS) was used in this study as the samples had very high percentages of fines over 50% passing the No. 200 sieves. Soil sample-A (muscovitic soil) had a Liquid Limit (LL) of 47 which by the classification rule is considered low as it is lesser than 50. The Limits of the muscovitic soil plotted in the hatched zone on the plasticity chart as such classifies it as CL- lean clay. The rest of the samples had higher LL values above 50. Sample-B (illitic soil) had its Limits plotted below the “A” line on the plasticity chart which classifies it as an MH- elastic silt. While sample-C (kaolinitic soil) had plotted Limits above the “A” line on the plasticity chart which classifies it as CH- fat clay.

3 RESULTS AND DISCUSSION

3.1 LEACHATE PERMEATION TEST LINER-LEACHATE INTERACTION CURVE- LLIC/ SWCC MODELS

In a similar study, series of curve-fitting parameters to describe the SWCC of six soils from Greece using the well-known three-parameter Fredlund and Xing (1994) and Van Genuchten (1980) equations were presented by Sitarenios et al. (2011). Although the authors discovered that both equations by Fredlund and Xing (1994) and Van Genuchten (1980) provided fairly accurate description to the experimental data, there was still no success in finding any statistically reliable correlation between x, y and z and any physical parameter. Where x, y and z are; the estimated curve-fitting parameters. However in the study herein, three LLIC/SWCC models, the Burdine (1953), Brutsaert (1966) and Mualem (1976), all of which incorporate two curve-fitting parameters x and z to simulate the LLIC/SWCC of the three clayey soils sampled from respective landfills around the CoJ, South Africa. The analyses were done for LLIC data in terms of the normalized gravimetric water content $W = w/w_0$ and suction s, where w and w_0 are; the gravimetric water content at each suction level and at full saturation respectively. Equations (1), (2) and (3) are the associated Brutsaert, Mualem and Burdine models respectively.

$$W = 1/[1 + (s/x)^z] \tag{1}$$

$$W = 1/[1 + (xs)^z]^{(1-\frac{1}{z})} \tag{2}$$

$$W = 1/[1 + (xs)^z]^{\left(1-\frac{2}{z}\right)} \tag{3}$$

Generally, the two-parameter models are less capable of producing adequate fits to experimental data as compared to the three-parameter models by Leong and Rahardjo (1997). As recorded by Sitarenios et al. (2011) this is plausibly due to their limited curve shape flexibility arising from the lack of a third parameter for independently adjusting the curve shape near the residual water content range of suction. However, in contrast to the aforesaid disadvantage noted by Sitarenios et al. (2011), with respect to simulation this could favour the aspects of correlation. Nonetheless, the partial flexibility of two-parameter for LLIC/SWCC models may be less affected by the scatter of the experimental data as such, creating best-fit curves that primarily define the general trend of the LLIC. Conversely, there is a possibility that the two-parameter equations will produce better and more reliable correlations between the soil index properties and curve-fitting parameters.

3.2 *SIMULATION AND CORRELATION*

This paper investigated the LLIC/SWCC of three clayey soils sampled from around the CoJ, South Africa. The muscovitic, illitic and kaolinitic soils were medium plastic lean clay, elastic silt and fat clay respectively. The water content against the suction data were obtained via drying paths on initially saturated reformed samples. The term “reformed” in this study denotes samples that have been initially reconstituted into slurry, then consolidated to their in-situ void ratio or stress level and finally unloaded prior to drying. The axis translation technique for controlling matric suction up to 1500 kPa and the salt solutions method for controlling total suction between 4 and 150 MPa were employed in conformance to Bardanis and Grifiza (2011), Bardanis and Kavvadas (2008). To obtain the best-fit parameters, a regression analysis was performed using a stochastic search algorithm. The approach defines the global minimum of nonlinear objective functions as exemplified by Sitarenios et al. (2011). Table 3 presents the calculated best-fit parameters along with their corresponding coefficient of determination R^2 values, while the acquired experimental data and the fitted curves are represented in Figures 7-9.

TABLE 3: CALCULATED BEST-FIT PARAMETERS WITH CORRESPONDING R^2 VALUES FOR THE MODELS

Soil	**Brutsaert (1966)**			**Mualem (1976)**			**Burdine (1953)**		
	x	*z*	R^2	*x*	*z*	R^2	*x*	*z*	R^2
A	118	0.6	0.9	0.1	1.2	0.9	0.1	2.4	0.91
B	1211	0.6	0.9	0.0	1.5	0.9	0.0	2.6	0.91
C	1058	0.6	0.9	0.0	1.5	0.9	0.0	2.7	0.92

Generally, all the tested models behaved well in the simulation. However, the Brutsaert model provided the best fit in consonance with findings by Sitarenios et al. (2011), Bardanis and Grifiza (2011), Bardanis and Kavvadas (2008) with almost identical outcomes as those of the three-parameter models, in spite of its lack of a third parameter. Moreover, it appeared that the Burdine and Mualem models were more appropriate for soils displaying a rapid decrease in the parameter correlated to suction.

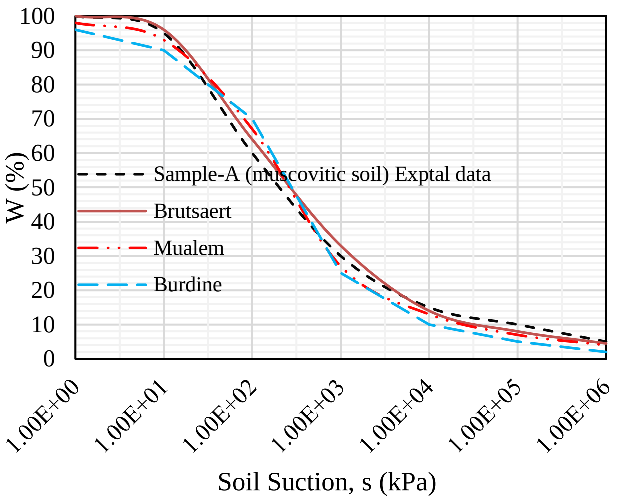


Figure: 7 Experimental data and calculated best-fit curves for Sample-A (muscovitic clayey soil)

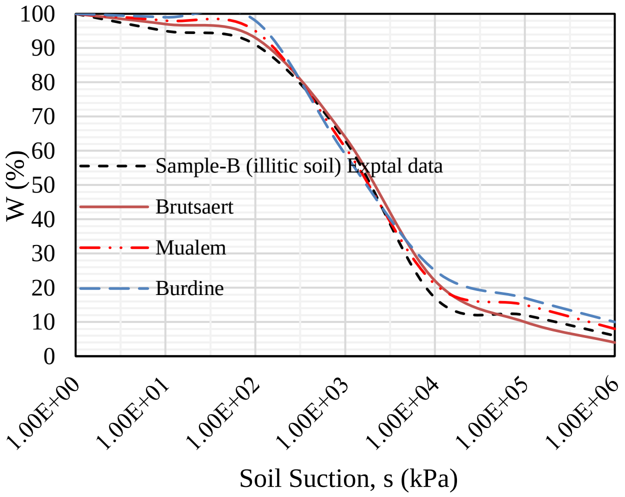


Figure: 8 Experimental data and calculated best-fit curves for Sample-B (illitic clayey soil)

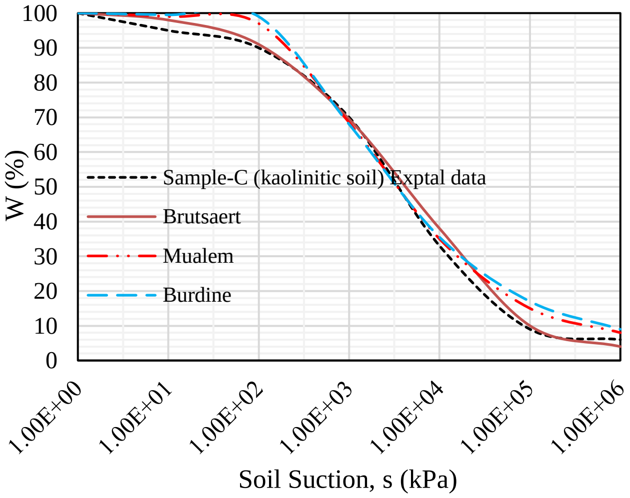


Figure: 9 Experimental data and calculated best-fit curves for Sample-C (kaolinitic clayey soil)

Furthermore, the calculated *x*, *z* parameters were correlated with soil index properties, particularly to the weighted Plasticity Index (PI). As recorded by Zapata et al. (2000) the weighted PI is the product of the material passing the #200 U.S. Standard Sieve expressed as a decimal with the PI expressed as a percentage. More to this, it was discovered that the *x* of the Brutsaert model or 1/*x* of the Burdine and Mualem models can be fairly described as a logarithmic expression of wPI. Similarly, it appears to be valid for the *x*/*z* and (1/*x*)/*z* parameters respectively, conforming to the results by Sitarenios et al. (2011), Bardanis and Grifiza (2011), Bardanis and Kavvadas (2008). For the sake of data revalidation, the proposed best-fit curves and their corresponding correlation equations are not presented in this study.

4 CONCLUSION

The study describes a series of experimental investigations on the characteristic permeation, suction and interaction of three clayey soil types as barrier liners with landfill leachate from around the CoJ, South Africa. From the outcomes therefrom, sequence of logarithmic relationships from the LLIC/SWCC were projected towards proposing rational approximations of the best curve-fitting bounds using models from the Brutsaert, Mualem and Burdine equations respectively. From the analysis of results the following conclusions were drawn:

- That the LLIC/SWCC of the three clayey soils from around the CoJ, South Africa were successfully modelled using the Brutsaert, Mualem and Burdine equations.
- That although all models gave reasonable outcomes, the Brutsaert model turned out to be the most reliable of the two-parameter models examined, as the R^2 values were slightly higher than the other two counterparts. This was closely identical to the findings by Sitarenios et al. (2011).
- Series of logarithmic correlation equations are proposed, capable of providing fair values of the *x*, *z* curve-fitting parameters with soil properties, however, at this stage some revalidation exercise is required.

In a nutshell, until revalidated experimental data are available to permit further evaluation of the proposed correlations, the present approach and outcomes should be used as indicative based-results.

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