Saturated Hydraulic Conductivity of Some Saprolites from Peninsular Malaysia

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ABSTRACT

A study was conducted to evaluate the hydraulic conductivity of saprolites and their potential use as a wastewater treatment in Malaysia. Samples of granitic, basaltic, schist, and shale saprolites were taken from 16 locations throughout Peninsular Malaysia. These samples were morphologically described and air-dried for physical analyses. The infiltration rate study of the saprolites was conducted both in-situ and in the laboratory. The study showed that granitic saprolite had the highest $K_{sat}$ value while basaltic had the lowest value in both laboratory and in-situ methods. Several factors influenced the $K_{sat}$ value, namely clay and sand content, porosity, pore shape and pore sizes. Both pore size and shape analysis influenced the $K_{sat}$ value especially mesopores, $M_m$ (30 ≤ 75 μm), macropores, $M_s$ (> 75 μm), vugh and channel shapes. A model to predict the $K_{sat}$ of saprolites was proposed as follows: $K_{sat} = 16.859 - 0.182 \theta_{so} - 0.183 \theta_{sw} - 0.128 S_1 + 0.112 M_{sw}$ where, $\theta_{so}$ and $\theta_{sw}$ is the moisture content retained at 9.8 kPa and 1500 kPa, respectively, $S_1$ is the silt content, and $M_{sw}$ is the air-dried moisture content. The study suggests that shale and basalt saprolites are suitable for in-situ wastewater treatment because of their slow to very slow infiltration rate. This will provide ample time for bacteria and viruses to be removed from the effluent by filtration and adsorption onto particle surfaces and for organics to stabilise the wastewater.

Keywords: Saprolite, infiltration rate, hydraulic conductivity, wastewater

INTRODUCTION

Saturated hydraulic conductivity ($K_s$) is an important soil hydraulic property that affects water flow and the transport of dissolved solutes. It is an important soil property for many agronomic, engineering and environmental activities. It is essential in many water-soluble transport and crop growth models (Clemente \textit{et al.} 1994; Van Dam \textit{et al.} 1997), and is used extensively in the measurement and evaluation of soil physical quality (Gregorich \textit{et al.} 1993). It is also a key parameter in the design and performance assessment of irrigation and drainage...
systems (Luthin 1978), earthen waste impoundments (Youngs et al. 1995), and waste water leach fields (Ward and Morrison 1984).

Saprolites are weathered rock materials that are soft and friable and which retain the fabric and structure of the parent rock (Pavich 1986). It is currently being used for on-site treatment and disposal of household and industrial waste (Vepraskas et al. 1991) and storage of some radioactive wastes (Vepraskas and Williams 1995) in a few developed nations. In developing countries, wastewater disposal is a serious problem. Poor urban planning and financial constraints had resulted in poor disposal of wastewater. In the tropics, weathering reached great depths (Thomas 1994) and had formed thick layer of saprolites. The potential for utilisation of these deep saprolitic layers for wastewater treatment in tropical countries is great and could ease the nation’s financial burden in the future.

The total imported wastewater equipment into Malaysia in 2001, for example, was around USD 719 million (Source: Malaysia Statistics Dept.). Several investigators have measured the \( K_{sat} \) of some saprolites. The \( K_{sat} \) values reported ranged from 0.16 to 0.20 cm hr \(^{-1} \) for metamorphosed quartz-diorite saprolite (Vepraskas and Williams 1995), 5.5 cm hour \(^{-1} \) for granite saprolite, 0.03 – 0.96 cm hr \(^{-1} \) for felsic gneiss and schist saprolite (Schoeneberger and Amoozegar 1990), and 0.01 – 1.71 cm hr \(^{-1} \) for mica-schist saprolite (Vepraskas et al. 1991). The results vary slightly in saprolites of similar origin, but generally coarser saprolites would have higher \( K_{sat} \) values in comparison to finer textured saprolites. Intensity of weathering, total porosity, foliation planes, and channel types of macropore were among the factors associated with \( K_{sat} \) values of saprolites.

The objectives of this study were to examine the hydraulic conductivity of some saprolites found in Peninsular Malaysia, to determine factors associated with their \( K_{sat} \) values and to develop a model to predict the \( K_{sat} \) of the saprolites.

**MATERIALS AND METHODS**

*Study Locations*
The study was conducted in Peninsular Malaysia which has an equatorial climate with an annual precipitation of 2500 - 3500 mm, and a potential evapo-transpiration of 1130 mm. The daily air temperature throughout Peninsular Malaysia is uniform and ranges between 28 and 33°C (Nieuwport 1983). The soil moisture regime is udic and the soil temperature is isohyperthermic with a mean annual soil temperature of 28.7°C. The geology of Peninsular Malaysia is predominantly granite, shale and schist on the west coast and basalt in the east coastal state of Pahang (Gobbett and Hutchison 1973).

Four types of saprolite of different geological origin, namely granite, shale, schist, and basalt were collected from 16 locations throughout Peninsular Malaysia (*Fig. 1*). Triplicate samples of saprolite were collected randomly at
Fig. 1: Locations of saprolites sampling areas in Peninsular Malaysia

each location, mostly along newly exposed road cuts and hills. Field morphological descriptions were done for all study sites (USDA Soil Survey Staff 1981). At each point, approximately 2 kg of samples were taken at depths of 0 – 10 cm. Prior to sampling, the exposed saprolites were removed to eliminate contamination and weathering effect. In-situ field infiltration rate was conducted using the double-ring infiltrometer method (ASTM 1994).

**Laboratory Analysis**

The bulk sample of saprolites were air-dried, homogenised, and sieved through a 2.0 mm sieve for physical analysis. The particle size distribution was determined using the pipette method (Gee and Bauder 1986). Saprolite bulk density was estimated using the core method while pycnometers were used to determine the particle density of saprolites (Blake and Hartge 1986). Total porosity was
calculated using the ratio of known bulk and particle densities. The saprolite-water retention curve was determined using the pressure plate method at different pressure regimes, that is, 0, 0.98, 9.8, 33 and 1500 kPa. The constant head method (Klute and Dirksen 1986) was used to determine the laboratory saturated hydraulic conductivity. All analyses were done in triplicate for each sampling point and reported as average values.

For the microstructure analysis, samples were collected in Kubierna boxes, dried and impregnated with unsaturated polyester resin. Thin sections of 5.5 cm x 7.5 cm were prepared and described following the scheme outlined by Bullock et al. (1985). The pore size classes and pore types were analysed using an image analyser, ImagePro® Plus from the images captured on thin sections. The pore sizes and shapes were classified according to Brewer (1964). The number of pore classes and types were calculated using a formula $S_h = A/Pe^2$ (VandenBygaart et al. 2000), where $S_h$ is the pore shape, $A$ is the area and $Pe$ is the parameter.

Correlation analysis was conducted to determine the degree of association between $K_{sat}$ and saprolite physical properties. Regression analysis was conducted to obtain the linear prediction equation. The best-fit equations from multiple regression were selected using the Stepwise and Model Fit Technique.

**RESULTS AND DISCUSSION**

*Saprolite Morphology*

Granitic saprolites consist of weathered materials that still preserve the rock structure. The variegated colours of white and yellow are composed mainly of weathered feldspar and fragments of quartz and muscovite, and therefore give a sandy texture. The schist saprolites have variegated colours of reddish yellow, red and grey. The shale saprolites have variegated colours of reddish yellow to dark yellow. The basaltic saprolites have predominantly darker colour with dark reddish stains. The schist, shale and basaltic saprolites are silty in field texture. The variegated colours of all saprolites were observed to change with depth. The reddish colour increased towards the top of the regoliths in line with the increasing degree of weathering. Saprolite colour tends to be less variegated towards the parent material.

Saprolite morphology also exhibited high compaction and this is attributed to the high amount of rock fragment and weathered minerals, accounting for 50 to 70 % of the saprolite volume. The frequency of rock fragments is higher in granitic and schist saprolite compared to basaltic saprolite where the ferromagnesian minerals are easily weathered. The percentage of these rock fragments decreases towards the upper saprolite as weathering increases. Taking wastewater treatment into consideration, the upper and middle saprolite would be more effective than the lower saprolite zone. At the saprock zone, however, the $K_{sat}$ values would be too slow as there is no formation of weathered matrix yet (Hamdan and Burnham 1995).
TABLE 1
Physical properties of studied saprolites

<table>
<thead>
<tr>
<th>Type of saprolites</th>
<th>Particle size distribution [%]</th>
<th>Total porosity [%]</th>
<th>Moisture content [%]</th>
<th>Bulk density [g cm$^3$]</th>
<th>Particle density [g cm$^3$]</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite</td>
<td>64</td>
<td>46</td>
<td>14.1</td>
<td>1.3</td>
<td>2.5</td>
<td>Sandy loam</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>56</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schist</td>
<td>30</td>
<td>42</td>
<td>15.6</td>
<td>1.3</td>
<td>2.3</td>
<td>Clay loam</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shale</td>
<td>48</td>
<td>36</td>
<td>16.9</td>
<td>1.4</td>
<td>2.1</td>
<td>Loam</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>42</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basalt</td>
<td>16</td>
<td>40</td>
<td>26.7</td>
<td>1.1</td>
<td>1.7</td>
<td>Clay loam</td>
</tr>
<tr>
<td></td>
<td>54</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSD$_{0.05}$</td>
<td>11.6</td>
<td>12.3</td>
<td>12.5</td>
<td>4.1</td>
<td>0.16</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>14.3</td>
<td>13.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Saprolite Physical Properties

The intensity of weathering and rock mineralogy has greatly influenced the
saprolite texture (Pavich 1986). The clay content is highest in basaltic saprolites
and lowest in granitic saprolites (Table 1), in the decreasing order of basalt >
schist > shale > granite. Under a tropical environment, the ferromagnesian
minerals in basalt weather easily into clay minerals. Other than granitic saprolite
which has a sandy texture, the schist, shale and basaltic saprolites have clay to
clay loam textures. Previous studies have indicated that sandy materials and
high porosity, as in granitic saprolite, would result in higher $K_{sat}$ values. The
nature and type of the pores, however, also determine $K_{sat}$ values (Chng Loi Peng
2002). Basaltic saprolites have high porosity but are clayey in texture, and would
have lower $K_{sat}$ values. Hamdan and Burnham (1995) who studied similar saprolites
reported that kaolinite is a common mineral in the clay size fraction besides
the formation of the 2:1 clay minerals. The 2:1 clay minerals, however, decrease
drastically towards the upper saprolite as weathering becomes more intense.

Bulk density is an indicator of soil compactness and porosity, as well as
a determinant of soil moisture content and hydraulic conductivity. Bulk density
of the parent material decreases as it weathers. The basaltic rock weathers to
produce saprolite of lower bulk density and is high in clay content. Their high
moisture content, however, suggests that the pores in basaltic saprolite are
predominantly of micropore type. Total porosity ranged from 36 – 45%, with
granite being the most porous. Coarse fragments content recorded ranged from
32 to 56% of the saprolite volume. The high amount of coarse fragments in
granite could also increase the $K_{sat}$ values.
**TABLE 2**  
The moisture retention and the $K_{sat}$ values of saprolites studied

<table>
<thead>
<tr>
<th>SAPROLITE</th>
<th>% Moisture retention (v/v)</th>
<th>$K_{sat}$ (cm hr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 kPa</td>
<td>0.98 kPa</td>
</tr>
<tr>
<td>Granite</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>Schist</td>
<td>78</td>
<td>47</td>
</tr>
<tr>
<td>Shale</td>
<td>82</td>
<td>48</td>
</tr>
<tr>
<td>Basalt</td>
<td>94</td>
<td>65</td>
</tr>
<tr>
<td>LSD$_{0.05}$</td>
<td>5.1</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Table 2 illustrates the variation in ability of saprolites to retain water. The granitic saprolite have low moisture content at saturation and field capacity, and very low moisture content at wilting point. The trend suggests that most pores are probably macropores that develop from fragments of weathered quartz, feldspars and muscovite. The sandy texture of granitic saprolite, also account for the low moisture retaining ability. Basaltic saprolite, on the other hand, showed an opposite pattern to that of the granitic saprolite. Their ability to retain high moisture content even at wilting point is probably attributed to the fine weathered groundmass of ferromagnesian minerals, indicating that the pores are predominantly micropores. The shale and schist saprolites showed an intermediate trend in water retention capability, indicating a mixture of macropores, mesopores and micropores.

**Saprolite Micromorphological Properties**

The microstructure and the coarse/fine distribution ratios have a direct influence on the $K_{sat}$ value of the saprolite. Basaltic saprolite had massive and vughy microstructure with a C/F ratio of 25:75. It had an undifferentiated b-fabric, where amorphous and pseudomorphs of rock fragments were common (Table 3). Granitic saprolite had a spongy to intergrain microstructure with C/F ratio of 70:30 and an abundance of pseudomorphs of primary minerals. The shale and schist saprolite had similar microstructure, b-fabric, and pedofeatures. The weathering behaviour and the weatherability of the saprolite parent materials could have influenced their micromorphological properties. Basalt, for example, has been reported to experience intense weathering even at early saprolite formation, and which has contributed to the high fine matrix in the C/F ratio (Hamdan et al. 2003).

**Saprolite $K_{sat}$ Values**

There were slight differences in the $K_{sat}$ values of saprolites recorded in the field and those determined in the laboratory (Table 2). Both methods showed a similar trend, where significantly higher $K_{sat}$ values were observed in the granitic
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![Graph showing mean distribution of pore size classes and types](image)

**Fig. 2: Mean distribution of pore size classes and types**

Saprolite and lower values in those of the basaltic saprolite. The shale and schist saprolites demonstrated intermediate $K_{sat}$ values. The laboratory method showed that the average $K_{sat}$ values for the granitic, schist, shale and basaltic saprolites were 6.5, 1.1, 0.25, and 0.1 cm hr$^{-1}$, respectively. The field *in-situ* results, however, were slightly lower that those of the laboratory method. The variability of the moisture content in the fields and disturbance during saprolite sampling could have probably influenced the $K_{sat}$ values under different analytical conditions. The $K_{sat}$ and infiltration rate trend in the saprolites was in the decreasing sequence of granite > schist > shale > basalt.

The $K_{sat}$ of different saprolites data obtained can be justified by the pore characteristics of the respective saprolites. The pore size classes and pore shape analysis using an image analyser (*Fig. 2*) revealed that the granitic and schist saprolites were highly porous and were composed of predominantly micropores and mesopores and a low amount of macropores. The basaltic and shale saprolites, on the other hand, were less porous, had a low amount of micropores and mesopores, and were extremely low in macropores. The vugh shape and channel shape pores were most predominant in all saprolites (Table 3). These pore characteristics are clearly determined by the percentage and distribution of the clay, silt, sand and gravel contents. The high clay content in basaltic saprolite created a lower amount of various pore types compared to the granitic saprolite.

The $K_{sat}$ values determine the suitability of a saprolite for wastewater treatment. An infiltration rate that is too fast is not considered as suitable as it would not allow ample time for the organisms or elements to be filtered and absorbed. The infiltration rate that is too slow would require utilisation of vast lands in order to accommodate continuous incoming wastewater.
TABLE 3
The micromorphological properties of saprolites studied

<table>
<thead>
<tr>
<th>Micromorphological features</th>
<th>Granite</th>
<th>Schist</th>
<th>Shale</th>
<th>Basalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microstructure</td>
<td>Spongy to intergrain channel</td>
<td>Fissure</td>
<td>Fissure</td>
<td>Massive and vughy</td>
</tr>
<tr>
<td>Coarse/Fine ratio</td>
<td>70:30</td>
<td>60:40</td>
<td>55:45</td>
<td>25:75</td>
</tr>
<tr>
<td>b-fabric of groundmass</td>
<td>Mosaic-speckled porostriated and crescentic</td>
<td>Porostriated</td>
<td>Undifferen tiated</td>
<td></td>
</tr>
<tr>
<td>Pedofeatures</td>
<td>Pseudomorphs of primary minerals</td>
<td>Typic and hypo clay coatings</td>
<td>Typic and hypo clay coatings</td>
<td>Amorphous and pseudo morphs of rock fragments</td>
</tr>
</tbody>
</table>

TABLE 4
Correlation analysis between the physical parameters and $K_{sat}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Saprolite ($n = 48$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle density</td>
<td>0.575**</td>
</tr>
<tr>
<td>Bulk density</td>
<td>0.338*</td>
</tr>
<tr>
<td>Sand content</td>
<td>0.776**</td>
</tr>
<tr>
<td>Silt content</td>
<td>-0.322*</td>
</tr>
<tr>
<td>Clay content</td>
<td>-0.710**</td>
</tr>
<tr>
<td>Moisture content at 0 kPa</td>
<td>-0.723**</td>
</tr>
<tr>
<td>Moisture content at 0.98 kPa</td>
<td>-0.750**</td>
</tr>
<tr>
<td>Moisture content at field capacity</td>
<td>-0.855**</td>
</tr>
<tr>
<td>Moisture content at 33 kPa</td>
<td>-0.755**</td>
</tr>
<tr>
<td>Moisture content at wilting point</td>
<td>-0.826**</td>
</tr>
<tr>
<td>Gravel content</td>
<td>0.644**</td>
</tr>
</tbody>
</table>

Note: * = r values; * = significant at 0.05% level; ** = significant at 0.01% level

$K_{sat}$ Empirical Modeling
The correlation analysis (Table 4) reveals that all of the physical properties were significantly related to $K_{sat}$, and this agreed with earlier reports by Vepraskas et al. (1991) and Vepraskas and Williams (1995).

The clay content is negatively correlated while the sand content is positively correlated with the $K_{sat}$ values of the saprolites. These properties are essential to develop a model for the prediction of the $K_{sat}$. The high clay content lowered $K_{sat}$ values. The clay content also plays crucial roles in the absorption of cations or anions from wastewater effluent.
An empirical model was predicted for each saprolite studied by using the backward Stepwise and Model Fit Technique, and regression results showed that independent variables were significant at 0.05 level with $R^2 = 0.855$. Only four variables were considered. The best model to predict the $K_{sat}$ for the saprolites was:

$$K_{sat} = 16.859 - 0.182 \theta_f c - 0.183 \theta_{wp} - 0.128 S_f + 0.112 M_{out}$$

where $K_{sat}$ is the saturated hydraulic conductivity, $\theta_f c$ is the field capacity (9.8 kPa), $\theta_{wp}$ is the permanent wilting point (1500 kPa), $S_f$ is the silt content and $M_{out}$ is the air-dried moisture content. *Fig. 3* illustrates the variability of the observed $K_{sat}$ and predicted $K_{sat}$ of the saprolites studied.

![Graph showing variability of observed $K_{sat}$ and predicted $K_{sat}$ of saprolites studied.]

*Fig. 3: Variability of the observed $K_{sat}$ and the predicted $K_{sat}$ of the saprolites studied*

The determination of a $K_{sat}$ value, particularly for saprolite, is laborious and time consuming. The equation would allow faster determination of the $K_{sat}$ values of any saprolite with the availability of common data set in the equation.

**CONCLUSION**

The ability of water to infiltrate the saprolites and then percolate vertically or laterally is a critical factor for most wastewater treatment concepts. To be suitable for wastewater treatment, the $K_{sat}$ must not be too low that exorbitant and areas would be required for disposal, or too high that wastewater flows through pores too quickly for adequate sorption or filtration of contaminants. In saprolites that are suitable for wastewater disposal, effluents move through saprolites relatively slowly so that there is ample time for bacteria and viruses to be removed from the effluent by filtration or absorption onto particle surfaces (Vepraskas and Williams 1995).
This study has shown that shale and basaltic saprolites can be used for in-situ wastewater treatment because of their slow to very slow rate of infiltration capacity. The schist and granitic saprolites can be adopted for similar purposes if, modifications are made by adding low permeability base materials and a protective filter layer (USEPA 1988) over the saprolites to lower the $K_{sat}$ values. All physical properties analysed were found to be significantly associated with the $K_{sat}$ values. Particle size distribution and gravel content play a dominant role in the effectiveness of wastewater treatment. The $K_{sat}$ is influenced by the clay, sand and gravel content. A higher proportion of sand and gravel content increases the $K_{sat}$. The clay fractions have a great capacity to assimilate contaminants from wastewater with lower percolation.

A model was developed to predict the $K_{sat}$ value of a saprolite, as in the equation: $K_{sat} = 16.859 - 0.182 \theta_c - 0.183 \theta_{wp} - 0.128 S_i + 0.112 M_{opt}$. This model would be useful to help predict any saprolite $K_{sat}$ values with minimum laboratory requirement.

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