Compacted Polymer-Enhanced Bentonite-Sand Mixture – Behaviour and Potential Applications

by Arifin Yulian F

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"Geotechnical Challenge for Mega Infrastructures"

Proceedings

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"Geotechnical Challenge for Mega Infrastructures"

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PREFACE

Assalamu'alaikum Wr. Wb.

The Association of Geotechnical Societies in Southeast Asia (AGSSEA) consists of the Southeast Asian Geotechnical Society (SEAGS), Vietnamese Society for Soil Mechanics and Geotechnical Engineering (VSSMGE), Hong Kong Geotechnical Society (HKGES), Geotechnical Society of Singapore (GeoSS), Thai Geotechnical Society (TGS), Chinese Taipei Geotechnical Society (CTGS), Indonesian Society for Geotechnical Engineering (HATTI) and Malaysian Geotechnical Society (MGS). It was decided at the General Committee meeting of SEAGS and AGSSEA on 31 May 2016 at Kuala Lumpur that the 20th Southeast Asian Geotechnical Conference and the 3rd AGSSEA Conference (20SEAGC-3AGSSEA Conference) is to be held at Pullman Hotel in Jakarta, from 6-7 November 2018. This is the first time in history of SEAGS that the conference is held at Jakarta, Indonesia, therefore the conference is also conjunction with 22nd Annual Indonesian National Conference on Geotechnical Engineering.

The theme of 20SEAGC-3AGSSEA Conference is "Geotechnical Challenge for Mega Infrastructure", to indicate how mega infrastructure rapidly constructed by Indonesian Government. This conference will cover the wide range topics:

1. Foundation and its problem
2. Deep excavation, basement and tunnels
3. Unsaturated soil mechanics,
4. Sedimentary and residual soils
5. Soft soils and marine foundation
6. Geotechnical and earthquake engineering
7. Geotechnical instrumentation
8. Ground subsidence and sea-water intrusion
9. Vibration and earthquake effect to the structure
10. Soil improvement
11. Slope stability
12. Geo-environmental engineering
13. Finite element method

There will be special keynote address delivered by Ministry of Public Work and Housing of Indonesia, 11 keynote lectures and 84 technical papers to be presented in parallel sessions.

Deep condolences for all victims during the Lombok - Palu - Donggala earthquakes. Liquefaction, flows and deep slide shown as phenomenom during the disaster.

Special gratitude to Menard as main sponsored, Geotekindo and Bauer as co-sponsored and all sponsored who participate in this conference.

Wassalamu'alaikum Wr. Wb.
Jakarta, 6 November 2018

<u>Dr. Pintor T. Simatupang</u>
Conference Chairman

MESSAGE FROM PRESIDENT OF INDONESIAN SOCIETY FOR GEOTECHNICAL ENGINEERING (ISGE)

Dear our honorable guest,

Dr. Basoeki Hadimuljono-Minister of Public Works and Public Housing of the Republic of Indonesia, Prof. Charles Ng - President of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), honorable guests from South East Asian Geotechnical Society (SEAGS) and Association of Geotechnical Societies in South East Asia (AGSSEA), board members of the Indonesian Society for Geotechnical Engineering (ISGE), Chairman of the Engineering Commision of the Indonesian Academy of Sciences, and all Participants; Welcome to our International Conference. This year we held the 20th SEAGSC together with 3rd AGSSEAC in conjunction with our 22nd ISGE annual conference.

"Geotechnical Challenge for Mega Infrastructure" become our theme to answer the challenge we face together from current rapid infrastructure construction. Many geotechnical construction was built in accordance with good soil mechanics and geotechnical understanding, but we need more than that. We need all stages in construction industry can work together, from theory, practical construction, detailing works, comprehensive supervision, and of course the quality assurance process. We need all parties to collaborate together, to move fast forward without no chance for mistake nor failure. No time for failure, ISGE/HATTI collaborate with all parties (national and international) try to ensure there is only one way, and its forward moving.

We understand that there is still many holes in our construction process, not only cause by man made construction but also by the mother of nature. We saw how horrible the Donggala – Palu earthquake last month and we mourn for the caused; but as engineer, we stand; we seek the cause, we learn, we give suggestion and the more important, we stand still, not only as engineers but also as a nation. We stand for the humanity-our pray for them.

Allow us to convey our gratitude to Menard, our main sponsored, Geotekindo and Bauer as our co-sponsored and all sponsored who participate in this event. Also to all speakers, writers, participants, especially to all committee who works to their best for the success of this event.

Last but not least, hopefully this event will brings good and new point of view seeing the geotechnical engineering. Please enjoy the event.

Geotechnical in our heart!!!

Jakarta, 6 November 2018
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Compacted Polymer-Enhanced Bentonite-Sand Mixture – Behaviour and Potential Applications

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ABSTRACT: An investigation into behaviour and potential applications of a polymer-enhanced bentonite-sand mixture (PEBSM) in its compacted state had been carried out in an environmental controlled laboratory. The experiments undertaken included microscopic visualization of the mixture, drying-wetting processes, consolidation and shear strength tests. The results obtained indicate that depending on the overburden pressure acting on the compacted mixture and its water content, settlement in combination with swelling and shrinkage may result in cracks or on contrary may close the initial cracks induced by the mechanical compaction in the field. The conclusions have been drawn based on an analytical assessment performed on the field and laboratory data gathered. A discussion is also brought up on the difference between two approaches used – single-valued effective stress and two-independent stress state variable approaches. The two approaches predict different values of suction at which crack starts to occur and different time-settlement behaviour.

Keywords: Bentonite, swell/shrink, settlement, shear strength, unsaturated soils, cracks.

1. INTRODUCTION

Polymer-enhanced bentonite-sand mixture (PEBSM) has been adopted as landfill liner and/or landfill cover in several countries particularly in Europe. A study on a PEBSM was undertaken pertaining to this application and a field measurement was taken in a location in Germany. This innovative material was developed for the landfill usage and mainly consists of a granular material (sand) mixed with a small amount of sodium type bentonite and a minute amount of polymer with certain proportions. The following figures show the environmental scanning electron microscopy photos taken and reported by Agus et al. (2007). The photos clearly depict bentonite-polymer nets that have been formed when water is added to the mixture. The minute amount of polymer added to the mixture covers the surface of bentonite clusters and sand grains.

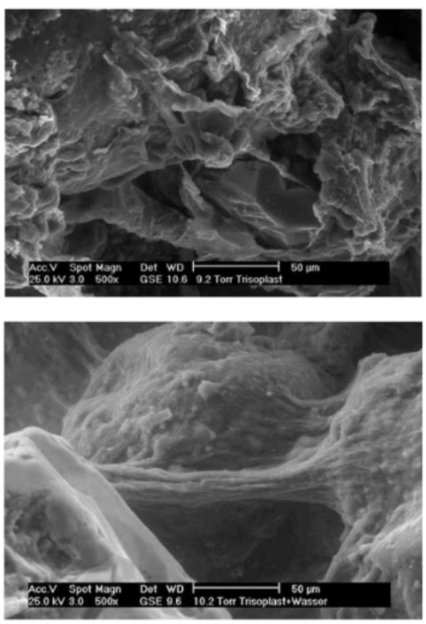
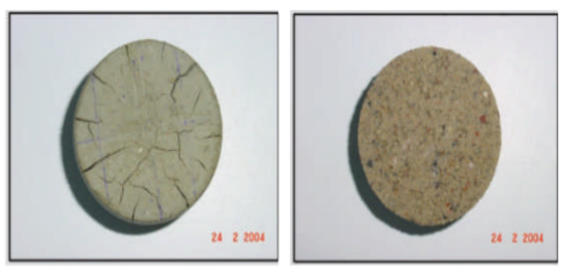


Figure 1 Polymer in interaction with bentonite particles (from Agus et al., 2007)

The bentonite presence is beneficial to the hydro-mechanical behaviour as reported earlier by Arifin et al. (2006). As described in various publications, the magnitude of swelling pressure of compacted samples containing bentonite and its hydraulic conductivity depend on the dry density of the compacted material.

Depending on the magnitude of vertical pressure acting in the field, the compacted mixture, when in contact with water, may exhibit swelling or settlement and/or cracks under the influence of weather i.e. during drying-wetting cycles. In contrast, another possible scenario may occur, whereby initial cracks earlier induced by mechanical compaction or some other processes close during the cycles.

During drying cycle, it is highly possible that suction exists in the compacted mixture and its magnitude changes with time and may reach zero value when saturation is attained. The addition of polymer in the mixture improves resistance of the compacted material to crack. Visual observation made by Schanz et al. (2004) indicates that when exposed to the same suction value the compacted PEBSM exhibits no apparent cracks in contrast to the compacted mixture without polymer addition.



(a) Without polymer addition (b) With polymer addition

Figure 2 Crack developed under suction application on compacted specimens (from Schanz et al., 2004)

Theoretically, the development of cracks in the compacted mixture can be predicted utilising the unsaturated soil principles. Two different approaches can be used for this purpose; namely, using the single-valued effective stress concept and the two-independent stress state variables approach. This is the subject brought out in this paper. Data from a field measurement have been utilised in the study. Critical suction at which cracks start to occur is also formulated.

2. FIELD TEST DATA

The field test data that have been used in the study had been gathered from a landfill site located in Germany. A test field of about 2,800 m^2 in area had been established at the site, where suction measurement by means of tensiometer had been undertaken in the PEBSM layer for about 4.5 years' duration.

The degree of saturation of the PEBSM was calculated from the measured suction (in this case matric suction) using its soil-water characteristic curve, which was measured and reported in Schanz et al. (2004).

The SWCC of the compacted PEBSM portrays its good water retention characteristic as indicated by a small drop in the degree of saturation over a "wide" range of suction (up to 100 kPa).

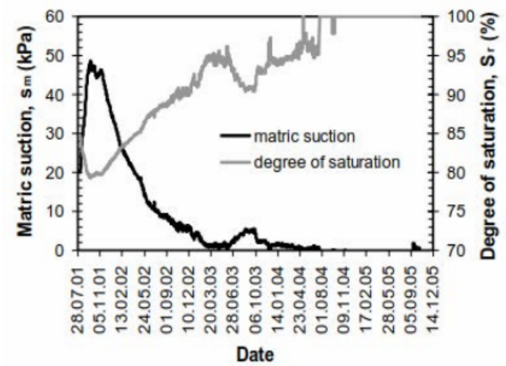


Figure 3 Measured matric suction and computed degree of saturation of the compacted PEBSM layer

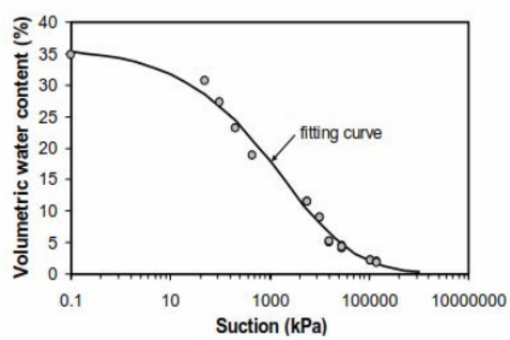


Figure 4 Soil-water characteristic curve for the compacted PEBSM speciemen (from Schanz et al., 2004)

On site, the PEBSM was laid approximately 1 meter deep from the final ground surface leading to a surcharge of approximately 20 kPa or slightly lesser. The initial conditions of the PEBMS in the field test are as following:

- Initial dry density (γ_d) : 1.75 Mg/m^3
- Initial void ratio (e) : 0.52
- Initial water content (w) : 5%
- Initial degree of saturation (S_r) : 25.6%

With a 1-m thick recultivation and drainage layer, the total vertical overburden stress acting in the middle of the compacted PEBSM of 7 cm can be computed to be equal to 20.6 kPa.

3. STRESS-STRAIN RELATIONSHIP

As described in the preceding section, the field experimental data had been analysed based on two approaches; namely, the single-valued effective stress concept and the two-independent stress state variables approach. The formulation of both approaches is described below.

3.1 Single-Valued Effective Stress Concept

This concept is based on the framework proposed by Bishop (1959), which is formulated as:

$$\sigma = (\sigma - u_a) + \chi s \tag{1}$$

Where (σ - u_a) is the net stress, χ is a coefficient which depends mainly on the degree of saturation, S_r, soil structure and cycle of wetting, drying, or stress change, and s is suction, which is defined as matric suction or (u_a-u_w).

The χ coefficient is a function of degree of saturation of soil and the following simple form can be used:

$$\chi = f(S_r) = S_r \tag{2}$$

Vertical and horizontal effective stresses can subsequently be defined as below, with K_o represents the coefficient of earth pressure at rest:

$$\sigma_v' = (\sigma_v - u_a) + S_r s \tag{3}$$

$$\sigma_h' = (\sigma_h - u_a) + S_r s = K_o(\sigma_v - u_a) + S_r s \tag{4}$$

As suction in the field changes, the effective stress of the liner will also change, which follows the following equation:

$$\Delta\sigma_v' = \Delta\sigma_h' = S_r \Delta s + s\Delta S_r \tag{5}$$

Assuming the K_o condition applies, which is reasonable for this case, the relationship below holds:

$$\Delta\varepsilon_v \; or \; \Delta\varepsilon_{vol} = \frac{1}{E}\Delta\{ [(\sigma_v - u_a) + S_r s] - 2\upsilon \, [(\sigma_h - u_a) + S_r s] \} \tag{6}$$

where E is the modulus of elasticity with respect to change in net stress and υ is the Poisson ratio of the soil. The following figure shows changes in the vertical and horizontal effective stresses due to changes in the soil suction, which have been derived using Figure 3, Figure 4 and Equation (5).

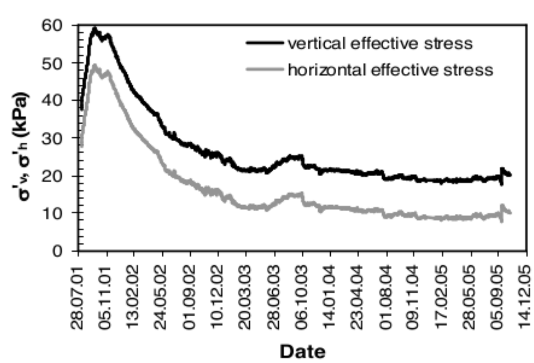


Figure 5 Changes in vertical and horizontal effective stresses with time

The K_o condition only holds when soil blocks do not develop as a result of cracks that develop due to desiccation. In the case of crack, the horizontal net stress follows:

$$(\sigma_h - u_a) = \frac{\upsilon}{(1-\upsilon)}(\sigma_v - u_a) - \frac{(1-2\upsilon)}{(1-\upsilon)} S_r s \tag{7}$$

The changes in vertical and horizontal strains in the event of crack can be expressed as:

$$\Delta\varepsilon_v = \frac{1}{E}\Delta\{[(\sigma_v - u_a) + S_r s] - 2\upsilon S_r s\} \tag{8}$$

$$\Delta\varepsilon_h = \frac{1}{E}\Delta\{(1-\upsilon)S_r s - \upsilon[(\sigma_v - u_a) + S_r s]\} \tag{9}$$

3.1 Two-Independent Stress-State Variable Approach

The formulation of this approach is outlined in Fredlund and Rahardjo (1993), where changes in two state variables used (i.e. net stress and suction) and the resulting effects are considered separately.

In the case of the K_o condition ($\Delta\varepsilon_v = \Delta\varepsilon_{vol}$), the volumetric strain is given as:

$$\frac{(1+\upsilon)(1-2\upsilon)}{E(1-\upsilon)}\Delta(\sigma_v - u_a) + \frac{(1+\upsilon)}{H(1-\upsilon)}\Delta s \tag{10}$$

In the above equation, H represents the modulus of elasticity of the soil with respect to suction change (the 2nd stress state variable), while as described before, E signifies the modulus of elasticity for the effect of net stress (the 1st stress state variable) change.

During crack, the horizontal net stress is defined as:

$$(\sigma_h - u_a) = \frac{\upsilon}{(1-\upsilon)}(\sigma_v - u_a) - \frac{E}{H(1-\upsilon)} s \tag{11}$$

The changes in vertical strain ($\Delta\varepsilon_v$) and horizontal strains ($\Delta\varepsilon_h$) after crack are formulated as:

$$\frac{1}{E}\Delta\{(\sigma_v - u_a) - 2\upsilon(\sigma_h - u_a)\} + \frac{1}{H}\Delta s \tag{12}$$

$$\frac{1}{E}\Delta\{(\sigma_h - u_a) - \upsilon[(\sigma_v - u_a) + (\sigma_h - u_a)]\} \tag{13}$$

4. PARAMETERS USED IN COMPUTATION

The following parameters have been used in the computation and the values have been derived as outlined in this section.

1) Coefficient of earth pressure at rest (K_o)
2) Poisson ratio (υ)
3) Modulus of elasticity with respect to change in net stress (E)
4) Modulus of elasticity with respect to change in suction (H)

4.1 Coefficient of Earth Pressure at Rest (K_o)

The Ko value was determined from the experiment carried out in Geodelft, Netherlands. The value is equal to 0.52.

4.2 Poisson Ratio (υ)

The Poisson ratio (υ) is calculated from the elastic theory as follows (with K_o equal to 0.52):

$$\upsilon = \frac{K_O}{1+K_O} = 0.34 \tag{14}$$

4.3 Modulus of Elasticity with Respect to Change in Net Stress (E)

The E value has been derived using the elastic theory from the saturated oedometer test data for the unloading-reloading, which is deemed to be within the elastic range:

$$m_v = \frac{\Delta e}{(1+e_0)}\frac{1}{\Delta\sigma'} = \frac{1}{E}\frac{(1+\upsilon)(1-2\upsilon)}{(1-\upsilon)} \tag{15}$$

where m_v is the coefficient of volume compressibility of soil. The average m_v value obtained from the saturated oedometer test results of the PEBSM specimen compacted at dry side as shown in Figure 6 is $1.798\text{x}10^{-5}$ /kPa. Thus, the corresponding E value is 36,134 kPa.

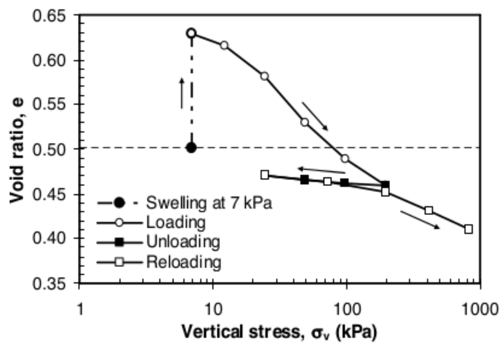


Figure 6 Oedometer test result on a saturated compacted PEBSM specimen

4.4 Modulus of Elasticity with Respect to Change in Suction (H)

The H value was computed from the e-log suction plot that had been obtained while determining the SWCC curve (Schanz et al., 2004). The SWCC had been determined at three-dimensional free swell/shrink conditions. Therefore, the following relationships hold:

$$\Delta\varepsilon_v = \Delta\varepsilon_{vol} = C_t\Delta(\sigma_v - u_a) + C_a\Delta s \tag{16}$$

$$C_t = \frac{\Delta e}{(1+e_0)}\frac{1}{\Delta(\sigma - u_a)}; C_a = \frac{\Delta e}{(1+e_0)}\frac{1}{\Delta s} \tag{17}$$

Analogous to the unloading-reloading path, from which the E value has been derived, the corresponding drying-wetting cycles of the PEBSM should also be used to determine C_a value. However, due to the unavailability of the wetting data, only the drying path has been considered in the derivation of C_a value. The following figure shows the drying test on the material.

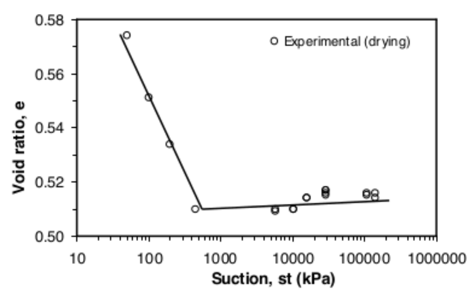


Figure 7 Change in void ratio with increasing suction from a drying test on compacted PEBMS

The void ratio-suction curve exhibits a bimodal characteristic with negligible changes for suction above 500 kPa. The linear portion of the curve up to 500 kPa suction is within the suction range, at which the material was subject to in the field and thus can be used to determine the C_a value. From the curve, the C_a value is 1.017×10^{-4} /kPa, and thus a H value of 29,500 kPa as for this case $C_a = 3/H$.

5. DEFORMATION AND SETTLEMENT

Computation of settlement and deformation as a result of the change in suction, which was measured by the tensiometer, has been carried out using the parameters derived as described in the preceding section.

5.1 Computation using Single-Valued Effective Stress Concept

As described in Section 2, a change in the net vertical stress ($\Delta(\sigma_v - u_a)$) of 20.6 kPa was applied on the compacted PEBSM layer after placement. The corresponding change in the net horizontal stress ($\Delta(\sigma_h - u_a)$) is therefore equal to 10.7 kPa. The initial suction of the PEBSM was determined from the SWCC given the placement water content and dry density of the compacted layer and the value was 4.4 MPa. Immediately after placement, the tensiometer measured 20.1 kPa and therefore the material was subjected to a significant suction change once placed in-situ. The corresponding change in degree of saturation of 59% can be computed from the SWCC.

The initial strain and deformation due to placement can be computed and the values are summarised in the following table.

Table 1 Initial Strain and Deformation Computed using the Single-valued Effective Stress Concept

	Without cracks	With cracks
Vert. strain, ε_v (%)	-3.3	-3.2
Hor. strain, ε_h (%)	0	-3.3
Vert. deform. ,d_v (cm)	-2.3	-2.3
Hor. deform. ,d_h (cm)	0	-3.3

Note: -ve indicates expansion

5.2 Computation using Two-Independent Stress-State Variable Approach

As mentioned earlier, the H value for the compacted PEBSM layer was derived from the drying path. Realistically, the value for the wetting path is much higher than that from the drying cycle. The following table summarises the initial strain and deformation due to placement computed using the two-independent stress state variable approach.

Table 2 Initial Strain and Deformation Computed Using the Two-independent Stress-state Variable Approach

	Without cracks	With cracks
Vert. strain, ε_v (%)	-3.3	-1.6
Hor. strain, ε_h (%)	0	-1.7
Vert. deform. ,d_v (cm)	-2.3	-1.3
Hor. deform. ,d_h (cm)	0	-1.7

Note: -ve indicates expansion

In this computation, the realistic H value used in the computation was first approximated by matching the settlement plot from both approaches. It is later demonstrated that taking the realistic H value of 8 to 10 that of the drying is reasonable and an average value of 9H (i.e. 265,500 kPa) was subsequently used.

The subsequent changes in vertical and horizontal strains were computed based on an assumption that the changes in vertical and horizontal net stresses are equal to zero. This is adopted for both approaches when computing the evolution of deformation and settlement due to changes in suction of the PEBSM layer on site.

5.3 Comparison of Computed Strain and Settlement

It is shown in the two tables that the use of two different approaches affects the initial strains and deformation computation for the case with cracks with the two-independent stress-state variable approach estimating half the values compared with the single-valued effective stress concept.

The following figure illustrates that, for the case of K_o condition, the use of H value from the drying curve result in much higher settlement estimated using the two-independent stress-state variable approach. This is inconsistent since at the K_o condition, cracks do not occur and both approaches should give approximately the same result.

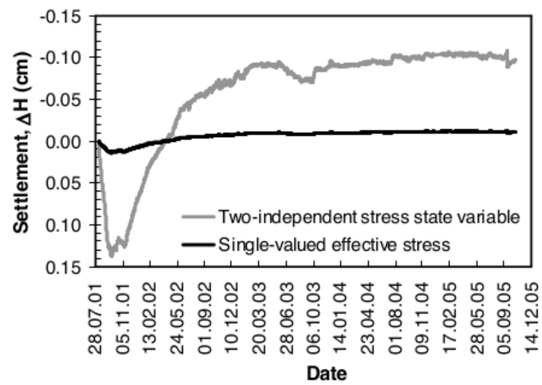


Figure 8 Comparison of settlement with time from two different approaches

The variation of time-settlement plot for the two-independent stress state variable approach is shown in the following figure using the realistic H value equal to 8 and 10 times that determined from the drying test as described earlier. It is demonstrated that an average value of 9H provides the best fit to the settlement plot from the single-valued effective stress concept.

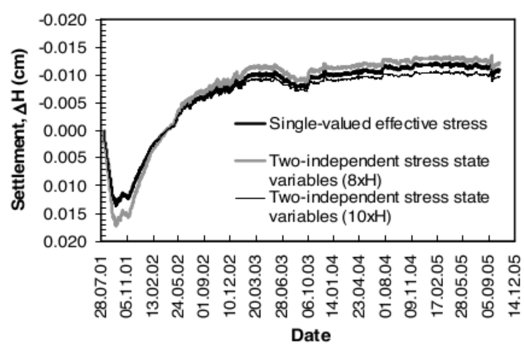


Figure 9 Determination of actual H value

The evolution of vertical strain assuming K_o condition is shown in Figure 10 for both methods. The single-valued effective stress concept consistently gives lesser vertical strain compared with that given by the two-independent stress-state variable approach, although the magnitude does not differ significantly.

Figure 11 and Figure 12 demonstrate that the two-independent stress-state variable approach produce lower values of vertical and horizontal strains for the case when crack occurs.

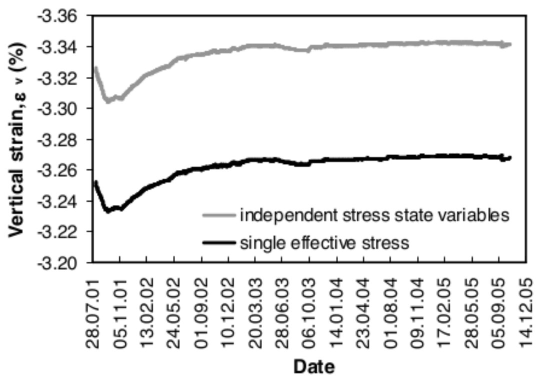


Figure 10 Vertical strain with time computed using the two approaches (K_o condition)

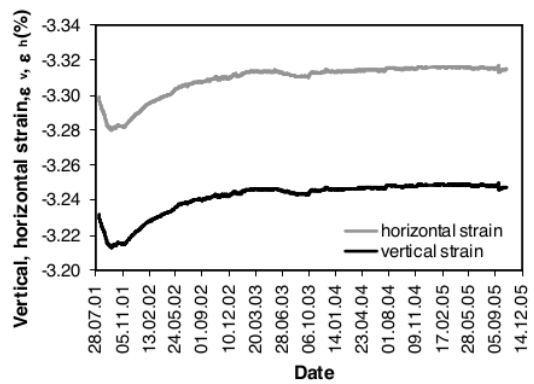


Figure 11 Vertical and horizontal strains computed using the single-valued effective stress concept (after crack occurs)

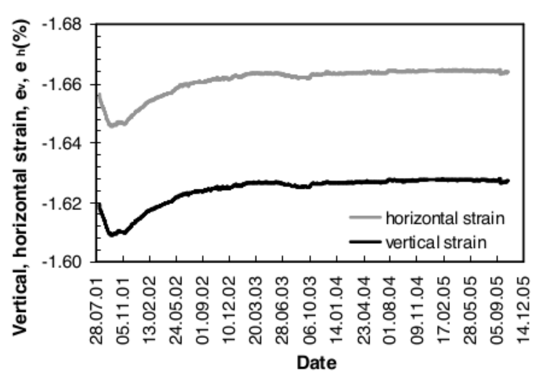


Figure 12 Vertical and horizontal strains computed using the two-independent stress-state variable approach (after crack occurs)

5. CRITICAL SUCTION AT FIRST CRACK OCCURRENCE

Resistance to cracks is provided by the tensile strength of the soil and thus crack occurs when the negative net horizontal stress exceeds this value. Nevertheless, when desiccation takes place, the extent of cracks in the PEBSM layer in the field may not be sufficiently deep to facilitate full development of preferential flow paths.

The suction value, at which cracks first occur is defined as the critical suction (s_{cr}) and the value can be computed by equating the net horizontal stress with the maximum tensile strength (t_{max}). Schanz et al. (2004) reported that t_{max} value of the PEBSM is 20 kPa on average.

The following equations represent the critical suction for the single-valued effective stress concept and the two-independent stress-state variable approach, respectively.

$$s_{cr} = \left[\frac{\upsilon}{(1-\upsilon)}(\sigma_v - u_a) - t_{max}\right]\frac{(1-\upsilon)}{(1-2\upsilon)}\frac{1}{S_r} \qquad (18)$$

$$s_{cr} = \left[\frac{\upsilon}{(1-\upsilon)}(\sigma_v - u_a) - t_{max}\right]\frac{H(1-\upsilon)}{E} \qquad (19)$$

Equation (18) must be solved iteratively since S_r is the function of suction, while s_{cr} from Equation (19) can be computed straightforward since both E and H are assumed to be constant with net vertical stress and suction, respectively. Nevertheless, it is imperative to note this assumption may not be always valid since in reality, E, H and t_{max} are also stress and suction dependent.

The critical suction can also be plotted as a function of the total vertical stress using both the above equations. The following figure shows such plot for the PEBSM studied.

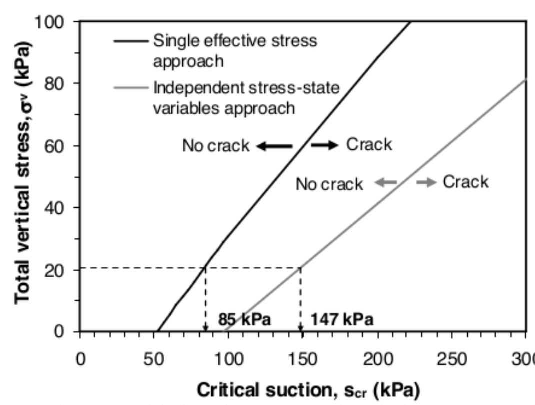


Figure 13 Critical suction versus total vertical stress computed using the two approaches

The above figure reveals that at the applied total vertical stress of 20.6 kPa (the air pressure is atmospheric), the s_{cr} value is 85 kPa computed using the single-valued effective stress concept and 147 kPa using the two-independent stress-state variable approach. At any given applied total vertical stress, the two-independent stress-state variable approach gives a higher value of s_{cr} compared with the other approach. Further detailed investigation will warrant clarity at which cracks really commence during drying.

Considering that the maximum measured suction is only approximately 50 kPa (see Figure 3), cracks will not occur in the compacted PEBSM layer. It may not be the case when polymer is not added to the compacted bentonite-sand mixture due to presence of macro- and micro-pores within the mixture.

The mechanism of crack in the compacted bentonite-sand mixture has been described in detail by Agus (2005). Consider a representation of a compacted bentonite-sand mixture in Figure 14. A rapid desiccation results in movement of water in the inter-aggregate pores (macro-pores), which is not accompanied by sufficient macro-pore volumetric contraction. The presence of polymer in the compacted mixture will prevent this rapid desiccation process to occur, at least at low suction (i.e. below 100 kPa), which is practically even higher than the maximum value that can occur in the field when the compacted PEBSM layer is used in landfill.

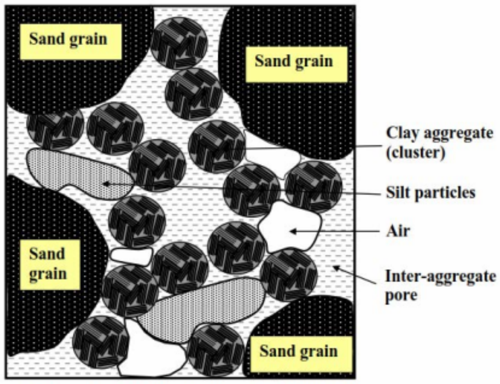


Figure 14 Possible representation of a compacted bentonite-sand mixture (from Agus, 2005)

6. POSSIBLE APPLICATIONS

Due to its characteristics as described, the compacted PEBSM is suitable for landfill application. The material is better placed under a drainage layer to ensure that suction remains low and deep cracks are not present during the landfill design life. The effectiveness of placing the compacted PEBSM below the waste is questionable since interaction between the bentonite-polymer with leachate from the landfill may degrade the beneficial properties of the mixture.

7. CONCLUSION

An investigation into the behaviour of a compacted PEBSM has been conducted by means of a field case study. The following conclusions can be drawn from the outcome of the study.

1) A maximum suction value of 50 kPa was measured during an approximately 4-year period in the case study presented in this paper. The corresponding drop in degree of saturation as computed from the soil-water characteristic curve (SWCC) is hardly below 80%, which indicate a good water retention capability of the material.
2) Strain and deformation computed using the two-independent stress-state variable approach are approximately half those derived using the single-valued effective stress concept. The former computation is realistic when adopting a realistic modulus of elasticity with respect to change in suction (realistic H) of 8 to 10 times H derived from the drying test.
3) Critical suction at which cracks start to occur (scr) has been computed and the value is consistently lower for the two-independent stress-state variable approach at any given net or total vertical stress (with atmospheric air pressure).

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Compacted Polymer-Enhanced Bentonite-Sand Mixture – Behaviour and Potential Applications

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