

A NEW METHOD FOR ESTIMATING THE MOISTURE CONTENT AND FLEXIBILITY OF POLYMERISED BENTONITE CLAY MAT

E. W. K. LOH^{1,*}, D. C. WIJEYESEKERA², M. A. CIUPALA³

¹Faculty of Built Environment, Linton University College, Negeri Sembilan, Malaysia

²Faculty of Civil & Environmental Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia

³School of Architecture, Computing and Engineering, University of East London, London, United Kingdom

*Corresponding Author: ericdrloh@gmail.com

Abstract

This paper presents a scientific development to address the current absence of a convenient technique to identify the ductile to brittle transition of bentonite clay mats. The instrumented indentation and 3-point bending tests were performed on different liquid polymer hydrated bentonite clay mats at varying moisture content. Properties measured include modified Brinell Hardness Number (BHN) and elastic structural stiffness (EI). The dependence of flexural stiffness on moisture content is demonstrated to conform to a best power function variation. The ductile to brittle transition of clay mat is affected primarily by the change in the moisture content and for the clay mat to remain flexible, critical moisture content of 1.7 times of its plastic limit is required. Results also indicate that a strong correlation between indentation hardness and the structural stiffness. The subsequent outcome in the development of a portable quality control device to monitor the acceptable moisture content level to ensure flexibility of the clay mats was also described in this paper.

Keywords: Clay mats, Indentation hardness, Flexural stiffness, Moisture content, Bentonite.

1. Introduction

Geosynthetic Clay Liners (GCLs) are sealing elements and commonly known as factory-manufactured contaminant / leachate / fluid barriers that consist of a thin layer of either calcium or sodium bentonite core sandwiched between two geomembranes or geotextiles. Over the past decade, design engineers and

environmental agencies have developed a growing interest in the application of GCLs as an alternative / preference to compacted clays in cover systems or as bottom lining of waste containment facilities. They have also gained widespread use in a variety of sealing applications, predominantly in hydraulic engineering, structural water proofing and groundwater protection. In order to meet the potential to be an effective contaminant barrier in hostile geochemical environments, a factory controlled prehydration with cation exchange resisting polymer prior to installation is always necessary [1-5]. The factory manufacturing process requires the Polymerised Bentonite Clay Mat (PBCM) to be at an appropriate moisture condition to facilitate the rolling process and also possess sufficient flexibility and tensile strength to remain integral [6]. These polymerised bentonite are essentially fine grained and it is critical that the consistency of the clay is preserved to ensure that the mat remains flexible with no possibility of it developing brittle fractures. However, if the PBCM undergoes isothermal drying, the flexibility can reduce to the point where it can become brittle.

The quality control measure for the PBCM could be improved significantly if the understanding of ductile to brittle transition with regard to flexibility of the PBCM was addressed. Research in this area, however, in comparison with other aspects of engineering behaviour of clay, has been minimal despite its obvious significance as a basic physical characteristic of clay. One could argue that this critical moisture content is near the plastic limit of the clay. This simple definition coincides with the necessity to quantify the flexural stiffness as a physical unit. In this paper, investigations were carried on the use of indentation technique to quantify the flexibility of PBCM and discusses the influence of isothermal drying of the flexibility of the clay mats. It then proceeds to establish the workable limits of moisture contents for the mats.

2. Model Development

2.1. Flexural stiffness measurement

The flexural stiffness observations comprised of load-deformation curves for specimen where simply supported to produce transverse bending as shown in Fig. 1. A modified version of the standard 3-point bend test, ASTM D790 [7] was used to quantify flexural stiffness, EI (where E is the Modulus of Elasticity and I is the area moment of inertia). The 3-point bending was chosen over alternatives such as 4-point or cantilever bending to prevent excess plastic deformation at the load point and failure under self-weight. With this procedure, a rectangular specimen (cross-section $a \times b$) was flexed across a small load point to provide the mid-span deflection. The sample dimensions ($120 \times 50 \times 5$ mm) were selected by a length/thickness and width/thickness ratio of 24 and 10. At the onset of testing, the specimen is balanced against self-weight on two supports. To avoid excessive plastic deformation, an increment of 5g was applied each time. The mid-span deflection of the specimens was observed with the help of a traveling microscope. EI can be calculated using Eq. (1) and the slope of the initial linear portion of the graph is used in the evaluation of EI , as shown in Eq. (2).

$$EI = \frac{WL^3}{48\Delta} \quad (1)$$

$$EI = \frac{\alpha L^3}{48} \quad (2)$$

where EI is the flexural stiffness [Nm^2], W is the load [N], L is the specimen length between two support point [m] and Δ is the mid-span deflection [m], α is the initial slope of the load vs. deflection curve.

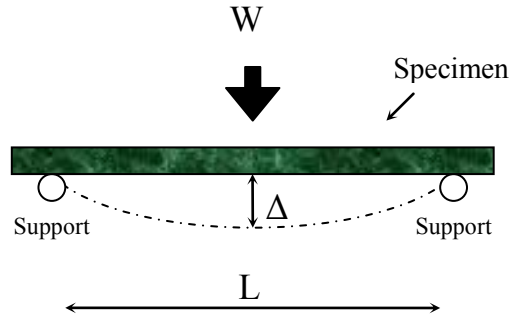


Fig. 1. Schematic diagram of the standard 3-point bend test.

2.2. Continuous indentation measurement

The Brinell hardness test, proposed by Swedish engineer Johan August Brinell in 1900, is widely used in industrial metallurgy [8]. The test observes the indentation made on the specimens by forcing a non-deformable sphere of a specified diameter under a specified load into the surface of a material and measuring the diameter of the indentation left after the test. The BHN is expressed by the following expression:

$$BHN = \frac{F}{\frac{\pi}{2} D \times (D - \sqrt{D^2 - D_i^2})} \quad (3)$$

where BHN is the Brinell hardness number [the result is equivalent to pressure measurement, but the units are rarely stated], F is the imposed load [N], D is the diameter of the spherical indenter [mm] and D_i is the diameter of the resulting indenter impression [mm].

To overcome difficulties encountered in measuring the size of the residual imprint, a continuous indentation test approach was adopted as an alternative to the conventional way. The continuous indentation testing was carried out on 50-mm diameter samples, using a standard loading frame with 12.7mm diameter spherical steel indenter fitted to the end of the loading ram. The indentation load-depth curve was obtained by continuously measuring the applied load and the penetration depth during the test. From the indentation load-depth curve, values for the continuous indenter diameter, D_i , can easily be obtained from the geometrical relationship as shown in Fig. 2. and can be calculated from the following equation:

$$D_i = 4t(D - t) \quad (4)$$

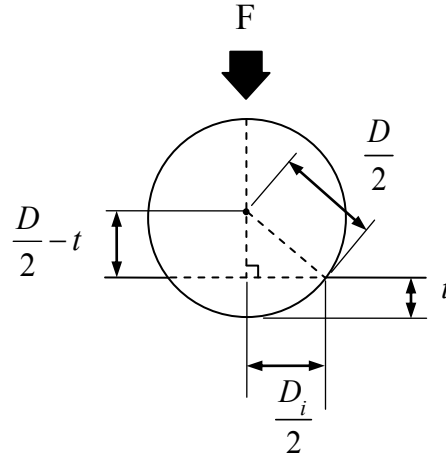


Fig. 2. Schematic diagram of Brinell hardness test.

3. Sample Preparation

The PBCM sample used in the experimental measurements was polymer hydrated and vacuum extruded bentonite. One of the primary purposes of the liquid polymer treatment is to improve the rheological properties of the clay mats. Discussion of these polymers and the compositions are beyond the remit of this paper. The pressure applied during extrusion and suction treatment remove any air trapped or potentially trapped within the mixture, so as to avoid any number of voids in the specimen as well as urging the molecules of the sample closer together. The X-ray diffraction (XRD) analysis showed the clay mineralogy of the bentonite to be smectite (93%), quartz (2%), feldspars (4%) and gypsum (1%). Bulk sample is composed of 87.5% of particles in a size range less than $75\mu\text{m}$ and air dried moisture content of 10 -14% by weight. The Liquid Limit (110%) and Plastic Limit (18%) of the PBCM were determined by standard test routines in the laboratory. Full detail of the procedures and apparatus are given in BS 1377: 1990 [9]. All specimens were cut with a razor blade to the required dimensions as required in each test. These samples were initially kept in the oven at 40°C for appropriate time intervals to achieve the desired equilibrium moisture content. The isothermal drying kinetic of the specimens have been described elsewhere [10-11].

4. Results and Discussion

The EI values of the PBCM samples have been determined from load-deflection curves by using Eq. (1) and (2). Moisture content variation effects on the flexural stiffness were investigated using a simplex exponential and power mathematical model and are presented in Fig. 3. The Power type regression was the most appropriate as the values of R^2 for the samples (0.9805) were greatest when compared to the Exponential type regression (0.9725). However, the Power regression at moisture content of 0% gives an indeterminate EI value which is possible to achieve. Therefore, Power regression was applicable for moisture contents greater than zero.

One can notice a decrease in the moisture content will increase the stiffness of specimens and thus reduce the flexibility of the clay mats, i.e., the flexibility of the clay mat is highly dependent on its moisture content. Figure 4 further illustrates the ductile to brittle transition with regard to flexural stiffness of the clay mat. It is evident that two unique moisture contents were identified in the ductile to brittle transition of the clay mat. They are namely at moisture content of: (a) 18% - the plastic limit of the clay mat; (b) 32% - the EI of the clay mat increases at a greater magnitude below this moisture content.

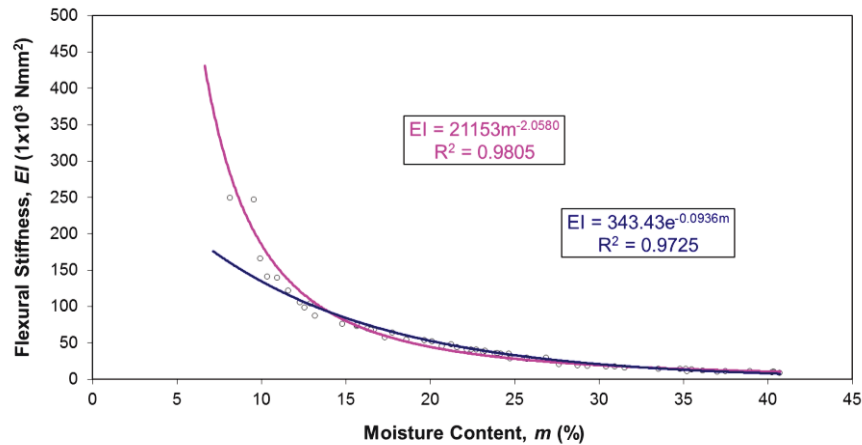


Fig. 3. EI of polymerised bentonite clay mat with power and exponential regression.

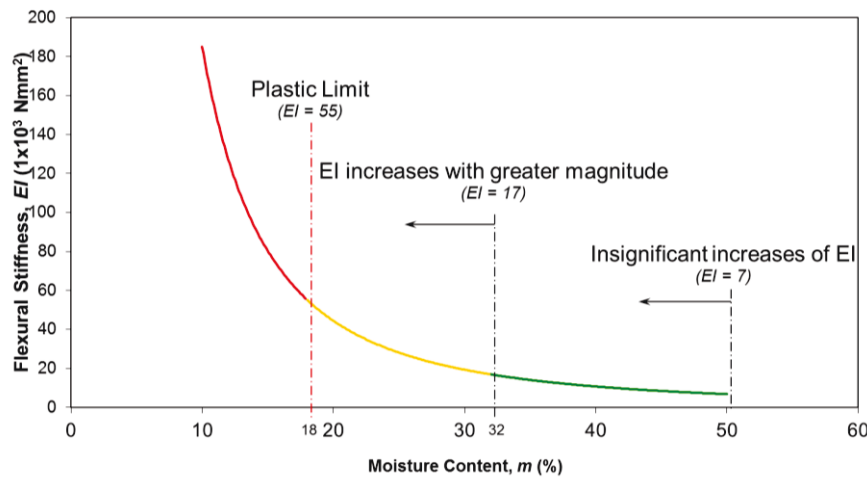


Fig. 4. Ductile to brittle transition with regard to flexural stiffness of the clay mat.

On the basis of Eq. (3) and (4), the BHN has been derived from the load-depth curve. The BHN for PBCM samples are plotted with change of its moisture content. The best fit curve was obtained to find the reliable correlation. Exponential and power functions were used for the curve fitting analysis as

shown in Fig. 5. The Power type regression having greater values of R^2 (0.9613) when compared to the Exponential type regression (0.9488).

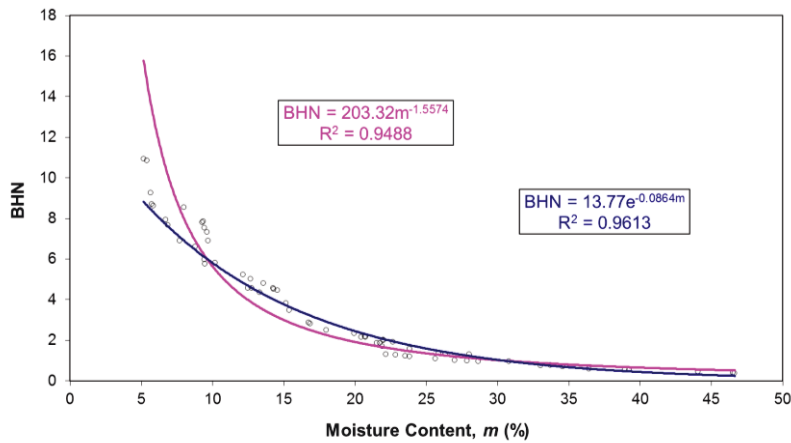


Fig. 5. BHN of polymerised bentonite clay mat with power and exponential regression.

From the best fit of the regression analysis, it is concluded that the most reliable regression for EI vs Moisture Content and BHN vs Moisture Content lies on a Power and Exponential trend respectively. The corresponding equations are:

$$EI = 21153m^{-2.0580} \quad (5)$$

$$BHN = 13.77e^{-0.0864 m} \quad (6)$$

It can be concluded that the most reliable regression for the clay mat follows a power and exponential trend for the EI and BHN respectively. Consequently, the correlation of BHN and EI was derived from Eq. (5) and (6) and is presented in Fig. 6.

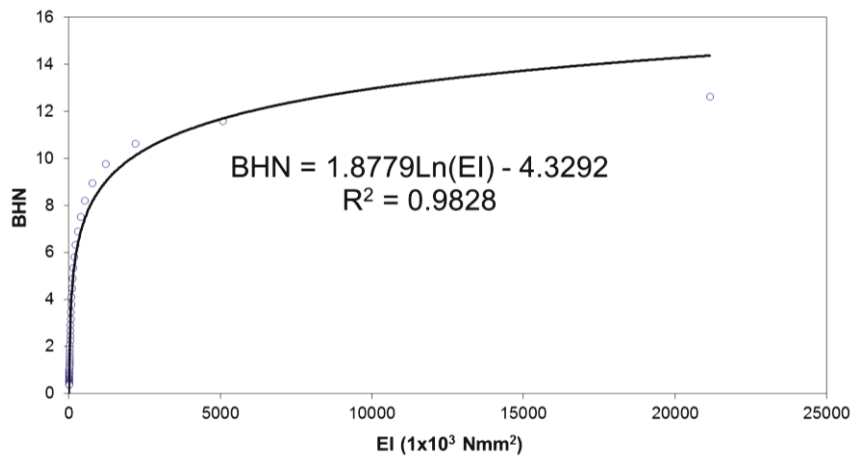


Fig. 6. Correlations of BHN and EI.

5. Contribution from Research Work

The resulting indentation diameter was shown to be dependent on moisture content of the clay mats. Rearranging Eq. (3), the resulting indentation diameter (D_i) becomes:

$$D_i = \sqrt{D^2 - \left(D - \frac{F}{BHN \times \frac{\pi}{2} \times D} \right)^2} \quad (5)$$

A known spherical diameter (D) and load (F) will give a unique indentation diameter (D_i) that will characterise the moisture content. Figure 7 shows a family of curves for different indenter mass with a 10 mm diameter sphere on the resulting indentation diameter. Within the moisture content range, the distinction of the indented diameter is more pronounced with an increase in the indenter mass. It can be seen that the family of curves for various indenter mass gave a good fit ($0.9968 < R^2 \leq 1$) to the resulting indentation diameter. However, the 0.10, 0.25 and 0.50 kg of indenter mass cause issues regarding existing range of the resulting indented diameter. Furthermore, the practicability to measure a dimension less than 1 mm is difficult without any magnification aid. This fact gives a very explicit suggestion that an indenter mass of less than 1 kg is inappropriate to be adopted. It is also observed that beyond a mass of 2 kg, the representative best fit curve reduced by a considerable magnitude. Therefore, based on the above arguments, an indenter with 2 kg mass and 10 mm diameter sphere was chosen in the design due to the ease of handling and its favorable range of resulting indentation diameters.

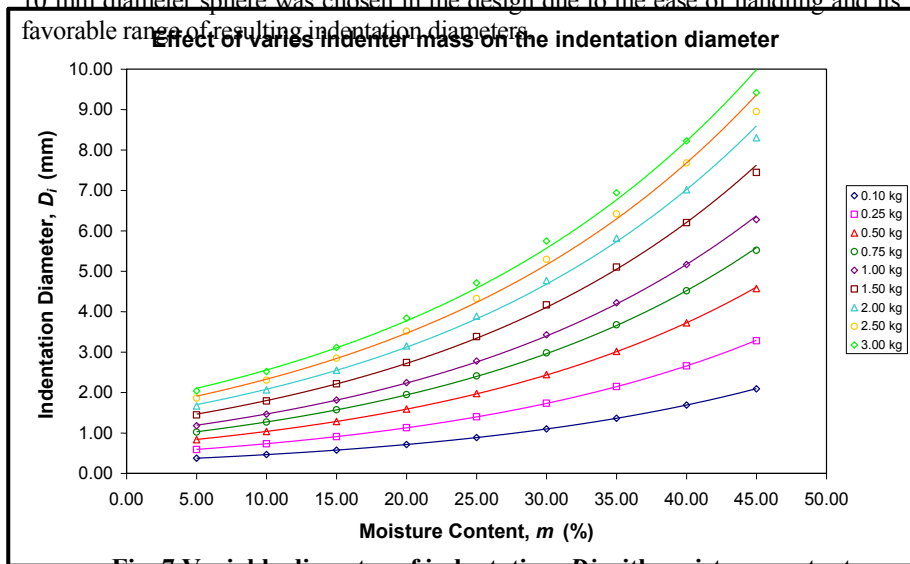


Fig. 7 Variable diameter of indentation, D_i with moisture content.

Figure 8 presents the analysis of the characterisation study of moisture content based on an indenter with 2.00 kg mass and 10mm diameter sphere. This refers exclusively to the developed indenter showing the resulting indentation diameter with moisture content. It is noteworthy that: (a) the resulting 3 mm and 5 mm indentation diameters occur at the moisture content of 18% and 32% respectively; (b) two tangent lines cross at the moisture content of 32%. This finding further helps to define the critical ductile to brittle transition for the clay mat to remain

flexible as 1.7 times its plastic limit. The moisture characterisation curve presented in Fig. 8 was divided into four different colour zones, i.e., red, amber, green and pink as an aid to interpretation

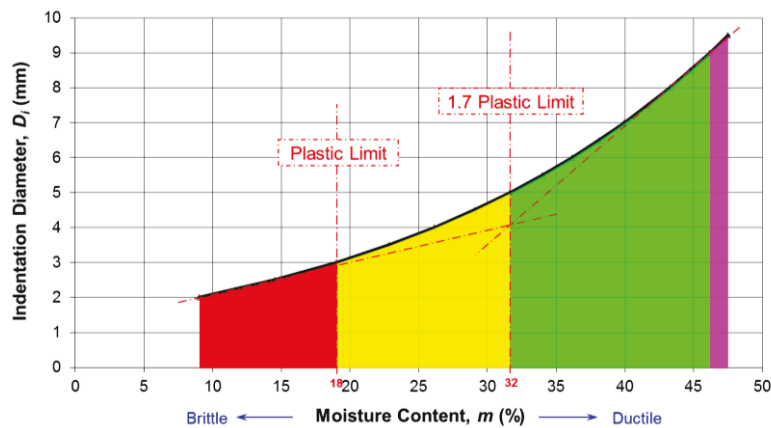


Fig. 8 Characterisation of moisture content based on an indenter with 2 kg mass and 10mm diameter sphere.

The quality control device developed by the authors for the assessment of the flexibility of the clay mat follows the principles based on the aforesaid discussion. The device helps to conveniently assess the level of moisture content by observing the indented diameter. Figure 9 shows the components of this quality control device. The core of the device consists of a steel cylinder with a handle attached at the top and 10mm diameter spherical steel ball soldered at the base to give a final mass of 2.0 kg. The nylon sleeve is a guide to hold the steel cylinder vertical during the test. Finally, the transparent measuring template with various diameter and colours is used to observe the resulting indentation diameter. In order to use this as a means to assess the moisture content/flexibility of the clay mat, a template was developed (see Fig. 10.). The template aids to measure the resulting indented diameter and is approximately colour coded in red, amber, green and pink to reflect the moisture content/flexibility scale.

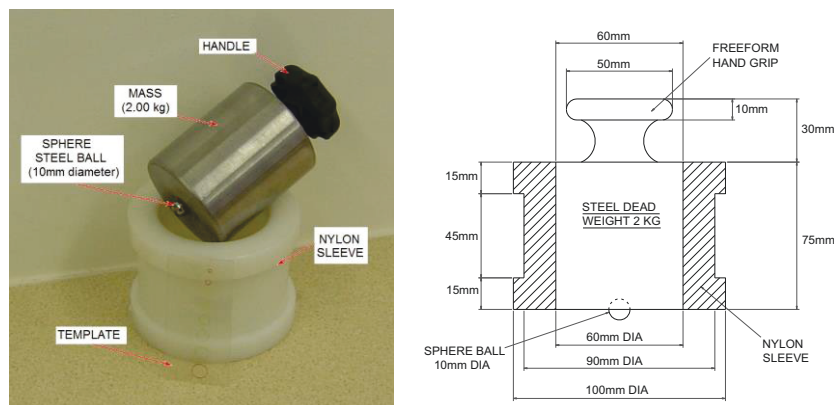
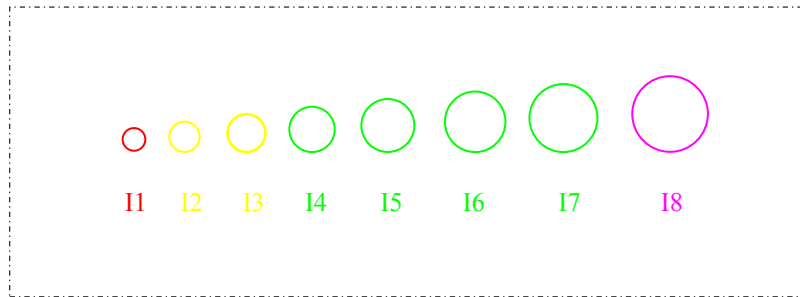


Fig. 9. Photo and schematic diagram of the portable quality control device.



**Fig. 10. Measurement template
with various diameter and colour (in real scale).**

6. Conclusions

The concept of relating an appropriately indented imprint to the flexural stiffness obtained from 3-point bending test was presented and developed to investigate the efficiency on flexibility study of the clay mat. The instrumented indentation and 3-point bending tests were performed on different liquid polymer hydrated bentonite clay mats at varying moisture content. Some concluding observations from the investigation are given below.

- The use of simplex exponential and power mathematical model to obtain the flexibility measurement as a function of moisture content gives satisfactory results for the clay mat.
- Flexibility of the clay mat evidently depends on moisture content and changes during the isothermal drying process. The ductile to brittle transition of clay mat is affected primarily by the change in the moisture content and for the clay mat to remain flexible, critical moisture content of 1.7 times of its plastic limit is required.
- A strong correlation between indented imprint and flexural strength has been established. This provided an insight into the workable limit of clay mats in a thermal-environment condition as well as a quality control in manufacturing process.
- The portable constant weight indenter provided a simple, reliable and fast approach to determine the flexibility of clay mat and enabled easy mean of estimating the moisture content at field.

References

1. Schroeder, C.; Monjoie, A.; Illing, P.; Dosquet, D.; and Thorez, J. (2001). Testing a factory-prehydrated GCL under several conditions. *Proceedings Sardinia 2001, 8th International Waste Management and Landfill Symposium*, CISA, Cagliari, Italy, 1, 188-196.
2. Kolstad, D.C.; Benson, C.H.; Edil, T.B.; and Jo, H.Y. (2004). Hydraulic conductivity of a dense prehydrated GCL permeated with aggressive inorganic solutions, *Geosynthetics International*, 11(3), 233-241.

3. Di Emidio, G.; Mazziere, F.; and Van Impe, W. (2008). Hydraulic conductivity of a dense prehydrated GCL: impact of free swell and swelling pressure. In *4th European Geosynthetics Conference*. Nottingham, UK: Golder Associates.
4. Katsumi, T.; Ishimori, H.; Onikata, M.; and Fukagawa, R. (2008). Long-term barrier performance of modified bentonite materials against sodium and calcium permeant solutions. *Geotextiles and Geomembranes*, 26(1), 14-30.
5. Wijeyesekera, D.C. (2003). Use and performance of bentonite in GCLs. In *proceedings of the An International Conference on Geo-Environmental Engineering*. Singapore, Keynote papers pp.27-46
6. Wijeyesekera, D.C.; Loh, E.W.K.; Siti, F.D.; Lim, A.J.M.S.; Zainorabidin, A.B.; and Ciupala, M.A., (2012). Sustainability study of the application of geosynthetic clay liners in hostile and aggressive environments. *OIDA International Journal of Sustainable Development*. 5(6), 81-96. ISSN: 1923-6654 (print); ISSN 1923-6662 (online).
7. ASTM: D790-03 (2003). *Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials*. ASTM International, United States.
8. Dieter, G.E. (1988). *Mechanical metallurgy*, second edition: McGraw-Hill.
9. British Standard BS 1377 (1990). *Method of test for soil for civil engineering purpose*. Part 2, Classification Tests, British Standards Institution, London.
10. Loh, E.W.K.; and Wijeyesekera, D.C. (2008). Moisture desorption isotherms and thermodynamic characteristic of prehydrated and extruded GCL. In *proceedings of the Advances in Computing and Technology*, The School of Computing and Technology 3rd Annual Conference, University of East London, UK, pp 148-153.
11. Loh, E.W.K.; and Wijeyesekera, D.C. (2009). Drying kinetic of prehydrated and extruded GCL. In *proceedings of the Advances in Computing and Technology*, The School of Computing and Technology 4th Annual Conference, University of East London, UK, pp 95-101.