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Investigation of the Effect of Multiple Wetting and Drying Cycles on the Shrinkage and Cracking of Engineered Clay Soil

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***Abstract* - limate change is predicted to result in warmer and drier summer as well as wetter winter which we are already experiencing. This could result in instability of earth structures hence this study. Durham boulder clay was used to investigate the crack patterns, crack geometric parameters, shear strength and infiltration time of 400 mm x 400 mm x 75 mm samples sieved through 20 mm sieve and compacted to 1.35 g/cm^3, 1.65 g/cm^3 and 1.70 g/cm^3 densities. Six cycles each were carried out and the samples were air-dried. The photographic images of the sample surface were used for crack analysis. Stability of crack pattern for each cycle was attained after 24 hours of drying. The final shear strengths of all the samples were higher than the control implying increased strength. The final crack depth of the VLC sample was 3.48 times that of the WC sample. The final crack width for the VLC sample was 2.12 times that of the WC sample. The CIF of all the samples reached stability by the 5th cycle. There was also stabilization in the infiltration of the samples by the third cycle and as such valid predictions could be made from this cycle. In practical scenarios, earth structures undergo more than 6 cyclic wetting and drying hence it can be inferred that they will attain stability by the fifth cycle. From this study, it can be noted that loosely compacted structures are more susceptible to failure than well-compacted structures.**

Keywords: Clay soils, cyclic wetting and drying, shrinkage, cracking, bionics embankment

1. INTRODUCTION

Clay is one of the oldest building materials on earth. About two – thirds of the world's population in both traditional and modern societies still live and use structures constructed with clay as an essential load bearing structure e.g. roads, embankments, buildings, railway, earth dams etc.

Clay materials used in construction possess varying degrees of plasticity. Soils with a measure of plasticity shrink or swell due to changes in moisture. Characteristically, a clay soil shrinks when it loses moisture and swells when it absorbs moisture. The shrink – swell behaviour of soil is a complex phenomenon that is not yet well understood despite its significance in engineering and environmental practice. Shrinkage in plastic soils generate inter- particle tensile stresses and it is widely accepted that when these stresses exceed the tensile strength, cracks can develop (Corte and Highasi, 1960; Nahlawi and Kodikara, 2006; Tang et al., 2008; Peron et al., 2009).

It has been proven that the hydraulic conductivity of cracked soil is about 3 to 20 times higher than that of intact soil (Albrecht and Benson, 2001). Embankments and other earth assets are constructed to prevent seepage of water into the structure as this leads to the development of positive pore water pressure in the soil. But when the soil is exposed to desiccation during summer, it shrinks thereby creating channels for water to permeate the soil and when it rains, the pores are filled up and the cycle continues.

Climate change has been a prevailing topic in the world for some time now with its numerous effects. The consequence of seasonal and diurnal fluctuation in climate is a cyclic shrink-swell action in the soil which forms the basis of this study. Warming of the climate due to variations in the sun's energy reaching the earth mainly caused by anthropogenic influences has been well researched and documented (Hulme et al., 2002). It is expected that there will be up to 5 times wetter winters over the next 100 years which is already taking place.

Also, warmer and drier summers are envisaged coupled with the risk of drought and heat wave. For instance, periods of dry weather in 1976/77 and 1988/92 led to a lot of subsidence in buildings in the UK. Existing report by Meteorological office and recent research by Newcastle University have shown that fewer high-intensity rainfall should be expected in summer and wetter winter due to climate change leading to more repetitive drying and wetting cycles per year.

It is a popular saying that water is the greatest enemy of civil engineers and climate change can be summarized as increase and fluctuations in the earth's water level. It is, therefore, reasonable to assume that the moisture within infrastructure slopes will change, even the vegetation growing on the slopes may also change. These expected changes have brought about new trends of research on its effect on the environment and earth – constructed structures, this research inclusive.

Desiccation cracking has a range of effects but in geotechnical engineering, there is evidence that cracking at the crest of the slope will trigger the initiation of slope failure

(Take, 2003). This is largely due to the fact that the cracks create seepage openings for the slope thereby increasing the destabilizing forces acting about its axis of rotation. Also, most flood dykes in the UK has been traced to desiccation cracking in the downstream slope (Dyer, 2004). Another effect would be the internal erosion of embankment dams resulting in piping failure and hence entire dam failures and accidents (Foster et al., 2000). Shrink-swell could also lead to structural movement and fracturing of buildings. Clay liners used in landfills are affected by desiccation cracking. This is very important because cracks create channels for widespread contaminations which may culminate to huge financial and health losses (Zhou et al., 2005).

Previous studies on desiccation cracking have mainly considered the surface characteristics and crack patterns of mostly slurry. In recent times, a lot of researches have been carried out on the cracking and shrinkage of clay soils with regards to the surface characteristics and crack pattern of slurry. Very little has been done on engineered soil so far which this research will be focusing on. Also, not much has been done on the effect of numerous cycles (up to 6 cycles) on the crack pattern of the soil. This research will also seek to investigate the influence of these numerous cycles on the shear strength and infiltration properties of engineered soil. This study will also seek to investigate the differences in these parameters on both well-engineered structures representing modern embankments and poorly engineered structures like Victorian embankments amongst others.

2. MATERIALS AND METHODS

Durham boulder clay is the only material used for testing in this research with the following properties as shown in Table 1;

Table 1: Physical properties of Durham boulder clay

Physical Properties	Values
Liquid Limit (%)	41.1
Plastic Limit (%)	23.4
Plasticity Index	17.7
Shrinkage Limit (%)	8.16
Percentage Passing 425 µm test sieve (%)	84
Optimum Moisture Content (%)	17.9
Maximum Dry Density (g/cm^3)	1.71

The sample can therefore be termed as having intermediate plasticity.

The sample was prepared by passing through 20 mm test sieve and removing foreign materials. The sample was kept in an air tight container for 48hours with a plastic seal to prevent moisture loss and to allow equilibration of moisture. The samples were compacted to 1.70 g/cm^{3,} 1.65 g/cm^3 and 1.35 g/cm^3 as very well compacted sample (WC), loosely compacted sample (LC) and very loosely compacted sample (VLC) respectively in a (400mm by 400mm by 75mm) metal pans. The samples were placed under a fan to aid in drying.

Six cycles were carried out for each cycle with each cycle constituting 4 days of drying. Rewetting was carried out on the fourth day of drying and the next cycle started immediately after ponding of the re-added moisture. Hand shear vane test was carried out on the samples at the end of the second, fourth and sixth cycle (as shown in Figure 2) hence three samples at each density were prepared to cater for sample disturbance after the vane shear test has been conducted. The setup of the experiment is shown in Figure 1.

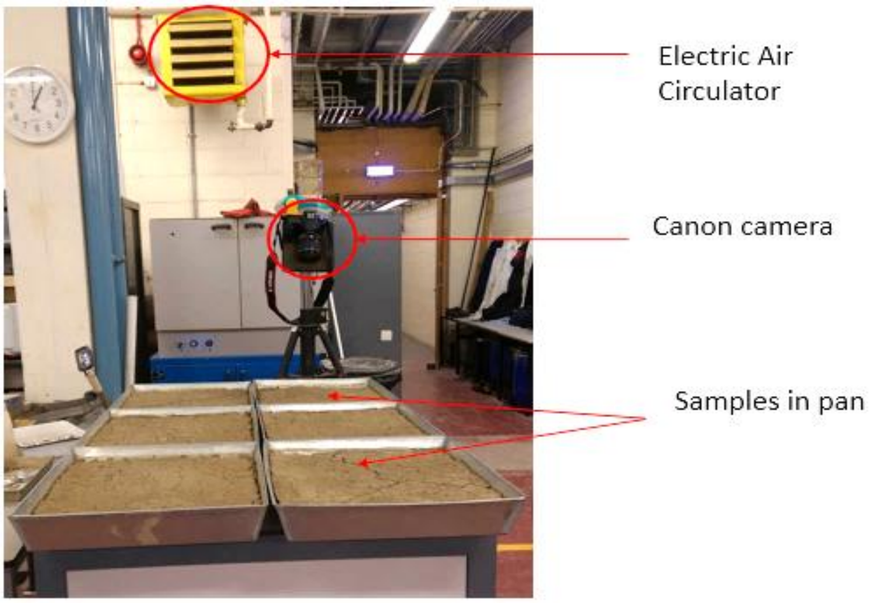

Figure 1: Setup of Test Experiment

Photographic images of the samples were captured daily and used for image analysis of the crack pattern.

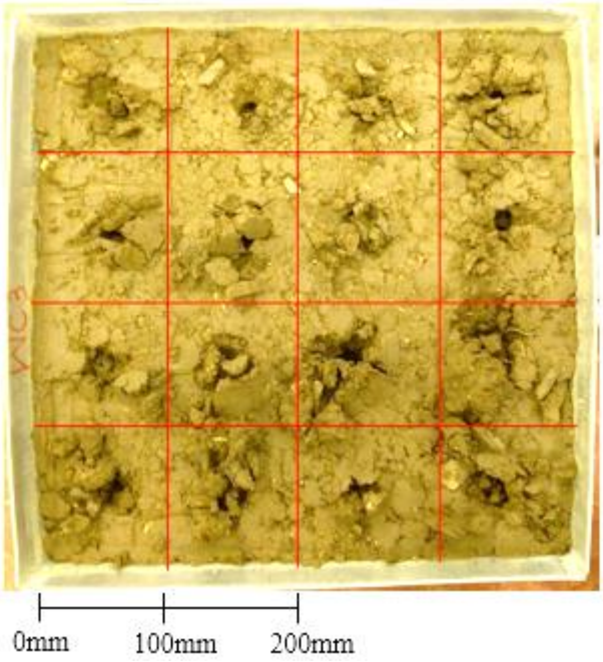

Figure 2: Grid showing how shear vane test was conducted

3. RESULTS AND DISCUSSION

3.1 Clod Width

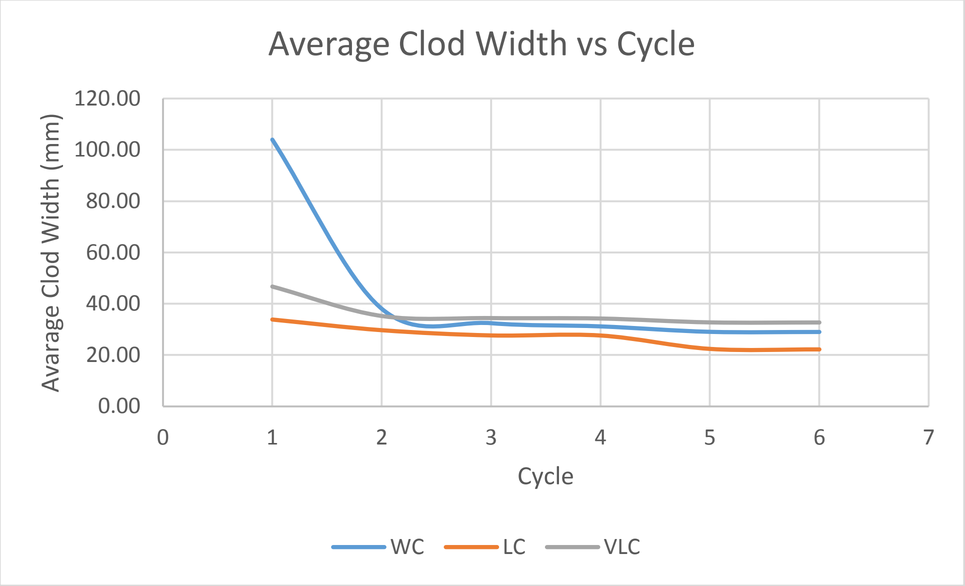

Figure 3: Graph of Average clod width vs. Cycle for 400 mm x 400 mm samples

3.2 Crack Width vs. Cycle

The average crack width at the end of each cycle for each sample was used in this analysis. It was observed that the crack width increased with cycle, reached a peak value and reduced as can be seen in Figure 4. For the WC and VLC samples, there was an increase in the average crack width per cycle from 1.41 mm at the first cycle to 4.64 mm by the fifth cycle for WC sample and from 2.97 mm at the first cycle to 9.03 mm by the fifth cycle for the VLC sample, then a reduction to 3.98 mm for WC sample and 8.44 mm for VLC sample in the crack width was noticed by the end of the sixth cycle. This reduction could be due to the fact that the sample attained structural stability as shown in the vane shear strength and clod width analysis by the fifth cycle, hence the crack width stabilised at the fifth cycle. By the fifth cycle also, the WC and the LC sample had the same crack width. For the LC sample, the peak of the width was reached by the fourth cycle and then it reduced to the same value as that for the WC sample.

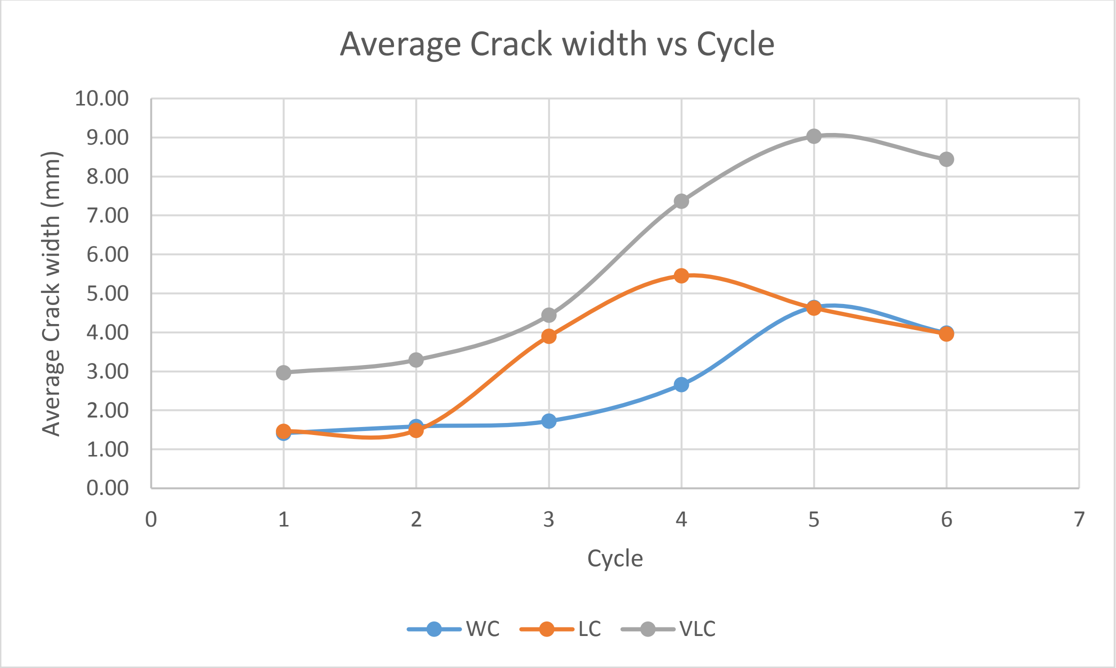

Figure 4: Average crack width vs. Cycle for 400 mm x 400 mm samples

3.3 Crack Depth vs. Cycle

The average crack depth on the last day of drying for each cycle was used in this analysis. The WC and LC samples had very similar crack depth. The crack depth increased with increasing cycle as seen in Figure 5.

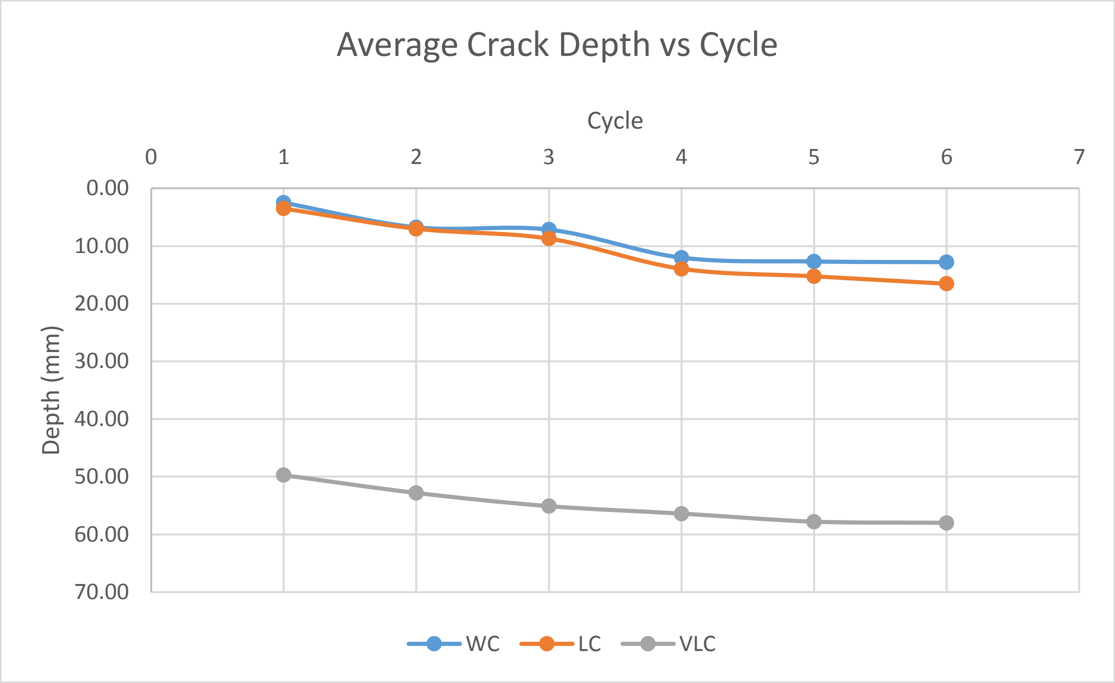

Figure 5: Average crack depth for 400 mm x 400 mm samples

*3.4 Crack Intensity Factor (CIF)*Crack intensity factor can be defined as the ratio of the crack area to the total surface area of the sample. The data used in this analysis was for the last drying day for each cycle.

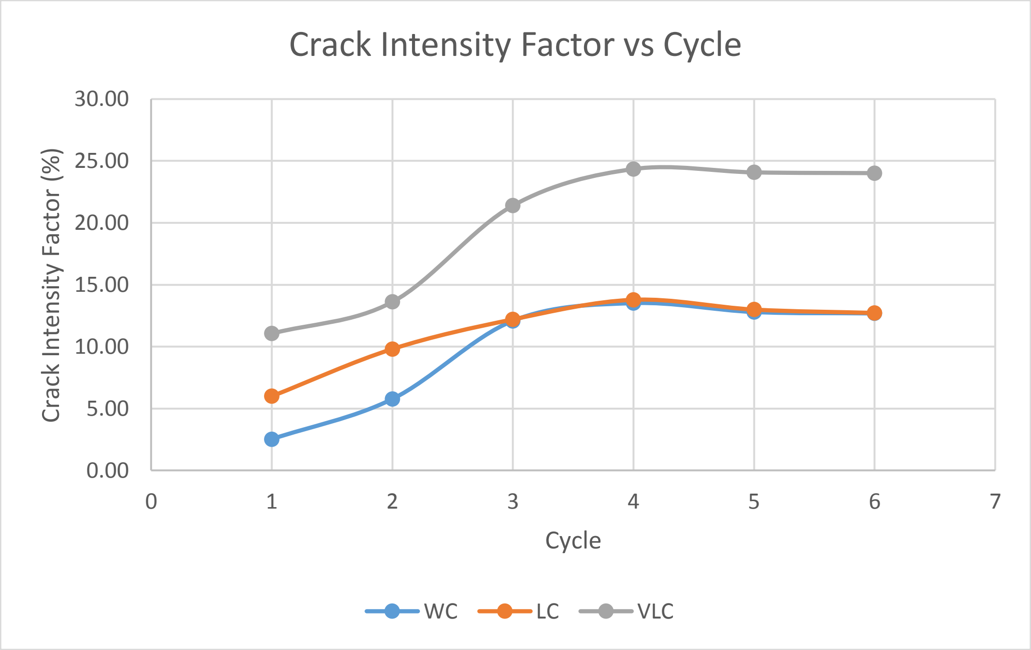

Figure 6: CIF vs. Cycle for 400 mm x 400 mm samples

The WC sample had the lowest CIF of 12.68% by the sixth cycle which is expected because it had the lowest crack formation. It peaked by the fourth cycle at 13.51% and stabilized by the fifth cycle at 12.79% which means the crack had reached stability. This correlates with the data obtained for the crack width in Figure 4. It has therefore been further proven that structural stability of the sample can be reached by the fifth cycle.

The LC sample followed the same trend as the WC sample. The CIF values coincided with those for the WC sample from the third cycle, peaked at the fourth cycle and stabilized by the fifth cycle.

The VLC sample had the highest CIF value of 24.01% at the sixth cycle. The CIF value also followed the same trend as for WC and LC samples.

3.5 Effect of Cyclic Wetting and Drying on Soil Shear Strength

Table 2: Vane Shear Strength for 400 mm x 400 mm samples

	Vane Shear Strength			
	Control (kPa)	Second Cycle (kPa)	Fourth Cycle (kPa)	Sixth Cycle (kPa)
WC	30.80	22.65	23.90	31.42
LC	30.67	21.44	25.99	25.23
VLC	7.94	7.57	7.74	8.86

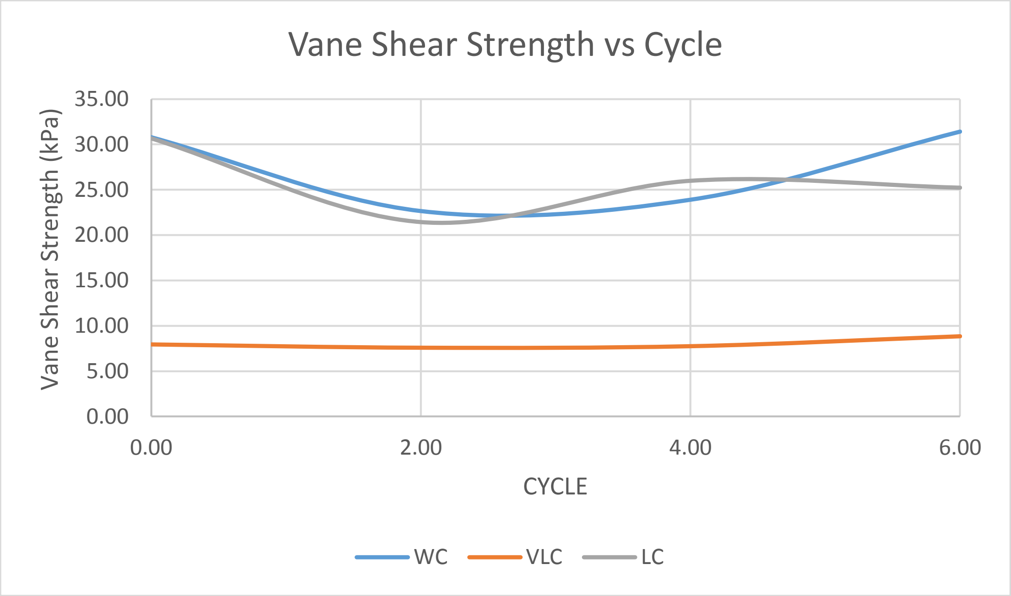

Figure 7: Vane shear strength vs. cycle for 400 mm x 400 mm samples

The vane shear strength of the soil was taken within the clods in a systematic pattern explained in the methodology. Hence the intact soil is what was tested and not the cracks. The average value gotten for each test was used in this analysis.

From the result obtained for the vane shear strength of the sample, the strength of the WC sample reduced by about 26.5% from the control after the second cycle. Nevertheless, the strength increased after the fourth cycle and by the end of the sixth cycle, the vane shear strength of the sample was higher by 2% than the control as seen in *Figure 7*.

For the LC sample, the vane shear strength decreased after the second cycle and increased by 21.2 % after the fourth cycle and then slightly reduced after the sixth cycle but fell short of the control value by 21.6% at the end of the 6th cycle.

For the VLC sample, it followed the same trend as the WC sample. The vane shear strength of the sample decreased from the control after the second cycle but increased by 2.52% after the fourth cycle and still increased further after the sixth cycle to a value higher that the control value by 11.59 %.

3.6 Effect of Wetting and Drying Cycles on Time Required for Moisture Infiltration

The rate of water infiltration was taken as the time difference from when water was re-added into the sample to when the moisture at the surface had completely infiltrated into the sample (end of ponding). Ponding primarily occurs when the rate of re-added water exceeds the soil absorption.

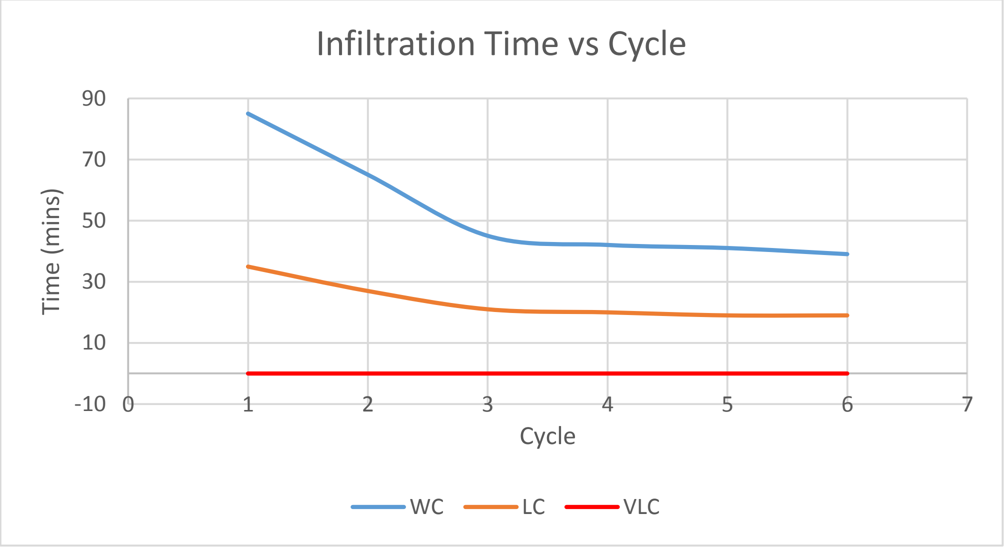

Figure 8: Moisture infiltration time vs. cycle for 400 mm x 400 mm samples

For the WC sample, the time required for infiltration of moisture at the end of the first cycle was 85 mins. This could be due to the fact that there was very minimal void between the particles of the sample (void ratio of sample compacted at OMC is zero) and also the crack width was small. But there was a decrease in the infiltration time to 65 min after the second cycle which was due to the larger formation of cracks on the sample and stabilized at 45 min from the third cycle onwards. Also, the WC sample had the highest infiltration time (39 mins) for the all the cycles with respect to the LC and VLC sample even when the infiltration time seemed to stabilize as shown in Figure 8.

The same trend can be noticed for the LC sample as well. The first cycle required 35 minutes for infiltration of the moisture lost and decreased subsequently but still stabilized by the third cycle at 21 min. The time required for infiltration after stabilization was lower than the WC sample even with just 0.5 g/cm^3 difference in compaction level. This emphasises the need for accurate compaction in the field so as to obtain a void ratio of approximately 1 which will culminate in a minimum crack width of the soil.

For the VLC sample, there was no ponding of moisture during rewetting and this means that the hydraulic conductivity of the sample was very high. All the moisture infiltrated into the sample immediately. This was due to the fact that the cracks within the sample were quite wide as well as the interconnected pores within the particles of the sample.

3.7 Desiccation Rate

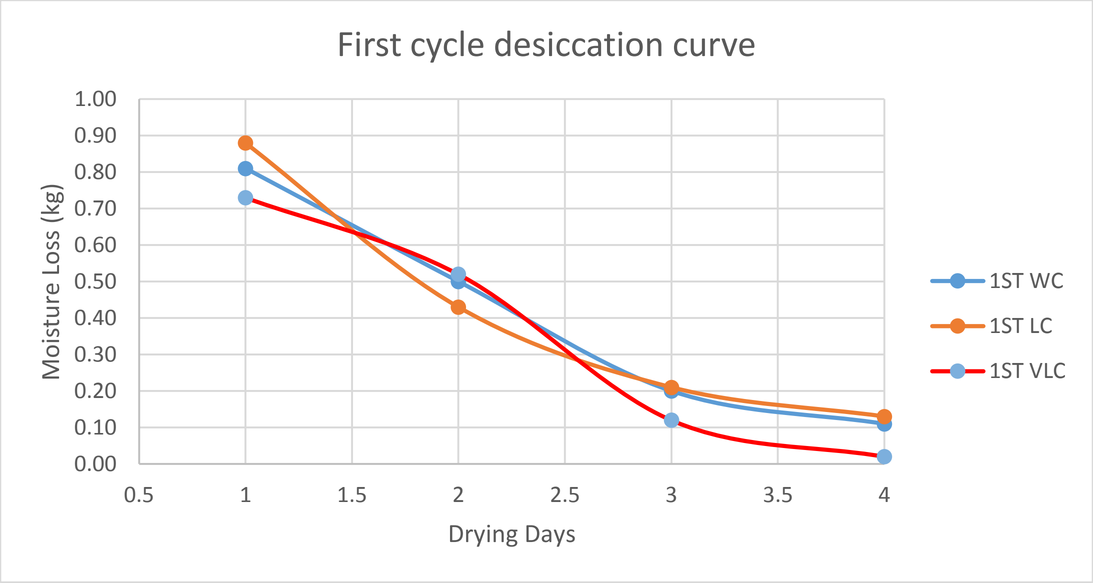

Figure 9: First cycle desiccation rate for 400 mm x 400 mm samples

There was a steadier and consistent pattern of moisture lost from all the samples by the sixth cycle as seen in *Figure 10*. But the moisture loss still followed the same trend as the first cycle with the highest moisture lost on the first day from the LC sample and the lowest moisture lost from the VLC sample. It can be observed that for all the samples, the moisture lost after the first day of drying was highest followed by the second day and kept decreasing subsequently until the fourth day. This could be due to the fact the moisture at the surface of the sample evaporated easily and so because there was much moisture at the surface at the beginning of the cycle hence the moisture at the surface was evaporated first, after most of the moisture at the surface had been evaporated it took longer for the moisture at deeper depth to be evaporated. Also, there was no much moisture in the sample anymore as most had been evaporated leading to a reduction in the moisture lost from the sample. The LC sample had the highest moisture loss of 1.65 kg followed by the WC sample (1.62 kg) and then VLC sample (1.39 kg) for the first cycle.

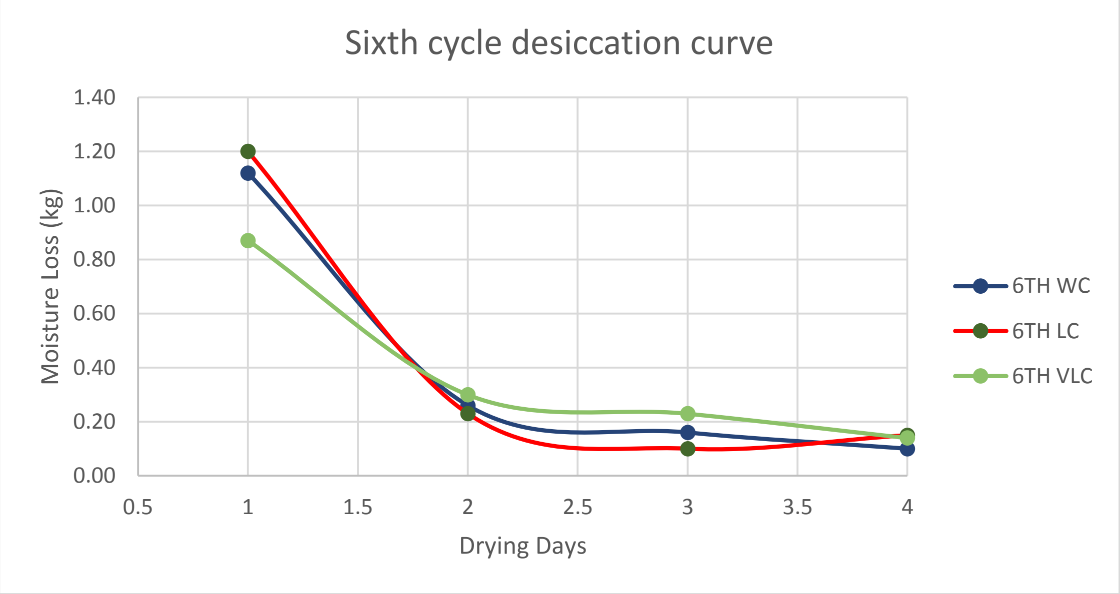

Figure 10: Sixth cycle desiccation rate for 400 mm x 400 mm samples

During the first drying day for the first cycle, moisture was evenly and uniformly distributed within the sample leading to lower moisture loss but with rewetting, the moisture lost on the first day of drying for subsequent cycle increased because there was readily available moisture to be evaporated from the surface of the sample.

For the VLC sample, a steeper trend could be noticed. There was a continuous increase in the moisture lost from the first cycle. A sharp increase could also be observed in the moisture lost by the fourth cycle and a steadier increase for the fifth and sixth cycle.

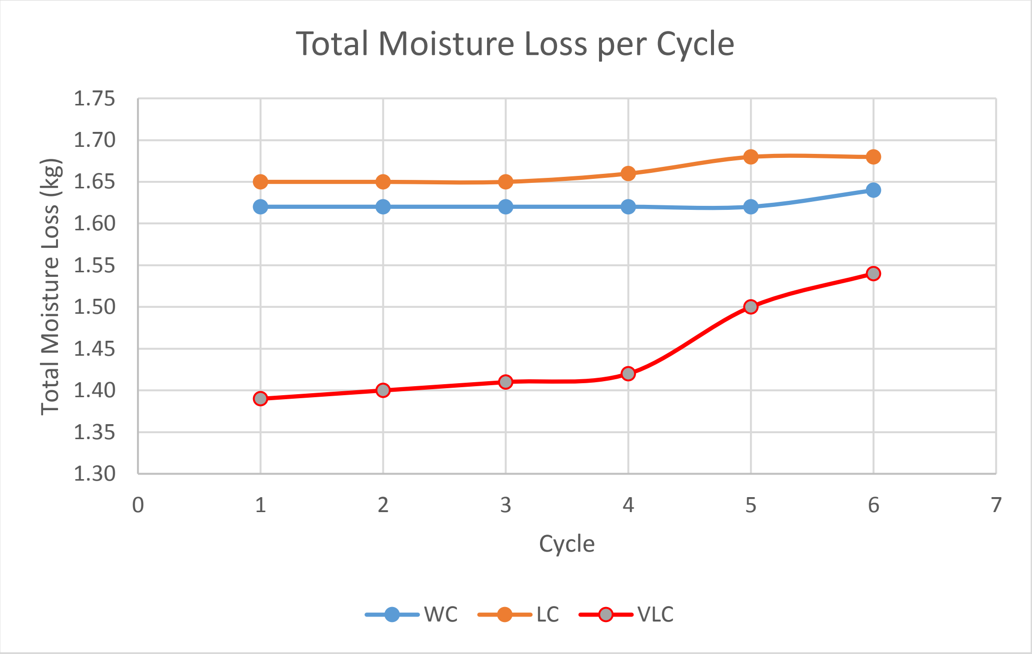

Figure 11: Total moisture loss per cycle vs. cycle for 400 mm x 400 mm samples

4 DISCUSSION

4.1 Crack Pattern

The cracks had been noted to originate from the middle of the sample for all the cycles. This is in correlation with Avila et al., (2013) and Nahlawi and Kodikara, 2006. They concluded that the maximum stress was built up around the middle of the sample as a result of restraining the free shrinkage strain in the soil which caused cracks to initiate first around the middle of the sample. That notwithstanding, flaws and imperfections like large stiff particles, air bubbles etc. can desaturate quickly and hence cracks could be initiated. Costa et al., 2013 has proven that the tensile stress development resulting in tensile failure and stress relief associated with clay fracture are the controlling factors in crack initiation and propagation.

4.2 Clod Degradation

The clods in the sample were observed to degrade differently with cycle until they reached stability. This could be attributed to the degree of compaction of the samples. For VLC sample, there were large voids in the sample and thus enhanced faster and larger crack development by the first cycle and hence there was more clod degradation unlike the well-compacted sample that had lower voids resulting in smaller clods from the first cycle. This same trend has been observed by Abdulrahman, 2011.

4.3 Daily Crack Pattern

From the visual inspection of the pans in the crack width by the edges of the pan were wider than those around the middle. Also, the depth of those cracks were deeper than those around the middle. This could be due to the contact of the sample with the pan which led to greater stress distribution around the edges hence the wider crack depth and width. Also during rewetting, a lot of the ponded water were stagnant around the edges and as such weakening the soil structure around the edges. By the edges of the pan, there are macro – pores due to the shrinkage of the sample away from the pan which creates channels for water to easily pass through. Water generally flows through the path of least resistance and hence, most of the water were clogged by the ends of the pan making the sample around the edges to be weaker thereby bringing about wider and deeper cracks as well as larger clods. This implies that measures should be put in place and adhered to while constructing the edges and boundaries of earthworks assets like embankments, landfill liners, dams and other earth structures as they are more vulnerable to adverse situations and as such could serve as weak zones leading to instability and subsequent failure.

Another observation from the crack pattern was that the crack intersection angle for WC samples were mostly orthogonal and four sided while those for VLC samples were mostly non – orthogonal and irregular in shape. According to Kodikara, 1999, this is because when a crack is formed, the tensile stresses pulling the crack apart are released near the crack. When other cracks are approaching the initial crack they tend to form perpendicular to the local maximum stress which is parallel to the initial crack and hence form roughly orthogonal (90°) cracks.

4.4 Clod Width

It could, therefore, be inferred that the crack pattern of sample irrespective of their degree of compaction reached equilibrium after the third cycle. Predictions can, therefore, be made from the pattern of crack from the fourth cycle and it holds for other cycles with little or no difference and adjustments required. The stabilization of the clod width by the third cycle also buttresses the point that there was not much horizontal shrinkage within the sample.

4.5 Crack Depth

The crack depth for VLC sample is much higher than the others implying that loosely compacted earth structures are more susceptible to failure because moisture can infiltrate into a deeper depth of the structure and hence, compromising the stability of the structure.

4.6 Vane Shear Strength

From the vane shear strength result, it was observed that the intact strength of the samples reached maximum value by the 6th cycle. This means that cyclic wetting and drying increases the intact strength of the soil and this can be related to over consolidation of soil. The stresses imposed on the soil as a result of cyclic wetting and drying causes an increase in shear strength of the soil leading to over consolidation of the soil and hence increase in shear strength. Also from the result obtained for the change in crack width with cycle, a stabilization can, therefore, be seen after the fifth cycle. The same trend is noticed with the clod width of the sample which stabilized from the 3rd cycle. It can also be noticed from *Figure 7* that the increase in strength was from the third cycle. In practical application, for a well-compacted structure with lesser void ratio and smaller crack width, cyclic wetting and drying over time would aid to increase the shear strength of the intact structure and since the infiltration is lesser, there is little to be bothered about. The same cannot be said of a loosely compacted earth structure because though the strength of the intact soil increases with cyclic wetting and drying, the high void ratio and large crack would definitely compromise the integrity of the structure. Kodikara et al., 2002 has noted that the initial level of compaction influences the stabilization of soil strength under cyclic wetting and drying. Sayem et al., 2016, also shares the line of thought that there is stabilization in the shear strength of the soil after the fourth cycle.

4.7 Infiltration Time

The infiltration time of the samples reduced with increasing cycle. This implies that the hydraulic conductivity of the sample increases with increased cycle but stabilises by the third cycle. The cracks and the void between the particles in the sample are mainly responsible for this behaviour. The larger the average crack width, the higher the hydraulic conductivity. The same also goes for the degree of compaction, the higher the degree of compaction (the higher the void ratio and the lesser the infiltration time). The WC sample still had a lower overall stabilized hydraulic conductivity. Relating this to real life earth structures are usually built to a slope of 1 to 2 which allows for runoff. Hence, lesser moisture will be infiltrated into well-compacted earth structures than loosely compacted earth structures. A loosely compacted earth structure with a higher hydraulic conductivity would lead to infiltration of the slope with moisture much quicker resulting in an increase in pore water pressure. This can result in high lateral stresses being built up in the soil causing the structure to fail in shear. This correlates with the findings of Shear et al., 1993 and Kodikara et al., 1999 that there is an increase in hydraulic conductivity with increase in pore size and vice versa. Albrecht and Benson 2001, also confirmed that the hydraulic conductivity of cracked soil is higher than that of intact soil while Rayhani et al., 2008 observed that cyclic wetting and drying decreased the hydraulic conductivity of soils. The reason for this increase in hydraulic conductivity of crack soil could be because of the inter-cluster pores according to Olsen, 1962. It has also been stated that particle arrangement occurs within the soil as a result of cyclic wetting and drying by Tang et al., 2011. This could also lead to the stabilization of the infiltration time by the third cycle. Rouainia et al., 2009 and Manning et al., 2008, have predicted through numerical modelling that slopes could attain increased stability over time as a result of the predicted changes in the climate.

4.8 Moisture Loss

The moisture lost from the WC sample at the end of a cycle (4 days) were the same for the first three cycles but increased by the fourth cycle and stabilized by the fifth cycle. This can be related to the vane shear strength. Soil moisture is an important factor in the strength of the soil. The vane shear strength of WC sample also showed an increase from the third cycle. The more moisture lost from the sample, the higher the vane shear strength of the sample.

5.0 CONCLUSION

Desiccation cracking occurs in the soil as a result of moisture loss creating channels for moisture seepage into these structures. With increase in wetting through rainfall and increase in drying expected from climate change, these cycles will be exacerbated.

In reality, we have more than six wetting and drying cycles but for the fact that the soil has reached stability at some point is an indication that from the point of stability of the parameters, valuable parameter predictions can be made using obtained data after the point of stabilization to estimate the behaviour of earth assets like embankments, landfill liners, dams and other earth structures. This could also serve as useful parameters in the design phase of earth structures. The shear strength of intact soils from this study is not negatively affected by cyclic wetting and drying but rather increases and as such should not be a cause of concern to Geotechnical engineers. However, the crack width and infiltration are causes of concern. The infiltration time of moisture decreases as a result of cyclic wetting and drying but measures can be put in place during construction of earth structures to mitigate excessive infiltration of moisture into the structure. The crack depth is another pointer to the channels available for moisture to seep into earth structures. In general, loosely compacted earth structures will be more affected negatively because of the degree of compaction of these structures, therefore, effective measures and monitoring has to be put in place to prevent failure of these structures.

Another point to consider here is the fact that the thickness of earth structures is deeper than the thickness used in this study and as such some behaviour of the soil may change and a different trend exhibited. Vegetation plays a major role in the absorption of moisture and presence of root system in earth structures but that could not be investigated in this study due to the scale used.

6.0 SUMMARY

In this study, the effect of cyclic wetting and drying on the crack pattern, geometric parameters like crack width, clod width, crack depth, CIF, time required for infiltration, shear strength has been investigated for different sizes of sample with varying degrees of compaction . The following inference can be drawn from the result of the testing:

- ✓ The crack pattern of the soil stabilized by the first 24 hrs. of drying
- ✓ There was no much clod degradation for a well compacted WC sample over cyclic wetting and drying
- ✓ The crack pattern of WC sample changed during rewetting but reached stability by the third cycle
- ✓ The crack pattern of VLC sample was consistent from the first to the last cycle
- ✓ Clod degradation as well as crack width widening was evident for VLC sample and reached equilibrium by the fifth cycle
- ✓ There was washing away of fines from the surface of the samples as a result of cyclic wetting of the sample
- ✓ Clod sizes of WC samples were smaller than those of VLC samples
- ✓ Intersecting cracks for WC sample were mostly at 90° and four sided while those for VLC samples were roughly at 120° and irregular in shape
- ✓ The clod width for all the samples attained stability by the third cycle
- ✓ The crack width for all the samples peaked at the fourth cycle
- ✓ The crack depth of the samples reached stability by the fourth cycle irrespective of the degree of compaction
- ✓ VLC sample had more vertical settlement than WC sample
- ✓ Also, VLC sample had similar horizontal settlement as WC sample
- ✓ The shear strength of a WC sample was generally higher than that of VLC sample
- ✓ Cyclic wetting and drying of soils brought about increased stability in shear strength
- ✓ Cyclic wetting and drying brought about a decrease in infiltration time of the sample
- ✓ Generally, VLC sample had higher hydraulic conductivity than WC sample
- ✓ Stability in hydraulic conductivity of the sample was reached by the third cycle
- ✓ The CIF of the samples peaked by the fourth cycle and stabilized by the fifth cycle
- ✓ VLC sample had lower desiccation rate than WC sample

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