Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 11, November-2016

Investigation of Shrinkage and Cracking in Clay Soils under Wetting and Drying Cycles

Oluwaseun Sunday Bamgbopa
Faculty of Science, Agriculture and Engineering.
School of Civil Engineering and Geosciences
Newcastle University,
Newcastle-upon-Tyne
NE1 7RU

Abstract - **Embankments failure in cohesive soils are often preceded by periods of cyclic wetting and drying due to changing climatic conditions. The resulting desiccation cracks tend to have significant effects on the stability of slopes and other engineered infrastructures founded on such soils susceptible to shrinkage and cracking. This research investigates the shrinkage and cracking behaviour of an engineered clay soil under series of wetting and drying cycles. Experimental cyclic wetting and drying were conducted using an intermediate plasticity Durham boulder clay and synthesis bentonite mix samples. These samples were subjected to four dry-wet cycles, the desiccation rate of the samples was observed and recorded using wind source and oven drying approach at 60^0C. The surface dimension of the samples cracks were quantified both virtually and using digital image processing. The results of the experiments indicated that the samples with higher plasticity index have a greater crack intensity factor (CIF) irrespective of the drying approach. Also both sample displays a significant increase in the cracks geometries and dimension after the first two cycles and tend to attain an equilibrium state after subsequent cyclic episodes. The mechanism of cracking was observed as initiating from the surficial or textural defects of the sample where the tensile strength is minimum and exceeded by the tensile stress. Further observations of the cracks indicated some obvious mechanism of closure especially the major cracks as the width size reduces with successive cycles. Within the context of this research, some recommendations were provided all directed towards improving the material thereby reducing it susceptibility to shrinkage and cracking.**

Key Words: Bionic Embankment, Cyclic Wetting and Drying, Desiccation Cracks, Shrinkage, CIF, Closure

1. INTRODUCTION

It is a generally arising phenomenon that Shrinkage often leads to cracking in clay soils as a result of consistent moisture loss. Cracking usually occur when soils are restrained while undergoing shrinkage, which generates high negative pore pressure otherwise known as soil suction, within the drying soil mass (Mitchell, 1993; Holtz & Kovacs, 1981). The desiccation cracking can induce detrimental impacts in cohesive soils, such as reduction in the strength, stiffness, stability of the overall soil mass, and also an increase in the compressibility and soil hydraulic properties (Chertkov, 2000). The cyclic reoccurrence of this phenomenon results in a worldwide problem which prompt considerable and far reaching damages and reduce efficiency (or performance) of engineering projects such as foundations, embankments, impermeable core of earth-dam, long term radioactive waste storage, excavations and structures which are constructed on cohesive soils vulnerable to cracking.

Cohesive soils such as clays are commonly used in engineering constructions like cuttings, support for foundations, embankments and also as impermeable layer for waste disposal. Within the UK, numerous embankments constructed in the transport industry are of over a century in age and were built principally using clay materials which are prone to a significant volume change either swell or shrink (Briggs, 2010). The clays within these materials may be a major risk to the above mentioned engineering structures owing to their capability to expand, shrink and crack with recurrent variations in soil moisture content particularly due to climate change and high water demanding vegetation (Britishgeologicalsurvey, 2012). More interestingly, an embankment failure or inefficiency of engineering projects can result in major issues within the industry like delays in transportation network affecting people going to work or travelling to and about.

This failure can unswervingly distress and cost the government or the transport establishments millions of pounds for either compensations or embankments and other infrastructures repairs. Research in the UK transport with respect to embankment stability is on the increase as seen in a new four years funded project futurenet (Future Resilient Transport Networks) which revolves around assessing the flexibility of the UK transport network in 2050 using series of models (Wilks, 2010).

The United Kingdom embankment projects are mainly constructed using variety of materials from a native source, and the possible failure of these embankments is usually associated with the reduction in the ultimate strength or possibly a zone of weakness developed within the structure (Wilks, 2010). It is expected that recurrent cyclic climatic conditions within the UK become continuous and more pronounced which in turn will result in more severe cycles of shrinkage and swelling. The pore water pressure in a soil increases and decreases the effective stress of a slope when subjected to cyclic wetting and drying condition which simulates the typical alternating UK climatic condition. *Figure 1.1* shows the swell and shrinking clay potential map

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

of the UK based on volume change potential. As expected, an embankment will be as close to failure as possible depending on the numerous cycles it had witnessed. The embankments which have experienced sequences of pore water variations are expected to be closer to failure than others with less cycles, meanwhile if these cyclic events are much more pronounced with extreme effects on the soil, it may take less cycles to fail such embankment.

Cracking which is as a result of desiccation is an unvarying event worldwide, evolving into a wide range of forms and dimensions, the endless cycles of opening and closing of soil crack easily modifies the permeability of the soil. Once a soil cracks, the cohesive force within the soil is destroyed and cannot be re-bounded even if the crack closes, this led to an increase in pores which in turn increase the permeability of the soil (Anderson *et al.*, 1982). Meanwhile the mechanism of cracking, the behaviour of soil under wetting and drying cycles, the crack initiation, advancement, closure and other resulting structures are still vague and need to be research. In general it is believed that shrinkage is due to water loss by evaporation and if drying continues from the surface down, the dried out upper layer shrinks first and a tensile stress develops leading to a negative pore water pressure resulting in cracking, meaning that shrinkage leads to cracking (Kodikara *et al.*, 2002).

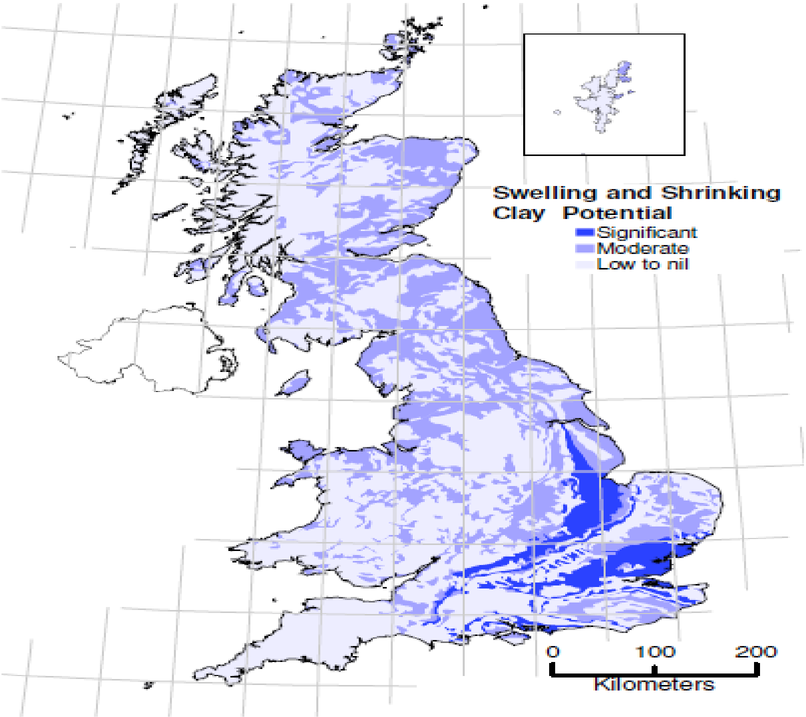


Figure 1.1: Swell and shrinking clay potential map, based on volume change potential (Britishgeologicalsurvey, 2012).

In preparation for the future to make proper evaluations and recommendations of proposed projects, as climatic conditions are expected to change and boost more extreme periods of shrink and swell cycles. Geotechnical engineers require both field and laboratory information to provide geological and geotechnical data needed to appropriately design structure on cohesive soils with swell and shrink properties within environments prone to similar climatic variation as the UK. This project focuses on geotechnical investigation of the shrinkage and cracking of clay soil under cyclic wetting and drying cycles through experimental techniques, using Durham boulder clay from the Bionic embankment (Biological and engineering impacts of climate change on slopes).

1.1 Aim

The aim of this project is to investigate the behaviour of clay soil as it undergoes shrinkage and cracking under repeated wetting and drying cycles.

1.2 Objectives

To effectively complete this investigation, the following objectives are set to be achieved:

1. To advance in the understanding of the processes involved in the formation of cracks during wetting and desiccation.
2. To determine the properties of clay soils which are directly responsible for altering its behaviour after numerous cycles of drying and wetting.
3. To understand the initiation of cracks and its geometry in clay soils of different properties through different drying conditions.
4. To estimate the crack geometry and dimensions using image processing technique.
5. To assess the repeatability and healing (closure) of the crack in different clay soils: Nafferton (Durham boulder clay), Bentonite and other manufactured clays in the laboratory.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

6. To evaluate the implications of this cycles on foundation works and slope stability.
7. To relate this research outcome to provide recommendations for appropriate design and construction measure in order to mitigate this problem.

1.3 *Scope*

This project will investigate mechanically compacted engineered clays from the Bionic embankment to simulate extreme conditions of the behaviour of the soils on foundations works, embankments and engineered slopes. This research work is primarily experimental based and will carry out the wetting and drying tests to examine the behaviour of clays in relation to crack initiation and its geometry, crack repeatability, the ratio of surface crack to surface area of the tested samples, and also determine the implication for long term behaviour of foundation and embankments. The Laboratory methods and analysis of data will be in accordance with British Standard. Limitation of this research work is that it might not fully address field scenario mainly because of the various processes going on in the field which is too complicated to replicate in the laboratory, but will certainly give an explanations to the initiation and closure of the cracks formed on the field. This research work is in collaboration with a current PhD project on the mechanism of desiccation on clay embankments.

1.4 *Background of Bionic embankment*

The samples for this project were taken from the Bionic Embankment which is about 21km west of Newcastle University at Stocksfield Northumberland, which is one of the university farm for research purposes. The embankment is a current full scale testing instruments of the United Kingdom, mainly for Biological and Engineering impacts of the effects of change in climate on engineering structures, such as slopes which describe an embankment constructed to the British standards of railways and highways agency (Hughes *et al*., 2009). The embankment has a width of 29 meters and a length of 90 metres with an angle of slope of 1:2 with a height of 6 metres and a crest of 5 metres.

The Bionic embankment is basically used by several educational institutions within the UK for research purposes. The embankment is divided into four segments each 18 metres long, the middle two sections (36 metres long) have been built using good compaction method, and is an illustration of a newly constructed embankment according to the rail and highway agency standards. The rest two outer sections have been built using poorly compacted technique which is expressive of the conditions that may be found in an old embankment. Figure 1.2 shows the current state of the embankment (Hughes *et al*., 2009).

Figure 1.2: Current state of the Bionic Embankment in 2015 (Photo by Bamgbopa Sunday).

The embankment was built using Durham boulder clay with plastic limit of 23%, and liquid limit of 41% (Hughes *et al*., 2009). The commencement of the embankment started in June 2005, the divisions of the embankment which were constructed to highway agency standards were compacted with a smooth drum vibrating roller with about 18 rolling passes. The section which is poorly compacted was constructed using a tracked excavator but was not compacted and hence did not received any passes (Hughes *et al*., 2009). The compaction results of the two sections are listed in

Table 1.1 below. Due to compaction the mid panel had an improved density and reduced in percentage of air void which in tum reduced the volumetric variation of the soil.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

Table 1.1: Construction values of the good and poorly compacted section of the Embankment (Hughes et al., 2009).

Compaction	Bulk Density (Mg/m³)	Water content (%)	Dry Density (Mg/m³)	Air Void	Degree of saturation (%)
Poor	1.93	20.7	1.6	6	85.3
Good	2.01	20.01	1.7	3.2	91.4

2. LITERATURE REVIEW

Over the past few decades, comprehensive research had been carried out to understand the mechanism of shrinkage and cracking of cohesive soils. Several scientists have described both field and laboratory evidences of desiccation cracking, even though many of these studies have concluded with some remarkable results which are quite pertinent to this research project, little is still known about soil cracking. Also an engineered clay soils present much more complexities, below are brief reviews of some experimental researches and theories applicable to this project with explicit references to the mechanism of cracking, cyclic wetting and drying, compacted soils, effects of environmental conditions and several drying approaches to the initiation and closure of cracks.

2.1 Mechanism of cracking

Various experimental tests had been conducted in the past, all trying to understand the mechanisms of cracks using different approaches and variety of base material varying from rectangular test, circular, long mould test and field analysis. Also numerical models had been set up to simulate the conditions that influence the formation of cracks. In line with Kodikara and Costa (2013), the essential requirement for desiccation cracks is the development of tensile stress which exceed the tensile strength with restrained shrinkage.

The study showed that if a drying soil is free from any restraint whatsoever, then the soil will shrink on a full scale without cracking and this will depend only on the soil properties and environment. Cracks initiation is mainly control by two factors, first is the distribution of tensile stress due to restraining of shrinkage strain within the soil mass. With respect to this control, studies had shown that cracks will initiate at the centre of the soil drying mass where the tensile stresses are concentrated most (Nahlawi and Kodikara, 2006). The second factor relates to the initiation of cracks as a result of flaws or imperfections on the soil surface, the initiation of cracks are affected by the tensile stress at these locations. Flaws can be due to micro cracks, air bubbles, large particles and surface texture as stated by Nahlawi and Kodikara (2006). The figure below indicates the influence of tensile stress and flaws on the initiation of cracks.

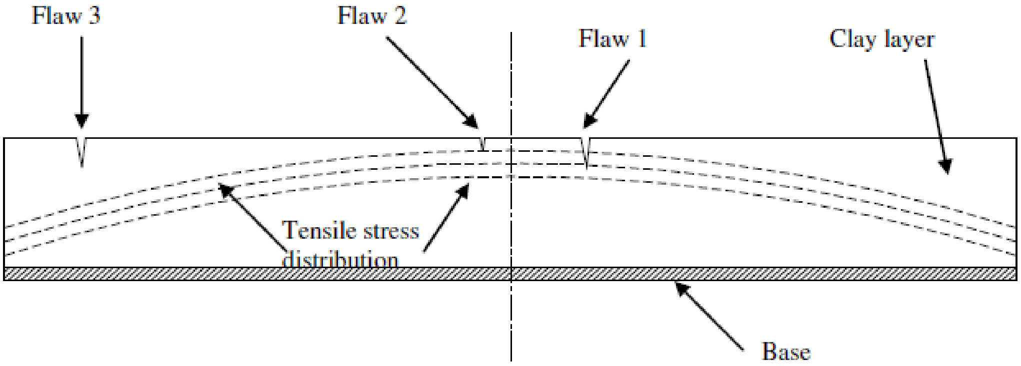


Figure 2.1: Flaws effects on crack initiation (Costa et al., 2013).

With reference to the fracture mechanics, the tensile stress needed to trigger a flaw is inversely proportional to the square root of the flaw size. Therefore it is likely for cracks to initiate at a place away from the location of maximum tensile stress if the flaws at these points are adequate enough to be triggered by the prevalent tensile stress (Nahlawi and Kodikara, 2006).

2.2 Cyclic wetting and drying

The unfavourable effects of reoccurring wetting and drying on the performance and behaviour of soil have received attention for several years, the mechanism of swelling, shrinkage and cracking are still not well understood. This area of focus received attention of more than a few researcher with uttermost interest in this genre. Laboratory observations and field studies were performed by Anderson *et al.* (1982) on the effect of shrinkage on the pore water pressure and stability of slopes contained by a clay embankment, which was vulnerable to variation in climatic conditions along a motorway within close proximity to Wootton Bassett, England. Several instruments were installed at depth across the site for the purpose of measuring both the positive and negative soil suction within the area. The area was divided into grids and marked for adequate spatial crack observation and precise monitoring with adequate measurement such as the occurrence at interval, width, depth within the grids. After careful monitoring, it was observed that most prevalent cracks occurred in August and consequent to that, there was a substantial rainfall which reduced the depth of these

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

cracks which continued to heal till the end of that year. It was recorded that the cracks finally closed by February of the next year following another heavy downpour. Assessments of the soils on the field indicated that there had been an increase in the permeability of the soil and also examination of the density of the soil indicated a variation.

The prompt variations in suction suggested that the desiccation cracks had increased its penetration and evaporation rates which is established by the variation in density which in turn suggest that the closed cracks only remain as a minute discontinuities in the soil as a potential weakness zone. The limitation of this research work was that the tensiometers used for measuring the soil suction were only fixed to a depth of 2m, whereas the embankment was 7m in thickness, hence only the performance of the upper surface was acknowledged and as discovered by radiography, the cracks were much deeper than initially recorded.

Albrecht and Benson (2001) studied the influence of wet/dry cycles on the hydraulic conductivity of compacted clays and demonstrated the fact that enormous increase in the hydraulic conductivity occurred when samples were compacted moist of optimum but not as much changes took place in dry compacted samples. Subsequent studies by Albrecht and Benson (2001) on the consequences of desiccation on compacted clays investigated how factors such as compaction conditions, properties of soil, drying rates, minerals constituents have influence on shrinkage and desiccation leading to cracking. Samples tested are both of low and high plasticity soil and the mineralogy of the samples were determined by the means of x-ray diffraction. The eight clay samples were compacted at different compactive efforts preceding saturation in a permeameter, and then allowed to dry at room temperature which took approximately 14 days. The cycles were repeated and samples that cracked in the course of drying were subjected to hydraulic conductivity testing subsequent to each drying cycle. It was observed from the testing that those soil samples with considerable amount of clay minerals undergo higher volumetric shrinkage as a results of their attraction to moisture.

After drying, tested cracked samples displayed a significant increase in the hydraulic conductivity which remained the same following further cycles. The most significant increase in the shrinkage strain and hydraulic conductivity occurred after the very first cycle of drying indicating that just one intense period of desiccation is completely enough to cause destruction to soil structure. Furthermore cracks formed during desiccation fail to close when exposed to prolonged period of hydration in a permeameter. These tests failed to reproduce field conditions correctly as the saturation method was not representative, also during desiccation the samples were open to the atmosphere which again was not realistic and therefore overestimated the effects and rates of drying, which in turn had significant impacts on the formation of crack.

Tang *et al.* (2011) worked on a laboratory experiment to investigate the effects of wetting and drying on the initiation of cracks on a clay layer from a slurry state. For this laboratory experiment, four duplicate slurry samples were prepared and subjected to five wetting/drying cycles. The rate of evaporation, initiation of cracks and the changes in the structures of the samples were monitored, the crack pattern formed were analysed using image processing. It was observed and recorded that the measured cracking moisture content, the ratio of the crack surface and the thickness of all of the samples increased considerably after the first three cycles and then approached equilibrium. The observed cracks formed after the second wetting and drying cycle were more uneven compared to the first cycle. The relative increase in the surface crack lead to decrease in the pore volume shrinkage during desiccation. In addition to their results, it was observed that the wetting and drying cycles led to the rearrangement of the samples structure as the original homogeneous structure was altered to a clear and aggregated structures with noticeable inter aggregate pores. The volume of the samples increased usually with cumulative cycles as a result of increasing porosity. Figure 2.2 (a & b) shows the setup and desiccation sample used for the experiment.

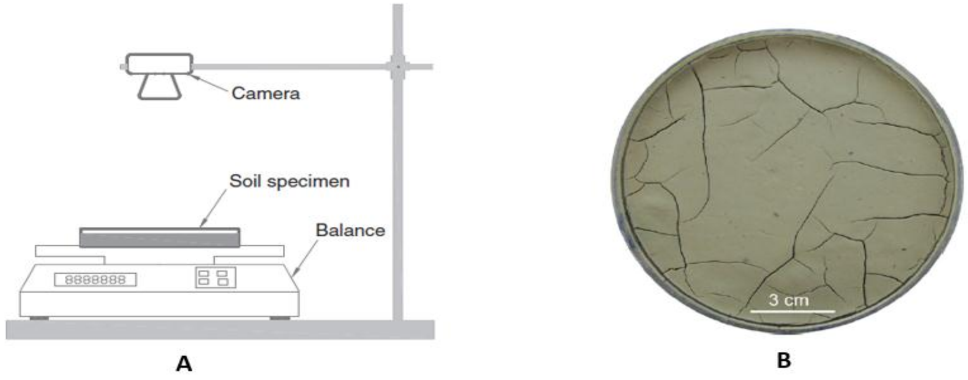


Figure 2.2: (A) Schematic drawing of set-up. (B) A typical desiccation crack pattern of specimen during the first drying path (Tang et al., 2011)**.**

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

2.3 Environmental and climatic conditions

Climatic change is clearly an issue to be considered as it cannot be controlled but only monitored to avoid its destructive impacts on engineering structures. Climate change and global warning has been an immense point of concern at this recent times with the summer of 1998 being the warmest global summer ever recorded in over 142 years and also the 1990's being the hottest period in the United Kingdom (UKCIP02, 2002). It is generally recognized that the latest climatic rise is associated to anthropogenic backgrounds with a considerable tendency of temperature increase with the commencement of industrial revolution as documented by Falkowski *et al.* (2000). The relevance of climatic condition with respect to this research is the significant and intense escalation in the wet and dry period which may result in more extreme cycles of shrinking and cracking leading to deterioration of embankments and other engineering structures.

2.4 Shrinking and cracking of clays

Expansive soil exposed to a slight change in moisture content can lead to a volumetric change in the crack surface area. These soils expand during precipitation by absorbing water into their structure and also shrink during desiccation within a period of dryness, moisture is also lost via evapotranspiration (Rao *et al*., 2004). These recurrent cycles have capacity to damage infrastructure and compromise the stability of slopes. The volumetric changes are determined by factors like the type of clay mineral present, the compaction of the soil, the depositional environment which are responsible for the arrangement of particles, the overburden pressure and as expected weathering (Mishra *et al*., 2008). Shrinkage of compacted soils was observed in three stages by Mishra *et al.* (2008), they are initial, primary and residual shrinkage.

With respect to the experiment performed by the aforementioned authors, soil samples of different composition were subject of 32ºC ± 3ºC observing the shrinkage rate as the samples desiccated. The void ratio and moisture loss occurred at the same time, this phase is the initial-primary shrinkage. Within the final residual phase moisture loss is apparent as well, but little or no significant void ratio variation was observed.

Soil cracking is observed in soil of high constituent of deformable clay minerals (Novák, 1999). The initiation and propagation of crack as observed by Tang *et al.* (2010) is due to the effect of capillary suction and rearrangement of constituent particles. As this suction advance, units of soil at the surface are exposed to tensile stresses which continues as evaporation proceeds, it got to a point where the tensile stress exceed the tensile strength of the soil, at that point cracking will occur.

With respect to Bradley et al. (2007) the formation of cracking that existed are: wide vertical cracks which are formed as a result of horizontal shrinkage, cracks associated to the matric pore within the clay which tend to varies over time depending on the moisture content and lastly the internal structural void with constant geometry. The understanding of all these functions and how they relates to the formation of cracks is vital to engineering as cracks formed can modify the surface properties by changing the soil permeability, infiltration and evaporation properties (Tang *et al*., 2010). Additionally these modifications can also affect the soil strength as zone of weaknesses are usually formed as shrinkage cracks initiate and propagate within the soil. Kodikara *et al.* (2002) appears to disagree with this as their research showed that as further drying and wetting cycles take place, the soil structure becomes more stable and will resist failure during wetting event which eventually improve to a more stable structure.

According to Haines (1923) referenced in (Lau, 1987), three distinct stages of shrinkage were acknowledged: they are normal, residual and no shrinkage. The samples categorised as normal are those that experienced significant variation in moisture content with time. The change in the moisture content was equal to the volume of the moisture loss. Moreover the residual shrinkage was regarded as the remaining volume of moisture minus the volume of the moisture loss. Hence when a variation in moisture can no longer be identified during drying, the soil sample is therefore at no shrinkage. Figure 2.3 below shows a shrinkage curve at different phases of shrinkage.

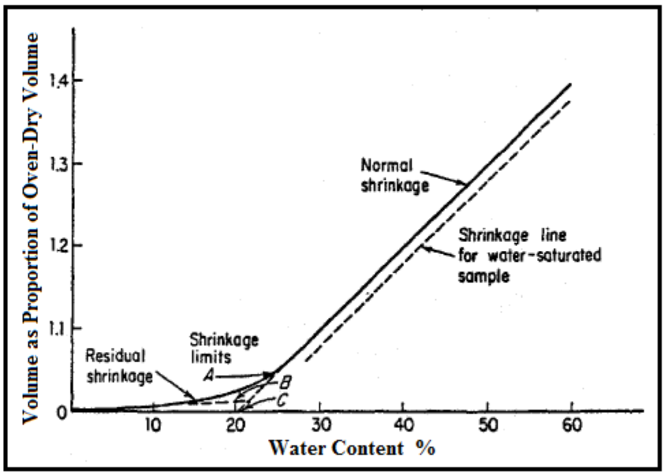


Figure 2.3: A shrinkage curve for clay soils emphasising the normal and residual shrinkage limits(Lau, 1987).

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

2.5 Temperature effect on cracking

Cracking has been studied by several researchers over time, meanwhile not too much has been established with respect to the connection between temperature, wind speed and the exact rate at which cracking develops (Tang *et al.*, 2010). With the obvious variation in climate, it is suggested that if the temperature of the UK is projected to increase, it is absolutely important to comprehend the effect of this adjustment on the cracking of soils. High clay content samples with 170% moisture content were subjected to three separate temperatures and humidity ranges (RH) (22°C 55% RH, 60°C 5% RH, 105°C 0%RH). At about 22°C the soil samples needed 7 hours to reach equilibrium which was nearly 13 times higher than the samples exposed to the other two greater temperatures.

The residual moisture content of the sample at the lower temperature at equilibrium was 4.5% which compared to 60°C, 0.6% and 105°C, 0% is significantly higher. Figure 2.4 shows the outcomes of nine soil samples in groups of three being subjected to three different atmospheric environments. The figure indicated that as the temperature rises the more moisture losses. Tang *et al.* (2010) settled that as temperature increases, water loss along with the percentage at which surface cracking occurs, therefore there rate of cracking will increase in the UK with respect to the increase in temperature.

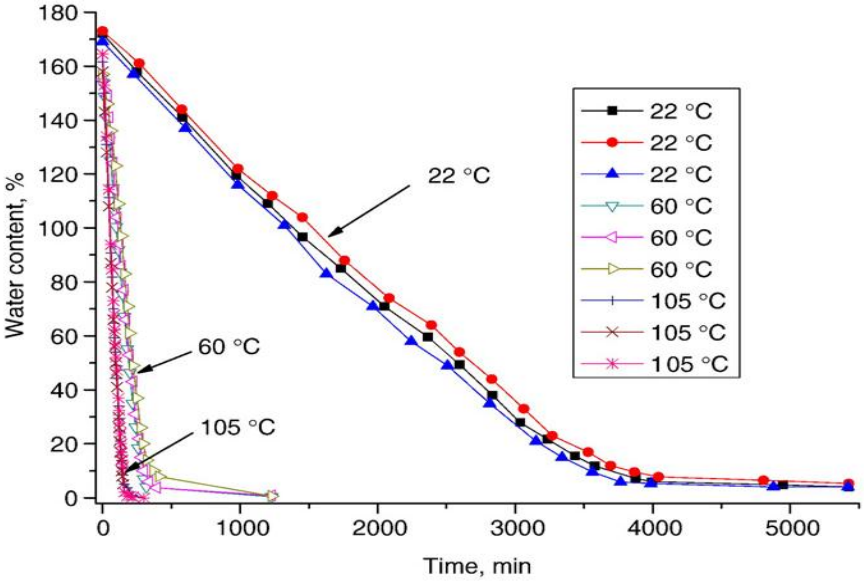


Figure 2.4: Desiccation curve of soil sample at 22ºC, 60ºC and 105ºC (Tang et al., 2010).

2.6 Wind Speed effect on cracking

Studies have also discovered a correlation between the rates of cracking and the effect of wind speed which is directly related to the rate at which moisture loss. The higher the wind speed, the greater the moisture loss which quickly accelerated the rate of evaporation (Ellah, 2009). Only few studies are seen in literature that actually demonstrated the effect of wind speed on the cracking of soil samples. Studies by Jacobson (1999) indicated the direct effect of soil moisture content on the speed of wind, temperature and concentration of pollutants in Los Angeles.

The studies showed that with higher day time wind speed, only low water content was achieved, whereas the opposite was observed with low time wind speed. Even though the desiccation performance was not experimentally observed through this investigation but the changes of soil moisture content with variation in wind speed gave a suggestion that greater wind would more probable stimulate greater desiccation as vapour loss is critical aspect to cracks initiation and development.

2.7 Compaction effect on engineered clays

Day (1994) investigated the swell-shrink behaviour of a compacted clay exposed to cycles of wetting and drying at temperature that represented field situations, the samples used are silty clay of liquid limit of 46% and plasticity index of 24%. The samples contain 9% of fine sand, 59% silt and 32% clay. The clay minerals identified are mostly kaolinite but montmorillonite was also detected. The sample was compacted to dry density of about 1.79Mg/m^3 at an optimum water content of 15%. This studies suggested that the first cycle of wetting and drying resulted in a low values of swell or shrink, meanwhile after repeated wetting and drying cycles, the amount of swell increased rapidly, this signifies that the effect the clay had when compacted at the moisture content above the optimum was destroyed by the cyclic wetting and drying.

Also Ferber *et al.* (2009) suggested that the failure of an embankment with respect to the shrink/swell cycles is influenced by largely on the mineralogy of the soil, the dry density, the moisture content and the amount of water intake, therefore it was concluded that the original compaction of the soil is very important and key to the failure of the soil. In this study, four samples with liquid limits greater than 50%, plasticity indexes greater than 30%

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

and a clay fraction higher than 60% were compacted at different stages using a miniaturized Proctor rammer. The compaction led to samples with different dry densities. The samples were retained in a conventional oedometric devices with 3kPa vertical stress. After 60 minutes the height of the samples were measured and then wetted, the tests was performed using different moisture content for each samples. Hence it was observed that less compacted soils were not as much as stable as those highly compacted (Ferber *et al*., 2009).

2.8 Miscellaneous

The aspect of shrinkage and cracking is an important issue to consider and several authors have a variety of approaches to this crucial engineering concern. Numerous numerical models have been created to investigate desiccation cracks and their behaviours. For example a model was established by Novák (1999) to simulate infiltration into dry cracked soils for the purpose of predicting soil water systems. Stirling *et al.* (2015) modelled desiccation cracking in the near surface of compacted soil using a finite difference modelling FLAC 2D which was considered to simulate the progression involved in the instigation and proliferation of cracking under laboratory condition. Chertkov (2002) also generated a model in order to characterise phases of saturated soil samples as they crack. Even though numerous investigations have been carried out, the essential mechanisms and consequences of desiccation cracking are still vague and not completely understood, therefore it is evident that more understanding of the issue is deemed necessary to precisely investigate soils exposed to repeated cyclic wetting and drying.

2.9 Summary of cracking

Cracking occurs both in engineering structures and natural settings. In the instance of engineering structures, negative equilibrium of energy arises within the soil which results in cracking. This is as a result of variation in moisture content and compaction energy within the structures, also during the construction phase (Fang and Daniels, 2006). In field conditions at a natural environment, the consistent shrinking and swelling of the soil as a result of cyclic weather pattern leads to cracking. Cracks are of various sizes and shapes, they can be major or extremely negligible and unnoticeable, but with time can be responsible for failure.

According to Fang and Daniels (2006) cracks can be classified into four major categories; shrinkage, tensile, thermal and fracture. Shrinkage cracks are the most common and they are formed due to moisture loss at the soil surface. During this process cracking occurs when the tensile stress generated is greater than the tensile strength of the soil. Thermal cracks take place when the soil mass experiences a rapid change in the thermal stress state of the soil. This can only happen in areas which experience high temperatures within the day and low temperatures at night which will cause freeze thaw effect on the soil mass.

Fracture cracks are as a result of pre-existing cracks within the soil formed due to deviations in precipitation, evaporation rate and water table which directly have an impact on the pore pressure. The continual variations in the pore pressure with time affect the water holding capability of the soil’s void configuration. During the desiccation process, tensional forces occur in the soil water structure and compression forces in the soil mass. The combination of these stresses led to fracture cracks. Tensile Cracking occurs as a result of overburden pressures which develop in a soil due to natural processes such as rainwater, snow, plants and surface creep. These processes led to an increase in the pressures within the soil mass and results in cracking (Fang and Daniels, 2006).

3. MATERIALS AND METHODS

This chapter provides details of the resources necessary for efficiently determining the effects of cyclic wetting and drying conditions on the shrinkage and cracking mechanism of Nafferton clay, along with the laboratory experimental techniques and apparatus used in this project. It also outlines the experimental plan that was followed in order to complete the testing in appropriate time. The principal objectives of this project were to investigate the shrinkage and cracking under series of cyclic events and also relating the laboratory behaviour of the samples to field conditions to observe the opening, closure and re-opening of the cracks. In order to accomplish all set out objectives, it was required to carry out a series of laboratory investigation and some other basic tests, therefore appropriate scheduling was essential to ensure all testing tailed a coherent and consistent manner within the time limits.

3.1 Materials

The Durham boulders clay was the primary sample used in this investigation, the physical properties are presented in the *Table 3.1* below. The sample was used in the construction of the Bionic embankment which is a current full scale testing instrument of the United Kingdom mainly for Biological and engineering impacts of the effects of change in climate on engineering structures.

Table 3.1: Properties of the Durham boulders clay (Hughes et al., 2009).

Durham Boulders clay	
Physical properties	Values
Liquid Limit	41.70%
Plastic Limit	23.20%
Plasticity Index	18.50%
Shear Strength	C=4kpa, ø=27.5°

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

3.2 Samples collection

Trip to the Bionic embankment was done on the 28th of April 2015 for sample collection, the Durham boulder clay was hand dug from the site using shovel and digger. It was paramount to collect enough samples for the laboratory experimental work to mitigate the risk of insufficient samples which might hinder the progress of the project as these samples are essential elements of this research. Figure 3.1 below shows the nature of the soil heap which was in a moist condition making it slightly challenging for removal.

Figure 3.1: Sample collection from a soil heap (Bionic Embankment 2015).

After the collection of the samples, they were transported back to the University geotechnical laboratory where the bags of samples were sorted and kept for use.

3.3 Sample preparation

The soil samples were placed in a big container and passed through 20mm sieve size to ensure appropriate mixture. The samples were left in the container for 48 hours to ensure adequate mixture and drying of the sample to a workable water content, therefore the moisture content was determine before the start of the experiment. The samples were then spread into a metal pan measuring 400mm in length by 400mm width and 75mm thickness using a spatula. The clay samples were compacted in the desiccation pan targeting a uniform thickness of 55mm. During the compaction process, consideration was made to uniformly distribute the samples to reach the above thickness by placing a steel plate on the top of the samples prior to tamping with the hammer. Also the surface of the samples were therefore smoothed by the aid of a spatula to facilitate observation of the cracks. A digital camera was also mounted on a stand clamp over the experiments set-up to capture the cracks initiation, development and closure at different time intervals. The mass of each sample was measured and recorded at interval during the drying cycles to determine the desiccation rate of the samples. Moreover adequate attention was focus on the mass loss during the first crack initiation. Figure 3.2 & Figure 3.3) shows the sample preparation and setup using a wind source desiccation approach.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

Figure 3.2: Sample preparation by tampering with a square base hammer

It was essential for the purpose of comparison and wider application to have soil of higher plasticity variable, therefore a synthetic soil with the addition of 5% Bentonite by mass was introduced to the primary sample.

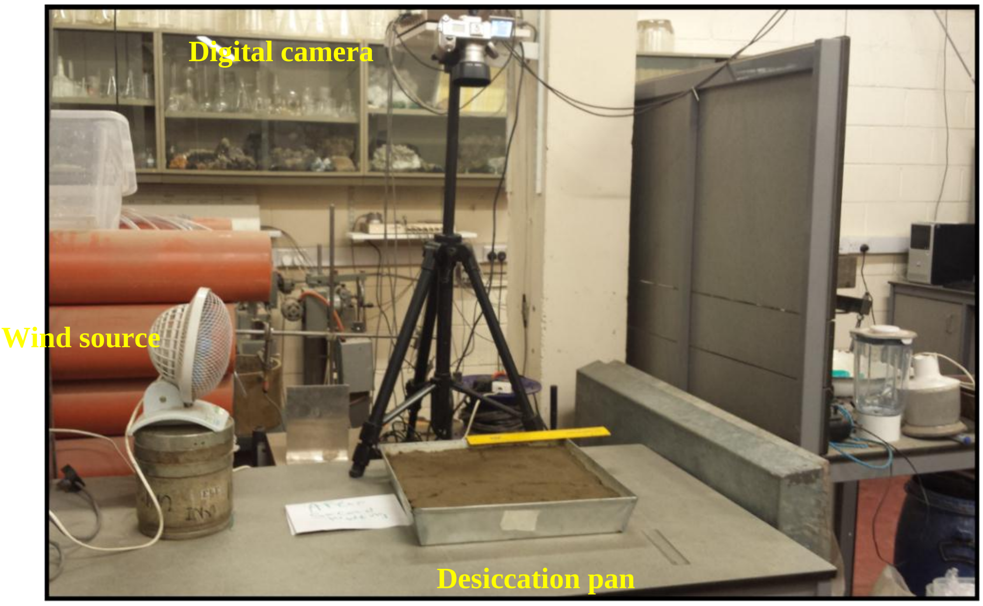


Figure 3.3: Sample setup using a wind source desiccation method.

3.4 Material properties determination

The material properties of the samples such as the liquid limit, plastic limit, and linear shrinkage were determined in the laboratory according to British Standard. Also with respect to the established facts that shrinkage lead to cracking, the surface of the samples was monitored closely every cycles to estimate the shrinkage in all the sides of the desiccation pan. This was achieved by creating a distinctive mark at the sides of the pan which serves as a reference point for measuring the amount of shrinkage which had occurred at the end of every wetting and drying cycles. Also since a thickness of 55mm was set constant,

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

vertical shrinkage was also observed and recorded as the soil shrink.

3.5 Drying and Wetting Experiment

Four similar samples were prepared as stated above and subjected to series of wetting and drying cycles under different desiccation techniques (Wind source and Oven).

3.5.1 Drying Approach

The samples were exposed to a wind source of 1.3m/sec average speed and the mass loss of the samples was recorded every hour to ascertain the desiccation rate. It is important to mention that the samples were dried for 48 hours and the residual weight of the sample was measured and recorded. At interval, digital camera was used to capture the cracks initiation, and propagation and this was analysed using Image J software to properly characterize the crack geometry such as the crack intensity factor, the crack widths and other interesting features. Meanwhile at the end of every cycles, manual measurements of the cracks were done such as cracks width, and depth with the aid of a vernier calliper and a meter rule.

The other desiccation method employed in this research work is oven drying at 60^oC. The prepared sample of known mass was placed in the oven and allowed to dry. The drying rate was measure every hour up to 7 hours and then 24 and 48 hours thereafter. A digital camera was also used to capture images at various interval between the crack initiation phases to about 24 hours. Also at the end of every cycle (dry/wet) an image of the sample was taken for analysis using the image J software.

3.5.2 Wetting Approach

During the wetting process, measure was taken to add back the water which was estimated to be the mass loss, this is a gravimetric quantification of the moisture loss. The samples were saturated back in phases with the aid of a spray bottle every 30 minutes and this continue until all the mass loss had been introduced back. After the wetting cycle, the samples were sealed up with a cling firm membrane to disallow evaporation. The samples were then left for approximately 24 hours to completely absorb all the water back to their previous state. This mark the end of the wetting cycle and the beginning of the second drying cycle as the samples were exposed again to the previous drying approaches (wind source/oven). Meanwhile several manual observations such as measurement of the crack depth and aperture were made before the beginning of each drying phase to ascertain if the cracks heal or not. These values were needed to compute for the total area of the cracks.

3.6 Quantitative analysis using digital Imaging

Digital imaging utilizes the aid of a digital camera to obtain images of the cracks for proper quantitative analysis. The Digital camera uses register images on an electric light beam which is composed of millions of pixels. The factors which are responsible for the quality of the images are the image resolution and image file compression. The former is associated with the amount of pixels in the light sensor (the more the pixels, the greater the resolution and enhanced images), while the latter reduces the quantity of memory space used up by the images, therefore permitting more images to be taken and stored. Also it is essential to frequently observe that the camera and lighten system are in a good condition (Yam and Papadakis, 2004).

3.6.1 Image analysis

The image J software was used to analyse the cracks surface area to determine parameters like, total surface area, cracks intensity factor and width. The methods used in the image processing are as follows:

1. The coloured images of the cracks were transformed to a grey level image (Figure 3.4(a)).
2. The grey images were divided into cracks and clods by the method of binarisation which resulted in a binary image (black and white) (Figure 3.4(b)).
3. The binary images were improved to skeleton images which resulted in a clear segment of the crack network system (Figure 3.4(c)).
4. The geometric parameters such as the crack intensity factor, cracks width and area were calculated.

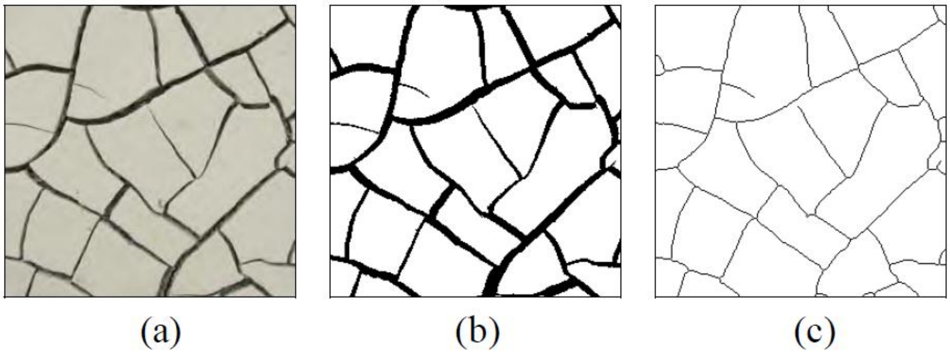


Figure 3.4: Development of image processing. (a) Initial grey level image, (b) binary image (c) frame of crack system (Tang et al., 2008).

3.6.2 Quantitative Analysis

For depicting the geometrical properties of the crack system, the below parameters were determined through image processing:

- Mean width of cracks (W_m). The width of cracks was estimated by calculating the distance from two opposite side of a chosen cracks and averaged to obtain the mean crack width.
- Crack intensity factor CIF. This is the proportion of the cracks area to the total area of soil sample. The CIF displays the level and degree of surficial cracking.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

4. RESULTS AND DISCUSSION

This chapter presents the results of the laboratory experiment for discussion and interpretation.

4.1 Liquid and plastic limit test

The liquid and plastic limits tests were conducted on the soil samples. The liquid limits of the Nafferton clay and Bentonite mix samples are 42.5% to 46.4%, whereas the plastic limits are 23.2% to 25.4%. These gave a plasticity index of 19.3% and 21.0% respectively which classified the samples as intermediate plasticity as indicated on the Casagrande plasticity chart (Figure 4.1). Note that the plasticity of the Bentonite mix is higher than the Nafferton sample.

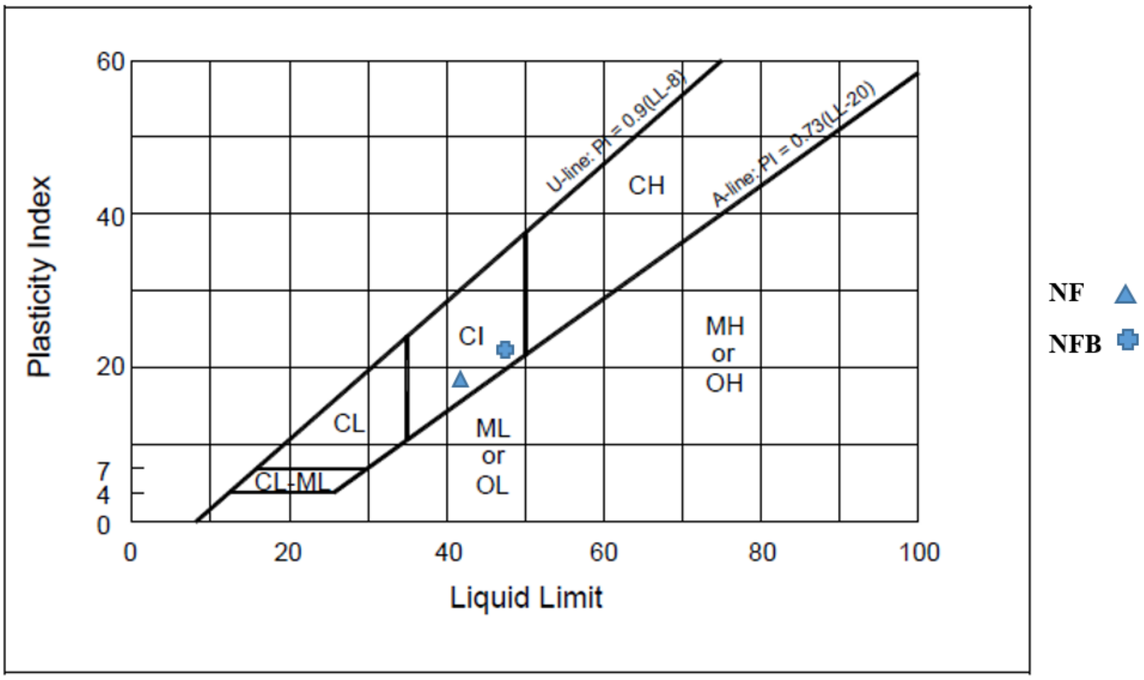


Figure 4.1: Plasticity chart for sample classification (NF-Nafferton clay, NFB-Bentonite mix)

4.2 Linear shrinkage

The linear shrinkage test is the estimation of the horizontal shrinkage of a sample at its liquid limit, the test was in accordance with British Standard 1377-2: 1990. The shrinkage capability of the Nafferton sample was observed by conducting a linear shrinkage test to investigate the extent at which the samples will shrink. This is a key factor in soil cracking when associated tensile stress within the sample exceeds the soil tensile strength (Kodikara *et al*., 2000; Peron *et al*., 2009). Three linear shrinkage tests were carried out on each of the Nafferton samples and the mean shrinkage was estimated. Interestingly, there were evidences of extensive curling in the three bentonite mix samples which is thought as the effect of the higher plasticity and the characteristic of high water affiliation of bentonite (Figure 4.2) which also enhanced its shrinkage potential as shown in the Table 4.1

.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

Figure 4.2: Linear shrinkage test (note the higher plasticity sample has curled)

The table below summarizes the result of the linear shrinkage test.

Table 4.1: Linear shrinkage test of NF and NFB samples

TEST DATA		NF			NFB	
Specimen Reference	C2	A1	A8	B9	A6	C8
Initial length L_o(mm)	140.00	140.00	140.00	140.00	140.00	140.00
Oven dried length L_d(mm)	128.36	128.19	127.51	123.59	126.90	125.09
Linear shrinkage $100[1-(L_d/L_o)]$ (%)	8.31	8.44	8.92	11.72	9.36	10.65
Average linear shrinkage (%)		8.56			10.58	

From the average linear shrinkage of the two samples with varying plasticity, it is evident that the higher the plasticity, the higher the linear shrinkage potential and vice versa.

4.3 Experimental wetting and drying cycles

Experimental wetting and drying cycles were conducted on the Nafferton samples to investigate their behaviour with respect to the mechanism of cracking and the disparity in the presence of some variables. For a successfully experimental program, a trial test need to be conducted to have a general feel of what is to be expected.

4.3.1 Trial Test

To ascertain the crack potential of the Durham boulders clay (Nafferton clay) and validate the method of restraint shrinkage test program, a trial test with slurry soil prepared by wet-sieving the clay sample through 2 mm was carried out. The moisture content of the slurry was 57% and the sample thickness was 55 mm. The test also represented a worst moisture content of an un-engineered condition. The sample was dried in the oven at 110°C. During the wetting cycle, the mass loss was added back to the sample at once to simulate a worst case condition in the field. Figure 4.3 below shows the states of the sample at different points.

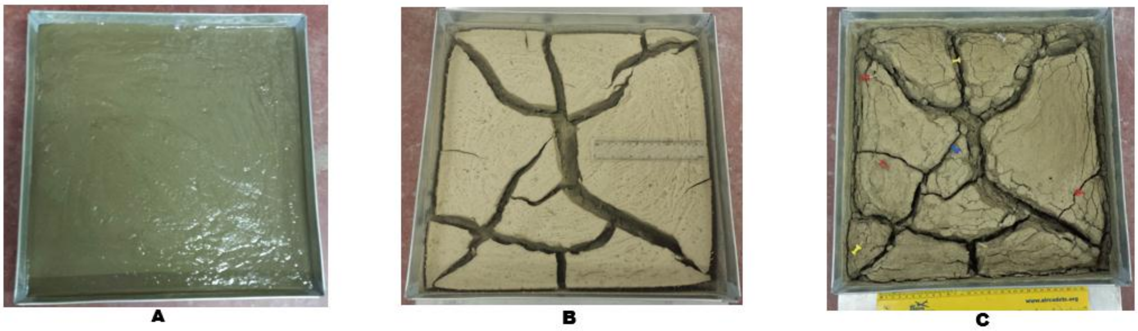


Figure 4.3: Validation of cracks in a slurry sample (A): Slurry at the start of the experiment (B) After oven drying at 110°C (C) Second drying cycle at 110°C

After the first drying cycle the mass loss was 3.84 kg, this was assumed to be the gravimetric mass of the water loss. From Figure 4.3b, the maximum width of crack measured was 34 mm with depth of 25 mm. The average width of cracks in the first drying cycle at 110°C was 20 mm. Shrinkage was also observed around the sides of the pan with an average width of 15 mm. With the aforementioned method of wetting, it was observed that the sample found it difficult to absorb all that water at once, therefore the slow and rapid infiltration of water led to the

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

initiation and development of new cracks. As the sample became gradually saturated, it heaved and increased in thickness.

During the absorption of water, the mechanism of closure was observed as a result of breaking off and falling in of weak particles of soil as they lost their cohesion at the edge of the cracks. The soil particles shed off into the gap leading to the gradual closure and the depth of the cracks reduces. This can be related to the field scenario as intense rainfall washed some particles into the open cracks and reduced their depth. After the second drying cycle, mass loss was 3.35 kg, the island created by the first drying cycle further developed into secondary cracks (Figure 4.3c). The new cracks met at an average angle of 90°. The infilling of falling material reduced the depth of the cracks and influenced closure. Since this is a trial test, only two cycles were observed.

4.4 Engineered clay soil

This project focuses on the engineered compacted soils, therefore the samples were prepared by passing through a 20 mm sieve mesh to fairly represent field situation. The sample were compacted by tampering with a square base laboratory hammer weighing 6 kg.

Table *4.2* below shows the laboratory test methods and sample properties used (refer to Appendix A).

Table 4.2: Laboratory test process and sample properties used.

Soil Samples	LL (%)	PL (%)	PI (%)	MC (%)	Classification	Desiccation Approach	Number of Cycles
NF 1	42.5	23.2	19.3	22	CI	Wind Source	4
NF 2	42.5	23.2	19.3	22	CI	Oven Drying	4
NFB 1	46.4	25.4	21.0	27	CI	Wind Source	4
NFB 2	46.4	25.4	21.0	27	CI	Oven Drying	4

Note: NF- Nafferton Clay, NFB- Nafferton clay plus 5% Bentonite, CI-Intermediate Plasticity
1-Wind Source, 2- Oven Drying.

4.4.1 Nafferton clay using wind source desiccation

The desiccation condition was through air drying using a table top electric fan which gave an average wind speed of 1.3 m/s, and the moisture content of the sample was 22%. The first sets of cracks appear within 90 minutes and began its propagation. It is interesting to note that some cracks initiated around some visible cobble size sand particles inclusion and surface texture roughness due to sample preparation. These serves as surface flaws which are often thought as a potential locations of stress concentration for crack initiation (Kodikara and Costa, 2013). Elias *et al*. (2001) also studied vertisols soils from three diverse areas of Sudan which had different particle sizes and established the facts that particle size had a significant effect on the development of cracks in the field. Figure 4.4 indicates the time series photograph of crack initiation and development. Note the crack initiation near stone inclusion in the desiccation pan.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

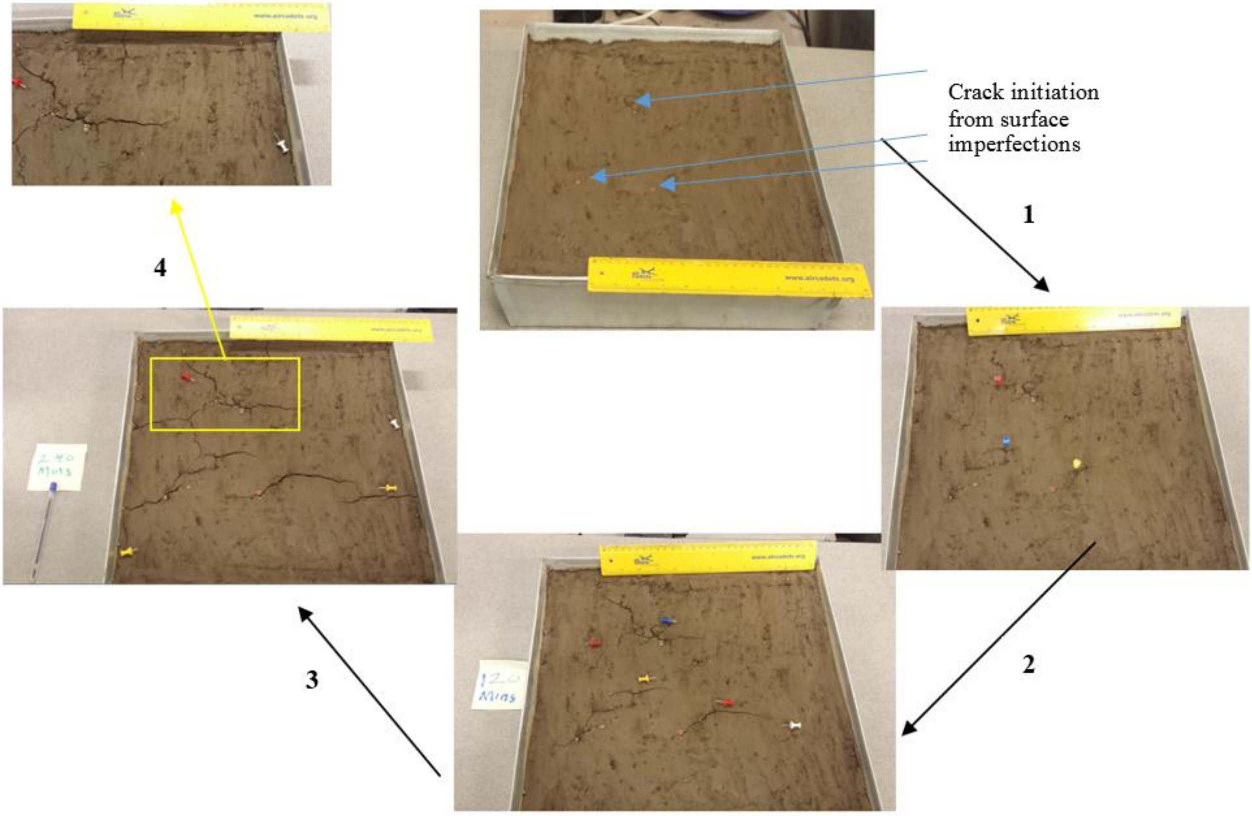


Figure 4.4: Crack initiation and development in an engineered clay soil.

The crack history of the different cycles is also presented in Figure 4.5. The cracks representing the start of the second, third and fourth cycles as shown in Figure 4.5 (e, f and g) do not completely close upon wetting. The cracks are seen repeated during subsequent drying, however there are secondary cracks development of similar geometry as shown at the end of each drying cycle (Figure 4.5 a, b, c and d).

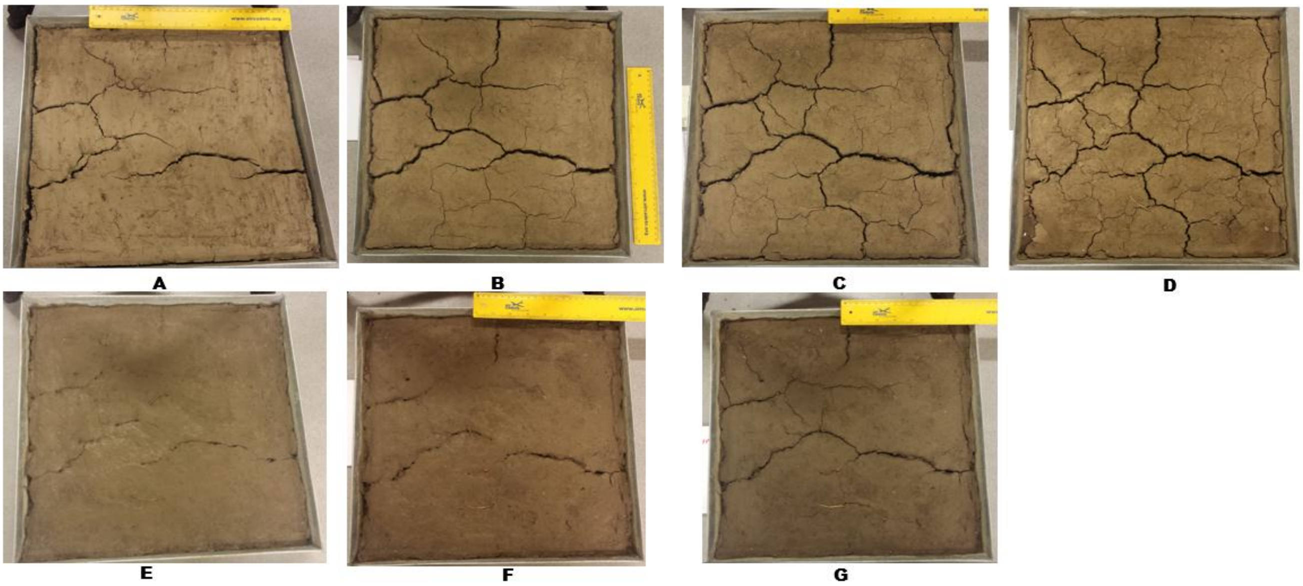


Figure 4.5: Nafferton sample at different wetting and drying cycles using wind source desiccation approach

A, B, C, D: Sample after first, second, third and fourth drying cycle
E, F, G: Sample after first, second and third wetting cycle

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

After the end of each cycles, manual dimensions such as the width and depth of the cracks were observed and recorded. It is clearly seen that the crack dimensions slightly varied with each consecutive cycle up to the third cycle. For example, the average crack widths were 4.3 mm, 6.5 mm, 7.1 mm and 7.3 mm showing that there were no significant changes between the third and fourth cycles. This agree with studies conducted by Tang *et al.* (2011) who indicated that an equilibrium state can be achieved after certain cycles which in this case is third cycle. After the wetting phase some minor cracks seem to close completely as they were not obvious at the end of the wetting cycle (Figure 4.5). Also the primary cracks appeared to close partially, besides new minor cracks formed which were prompted by the wetting phase and caused as a result of the variation in swelling stress due to re-wetting.

4.4.2 *Nafferton clay by oven drying*

Nafferton clay was prepared in a similar way as above but subjected to desiccation through oven drying means. It was expected that rapid drying of the sample will occur due to the method employed in the drying process at temperature of 60°C. Figure 4.6 relays the samples at different cycles.

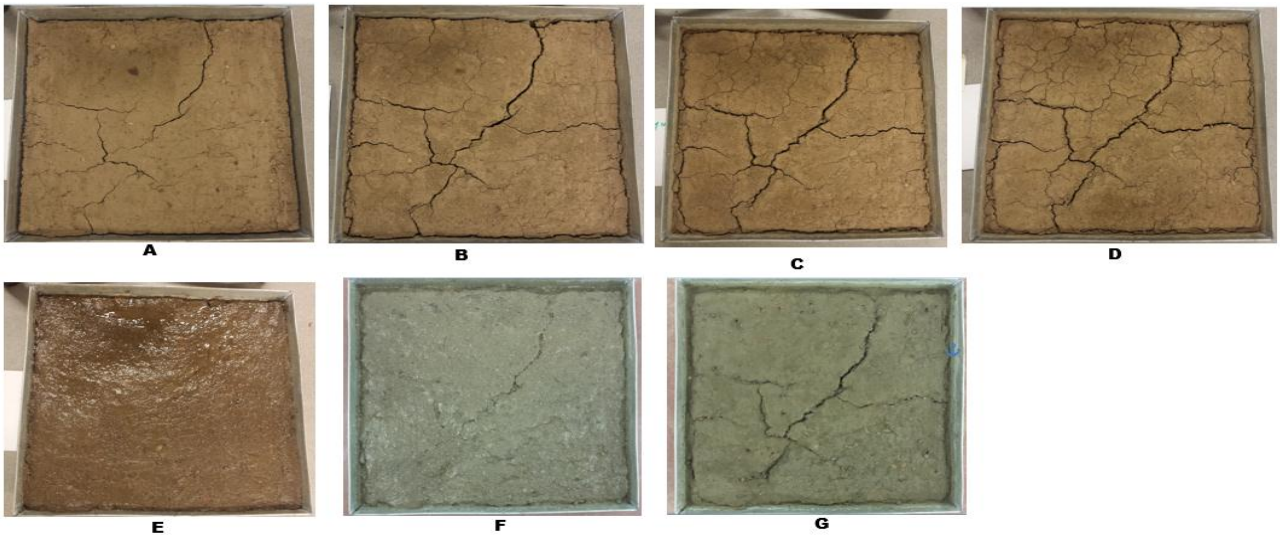


Figure 4.6: Nafferton clay sample at different wetting and drying cycles using oven drying desiccation approach

A, B, C, D: Sample after first, second, third and fourth drying cycle
E, F, G: Sample after first, second and third wetting cycle

Also similar observation of the crack width and depth was done and recorded. The average crack widths of the four cycles are 3.1 mm, 5.2 mm, 5.9 mm and 6.1 mm respectively. These also shows a trend of gradually attaining equilibrium state after the third cycle as there seems to be a rearrangement of sample structure into a more stable configuration. Visual observation showed that more cracks were formed with increasing cycles. Similarly the re-wetting phase showed some closure of the cracks which completely closed the minor cracks but partially heal the major ones (Figure 4.6).

4.4.3 *Bentonite mix by wind source desiccation*

Sample NFB1 contains the mixture of Nafferton clay with 5% Bentonite using a wind source drying approach. From the wetting and drying experiments on this sample, it was observed that this sample exhibited an increase in the extent of cracking with the number of cycles. Cracking was observed as the surface of the sample gradually dried out, it started with an appearance of few cracks which later developed increasingly with time, with full crack developed within 48 hours of desiccation using the aforementioned desiccating approach. Wetting resulted in the obvious closure of most minor cracks which were visible after the drying cycle, but the next drying led to both the re-opening of the primary cracks caused the first drying cycle and the initiation of additional minor closely spaced cracks. Figure 4.7 shows the sample at the end of each cycle.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

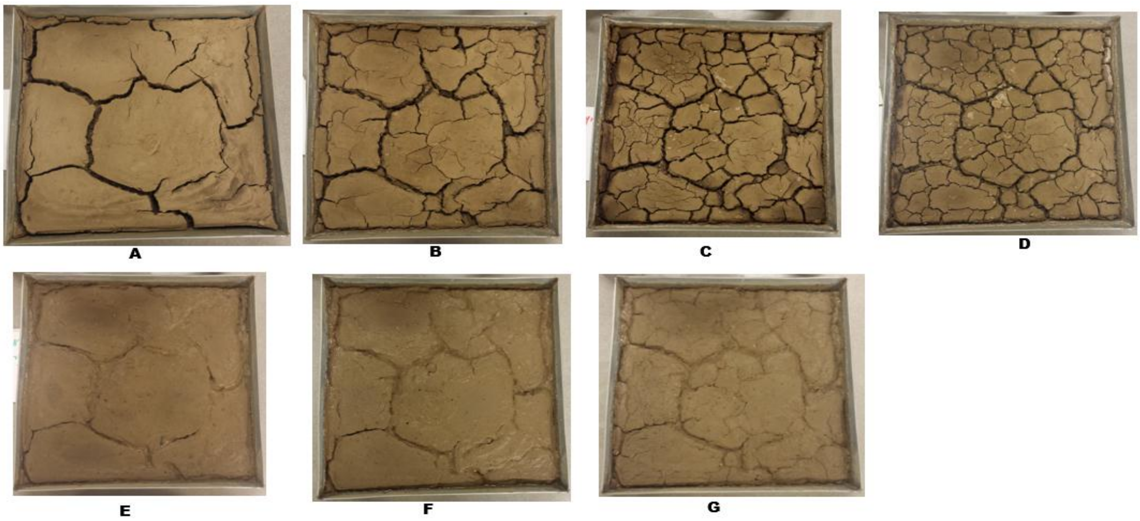


Figure 4.7: Bentonite mix sample at different wetting and drying cycles using wind source drying desiccation approach

A, B, C, D: Sample after first, second, third and fourth drying cycle
E, F, G: Sample after first, second and third wetting cycle

During the crack initiation and development, as desiccation proceed from the surface down and moisture is being loss, there exist an interesting features which will be of uttermost interest to engineering as far as cracking is concern. The bentonite mix sample seemed to have a layered cracks as the cracking depth terminated within the sample and continue in a horizontal manner forming a kind of horizontal cracking. The sample also exhibited an extensive heaving and shrinking from one side of the sample with respected to the others. This might be as a result of the physical properties of bentonite as it absorbed water but reluctant to release it. Therefore as moisture is being loss from the sample, there seem to be a redistribution and absorption of moisture from one region to the others.

4.4.4 Bentonite mix by oven drying

Similarly, the prepare bentonite mix sample as above was desiccated at a temperature of 60^0C in the oven. The intensity of crack was also significant and similar to the air dried equivalent sample as the crack intensity factor increases with cycles. The crack widths ranged from 3 mm to about 25.6 mm. These widths decreased with cycles as closure was observed and more crack developed. Figure 4.8 shows the sample at the end of each cycles. This sample also displays layered and horizontal cracking as observed in wind source equivalent.

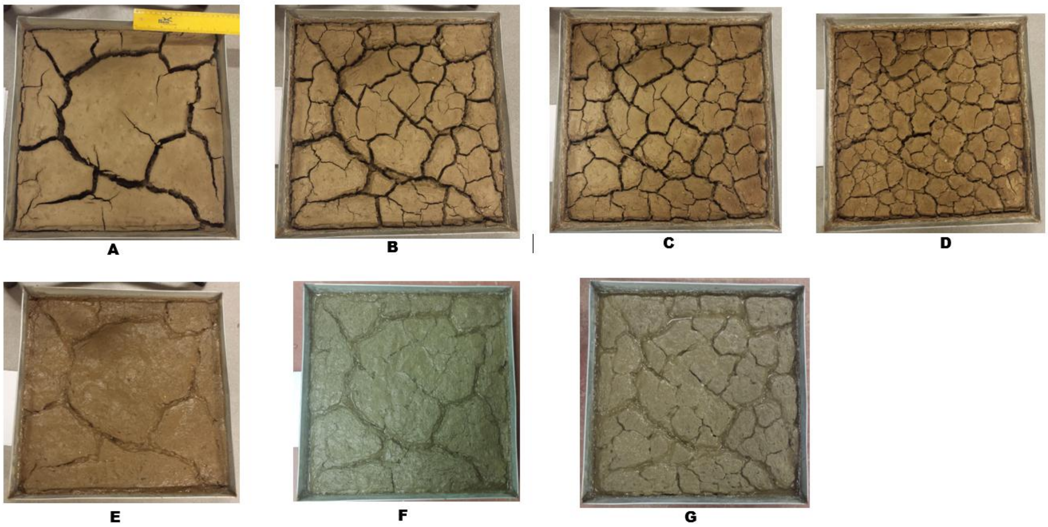


Figure 4.8: Bentonite mix sample at different wetting and drying cycles by oven drying desiccation approach

A, B, C, D: Sample after first, second, third and fourth drying cycle
E, F, G: Sample after first, second and third wetting cycle

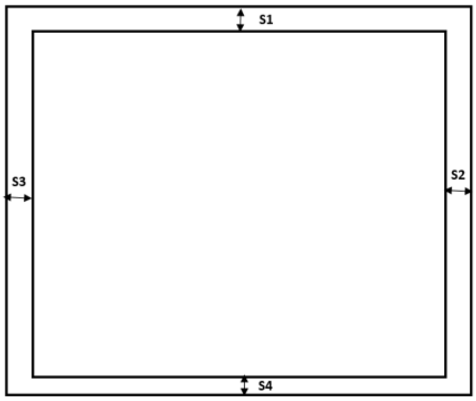
4.5 Shrinkage monitoring

The shrinkage of the samples was monitored and recorded at the end of every cycle to investigate the linear shrinkage. Figure 4.9 shows the method of shrinkage estimation. The table below shows the variation of the shrinkage:

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

Table 4.3: Linear shrinkage of the test samples

		Linear shrinkage (%)					
Samples	Wet-Dry cycle	S1 (mm)	S2 (mm)	S3 (mm)	S4 (mm)	Final Length (mm)	Linear Shrinkage (%)
NF 1	First	4	10	10	3	373	6.8%
	Second	4	8	7	2	379	5.3%
	Third	3	6	7	2	382	4.5%
	Fourth	3	2	2	2	391	2.3%
NF 2	First	7	8	9	4	372	7.0%
	Second	7	6	5	3	379	5.3%
	Third	6	5	4	3	382	4.5%
	Fourth	2	2	4	2	390	2.5%
NFB 1	First	3	4	1	3	389	2.8%
	Second	2	2	1	2	393	1.8%
	Third	3	2	2	2	391	2.3%
	Fourth	3	2	3	4	388	3.0%
NFB 2	First	1	2	2	2	393	1.8%
	Second	2	2	2	2	392	2.0%
	Third	2	1	1	1	395	1.3%
	Fourth	5	5	4	5	381	5.5%



$$\text{Linear shrinkage} = 1 - \frac{[400-(s1+s4)+(s2+s3)]}{400}$$

Figure 4.9: Methods of Shrinkage measurement

4.6 Method of desiccation justifications

The method of desiccation in this research is through a wind source approach and oven drying at temperature of 60^0C. The wind source method represents a slow drying process where the moisture content within the sample is expected to reduce steadily depending on the wind speed which in this case is 1.3m/sec. The oven drying approach represented a thermal desiccation at a rapid rate, this is aimed at observing the effect of a rapid drying rate on the crack development. As thermal drying increases, the soil tensile stress increase which is expected to reduce the soils strength and results in cracks formation. This approach is also aimed to observe the cracking moisture content of the samples with cycles, even though this was achieved by estimation as the exact cracking time was unknown due to sample drying in the oven. Another justification is the fact that United Kingdom weather can be a little bit unpredictable, hence simulating a rapid and slow desiccation approach was considered.

4.7 Summary of the cyclic experiment

From the wetting and drying experiments, it was clearly observed that surface imperfection, texture, defect or flaws caused by tampering hammer or other sample preparation procedures significantly influenced the cracks initiation and pattern. In addition, comparing the air dried Nafferton sample to the oven dried Nafferton sample, it was evident they both have similar crack pattern as most of the cracks intersected at an angle of 90^0. Moreover, the CIF was considerable less compare to the bentonite mix samples. The variables introduced between the two samples were the addition of 5% Bentonite to the Nafferton clay to attain at a more plastic soil sample, the variation in moisture content which differ by 5% and also the desiccation approaches (wind source and oven). These variables had a major impact on the crack pattern, crack geometry, crack intensity factor, repeatability and healing. Therefore from the laboratory test as illustrated previously, it can be concluded that all these variables are worthy of attention when considering cracks initiation, propagation and closure. Table 4.4 below shows the drying procedure water content results.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

Table 4.4: Drying procedure water content results

Samples	Wet-Dry cycle	Residual water content (%)	Test duration
NF 1	First	8.7	12 days
	Second	6.2	
	Third	9.72	
	Fourth	12.03	
NF 2	First	6.16	12 days
	Second	7.33	
	Third	6.15	
	Fourth	5.43	
NFB 1	First	12.14	12 days
	Second	13.57	
	Third	13.56	
	Fourth	13.51	
NFB 2	First	4.51	12 days
	Second	7.66	
	Third	5.23	
	Fourth	4.85	

Note: NF- Nafferton Clay, NFB- Nafferton clay plus 5% Bentonite
1-Wind Source, 2- Oven Drying.

Note that NF and NFB samples have a starting moisture content of 22% and 27% respectively. From the results above, the significant differences in the residual moisture content of the wind source and oven dried samples signifies a higher desiccation rate of the sample dried in the oven. It is of interest to note that within the context of this project each cycle took 3 days.

DISCUSSION

Consequent to the completion of the cyclic experiments, below are some notable observations and discussions.

4.7.1 Visual observations

Quantitative analysis of the crack pattern is essential when examining cracking in clay soil, these geometric factors are helpful to understand the hydro-mechanical properties of the clay water system (Tang et al., 2011). They provide essential mechanism to comprehend the formation of cracks. Similarly the crack propagation behaviour and the geometric parameters reveal the plasticity and mineral composition of the soil. Perrier (1995) suggested that if the actual structure and features of crack pattern can be determined, then soil response to wetting and drying may be predicted. Visual observation of the cracks was done at the conclusion of each drying cycle to quantify the width, depth and thickness of the cracks and compare the variations with subsequent cycles.

Table 4.5: Quantitative parameters of the cracks at the end of each cycle

Samples	Wetting- Drying cycle	Average Width (mm)	Average Depth (mm)	Average thickness (mm)
NF 1	First	4.3	28.8	48.2
	Second	6.5	29.5	50.3
	Third	7.1	28.1	48.7
	Fourth	7.3	23.1	50.9
NF 2	First	3.1	7.5	52.0
	Second	5.2	10.7	53.2
	Third	5.9	10.9	51.9
	Fourth	6.1	11.2	52.2
NFB 1	First	20.2	22.3	49.8
	Second	18.4	17.4	51.2
	Third	17.9	17.1	52.7
	Fourth	18.2	17.2	52.7
NFB 2	First	25.6	25.3	50.9
	Second	21.4	17.6	51.7
	Third	20.9	16.3	51.1
	Fourth	20.1	16.4	52.0

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

Table 4.5 summarizes the quantitative parameters measured at the end of each wetting-drying cycle using a Vernier calliper. The average final thickness of each sample was measured and plotted with wetting-drying cycle (Figure 4.10). It was observed that consistent increase in soil final thickness with cycle was as a result of consecutive reduction in drying rate. This is supported by increasing residual moisture content with drying, however it seems soil structure had re-organised from the third cycle as observed by Kodikara *et al.* (2002). Hence this trend is completely reversed as more secondary cracks leading again to increase desiccation and greater settlement.

Also from the chart below, the final swelling height of the wetting showed minor differences, however it was observed that the sample with Bentonite mix heaved and curl as the soil cracked. This is considered as result of the greater affinity of bentonite to water which reduced the rate of desiccation and consequently the dynamics of cracking.

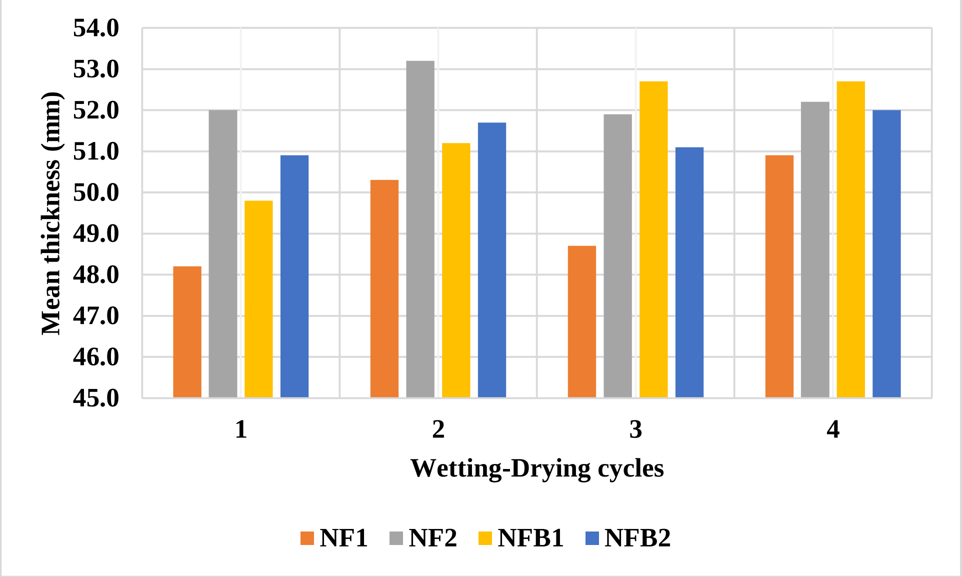


Figure 4.10: Average final drying thickness with cycle

The result above illustrated that the cyclic wetting and drying considerable have an effect on the characteristic of the samples, meanwhile the degree of influence tend to decrease after the third cycle and approach an equilibrium state.

4.7.2 *Evaporation, Shrinkage and Crack Initiation*

In order to investigate the desiccation, shrinkage and cracking rate of the samples, the mass of the four samples were measured during the drying cycles at interval to estimate the moisture content within the sample at different point in time by gravimetric method as follows:

The mass m_1 of the desiccation pan was measured at the beginning of the experiment, the total mass of the pan and the wet sample was measured at the start of each cycle after sample was prepared and ready for desiccation as m_2, the mass of pan and the sample after each cycle of drying was measured as m_3. After each drying cycle, the final mass of the sample was m_3-m_1. The mass of water loss was estimated as $m_w = m_2 - m_3$; the moisture content at each point in time during the period of desiccation was estimated as:

$$\textbf{Moisture Content} = \left(\frac{\textbf{Mass of water}}{\textbf{Final Dry mass}}\right) = \left(\frac{\mathbf{M_2 - M}_x \ \textbf{at (mass of the sample at time} = t}{\mathbf{M_{DryFinal}}}\right);$$

Time t (hrs) is the time at which the m_x was measured and recorded.

According to Tang *et al.* (2011), two distinctive evaporation phases exist in the desiccation curve referred to as constant and falling evaporation phase. The constant evaporation phase is the duration of which moisture decrease linearly with time and a consequent falling evaporation phase is the stage during which moisture loss reduces gradually until the residual water content is reached. Since the drying phase of each sample only took 48 hours, Figure 4.11 and Figure 4.12 show the desiccation curves for the samples at different drying approaches. The residual water content is the estimated moisture remaining in the sample at the end of the drying cycle. From Figure 4.11 and Figure 4.12, the residual moisture content is about 8.7% and 6.1% for Nafferton clay through wind source and oven in the first drying cycle respectively.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

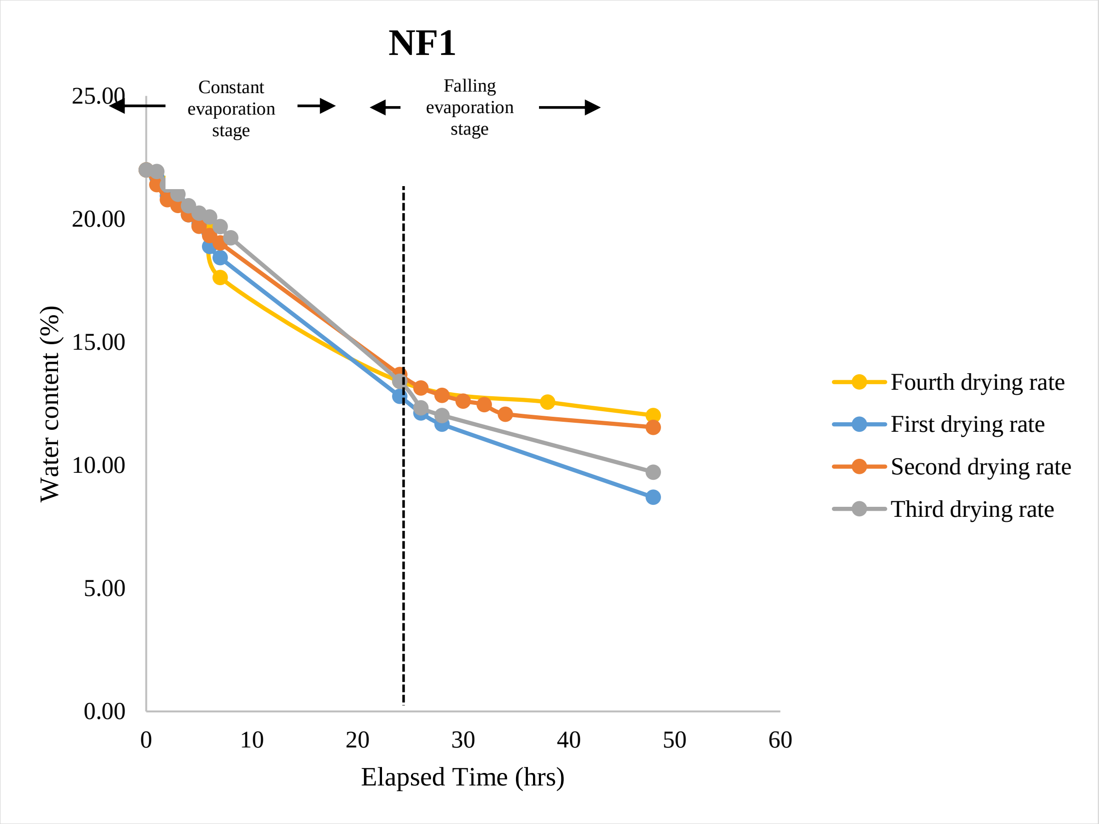


Figure 4.11: Desiccation curves for Nafferton clay using wind source.

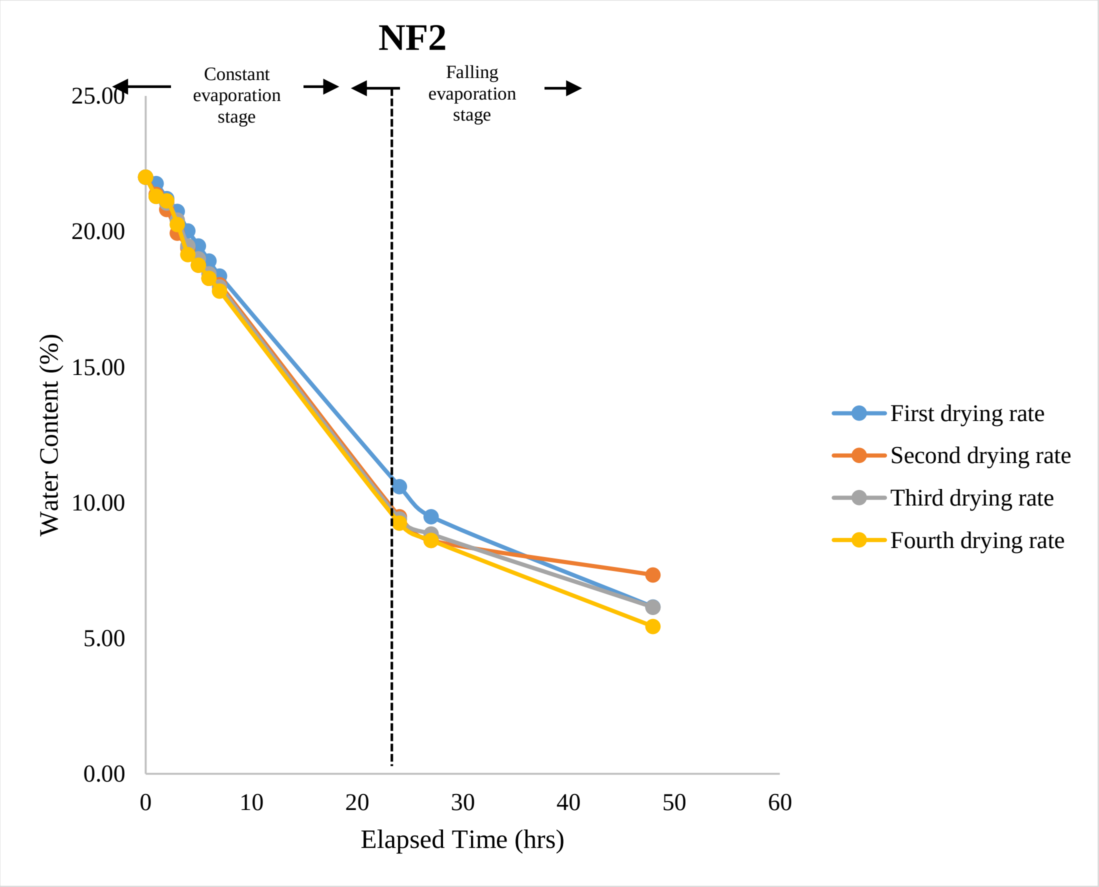


Figure 4.12: Desiccation curves for Nafferton clay using oven drying.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

The same trend was observed in the bentonite mix as moisture content decreases linearly with time within the first 24 hours before slowing down to its residual moisture content after 48 hours. Comparing the desiccation rate of samples, it was observed that as expected oven drying at 60°C had a rapid drying rate 40 g/hr compared to the wind source approach which was at 70g/hr. This was also confirmed as the residual water content of 12.14% and 4.51% for Bentonite mix sample (NFB) through wind source and oven respectively. Furthermore in the tests carried out, it was pragmatic that the cracks instigated at the initial stage of desiccation when the samples had lost about 2% of their moisture content, the above desiccation curve had similar pattern from the constant evaporation stage to the falling evaporation stage as the sample approaches an equilibrium or residual state toward the end of the drying cycles.

4.7.3 Cracking water content

During desiccation, as the sample witness moisture loss consistently with time, as soon as the first crack appears on the sample, the amount of water within the sample at that time is defined as the cracking moisture content (w_c) (Tang et al., 2011). This is however an important observation in the understanding of the mechanism of cracking in different soils. The suction developed during the drying process is a direct function of the water content of the sample as observed in the desiccation curve. It was earlier established that for cracking to occur, the tensile stress developed must exceed the tensile strength of the soil. Similarly for the samples dried in the oven, it was difficult to know the exact cracking time and therefore the cracking time was estimated using the desiccation curve from the first visual crack observation.

The observed cracking moisture content of the samples is indicated in Figure 4.13 and Figure 4.14, the graphs both for the Nafferton and bentonite mix samples reasonable compare with that of Tang et al. (2011) indicating increasing cracking with increasing cycle. However in this study, the initial portion of the air dried Nafferton sample between the first and second cycles behave approximately due to the close starting moisture content value of the two cycles. This was attributed to the method of wetting as the soil was wetted back to the starting mass which implies almost the same starting moisture content. The slight different behaviour here could be attributed to engineered condition as compaction will impact a different response change to drying, and enable the soil to display a more gradual pattern of desiccation with time which eventually displays the three different segment of crack as documented by Li and Zhang (2011).

The cracking moisture content changed significantly just after the second drying cycle between the air dried and oven dried Nafferton sample (at the prepared moisture content of 22%), but this differ significantly from the first cycle between the air dried and oven dried bentonite mix samples at the same starting moisture content of 27%. The average of the first drying cycle for NF samples is 20.71%, increasing to 20.78% in the second cycle, then increases by about 0.61% (21.39%) in the third cycle and up to 21.46% (0.07% increase) in the fourth cycle. This indicate a rapid increasingly trend with the first three cycles and then a lower increase at the fourth cycles.

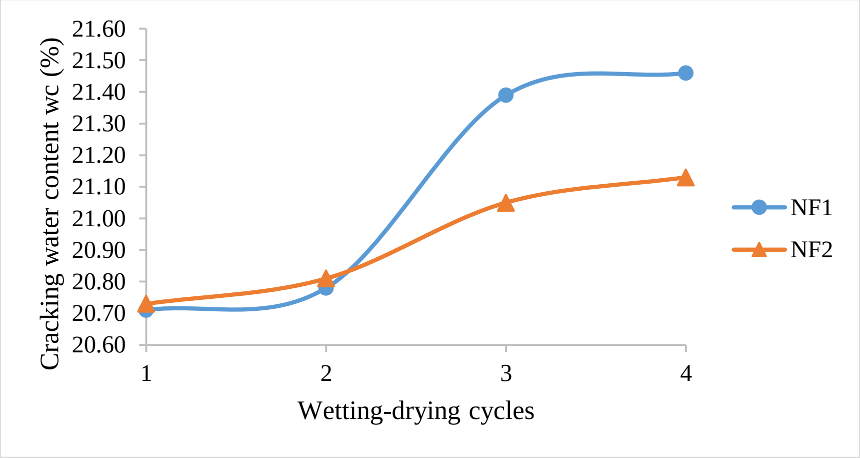


Figure 4.13: Cracking moisture content of NF samples during each drying cycle.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

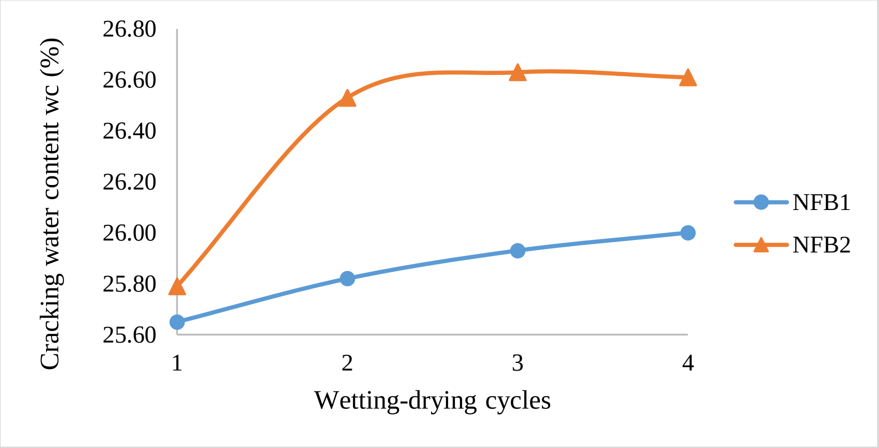


Figure 4.14: Cracking moisture content of NFB samples during each drying cycle.

Similar trend was observed in NFB samples but the significant increase in the cracking moisture content was observed within the first two cycles and a slight variation within the subsequent cycles. Generally cracking moisture content displays by the above sample showed an increases with cycles especially the first three cycles. This is as a result of the wetting phase of each cycles as crack usually occurs as soon as the sample begin desiccation depending on the drying approach. Nafferton clay was observed to begin it crack initiation within 2-3 hours of drying. Meanwhile this can differ in other clays depending on the variables such as its starting moisture content, drying approach, drying rate and most importantly the material properties.

4.7.4 *Effects of wetting-drying cycle on cracking moisture content*

The effect of wetting and drying cycles on the cracking moisture content was demonstrated above, the rate of increase in cracking moisture content (w_c) in the first, second and third cycles was significant. According to Morris *et al.* (1992) and Kodikara *et al.* (2002) cracking takes place once the tensile stress prompt during desiccation surpass the tensile strength of the sample. Therefore, below are the effect of the wetting and drying cycles on the samples behaviour.

1. During desiccation, the shrinkage of the sample increases persistently which results in an irreversible change and increase in the weak zone of the sample due to the increasing tensile stress (Yong and Warkentin, 1975). The tensile strength of the sample is reduced considerably which influences cracking at high cracking moisture content (w_c) during consequent desiccation cycles.
2. During the first wetting-drying cycle, the initial sample structure and arrangement are distorted and rearranged giving rise to heterogeneity in subsequent cycles. Due to these non-uniform particle distribution, the tensile stress develop during desiccation of the next cycle would concentrate on the weak zone within the sample structure with lower tensile strength. Tang *et al.* (2008) observed that the initial crack formed at the surface defect can promote more cracks within its surrounding and tensile stress concentration. This was seen in NF and NFB samples as the primary crack at the end of the first drying path developed into series of minor crack within their surrounding during the subsequent cycles. This was noticed visually and also proven by estimating the crack intensity factor.

4.7.5 *Structure changes effect of wetting and drying*

During the cyclic wetting-drying experiment, it is expected that some changes will occur within the soil pore spaces. Kodikara *et al.* (2002) recorded some important evidences of changes in the micro and macro-structure of a surficial clay material subjected to wet-dry cycles. The process of structural changes is usually refer to as maturity of soil and considered to be due to the redistribution of the pore spaces during the drying episodes. Similar changes were observed in Nafferton clay samples during the cyclic experiment as the desiccation rate, cracking moisture content, crack intensity factor vary with cycles. The mechanism and consequence of this structural changes are explained as follows:

1. The rate of moisture loss during desiccation is very important especially comparing with consequent cycles. Generally moisture is stored within the inter-particles pores, moreover with subsequent cycle, the desiccation rate decreases as moisture is now shifted and stored with the intra-particles (adsorbed water). This delayed evaporation rate is evidence in the desiccation curve of NF1 sample. During the first drying cycle, moisture was lost at the rate of 40 g/hr and the residual mass after 48 hrs was 14.30 kg. While in the second cycle after wetting, the residual mass after same period of drying was 14.61kg which indicated the desiccation rate was slower in the second cycle.
2. During wetting, the aggregates particles masses formed in the drying cycle was seen breaking down and collapsing as a result of separation of particles. This process of separation end up affecting the pre-existing bond between the soils mass. This is evident as the sample swell and attains a considerable thickness upon wetting as water mount up over the increase particle area. During this period, the structural instability of the sample led to particle realignment in a more disperse form, moreover if the soil had previously witness this, then more bonds will be made within the sample leading to a more stable structure as cycle progress.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

3. As the number of cycle progress, the soil sample becomes more stable and will be resistant to further rearrangement and therefore will be eventually matured. These changes tend to attain equilibrium in this cases after three cycles depending on the soil structure and material properties.

4.7.6 Equilibrium state during wetting-drying cycles

Several researchers have worked extensively to understand the variation of cracks formation and the differences in the behaviour of soil during numerous wetting and drying cycle. Based on the result obtained from the cyclic wetting-drying of Nafferton clays samples, it was observed that after the samples were subjected to the first, second and third cycles, the subsequent fourth cycles experienced little of no significant variation in the cracks formation and the major cracks re-opened again with similar dimensions and geometry (this will also be referred to in the image analysis of the cracks). This is assumed to occur as result to the re-arrangement of the sample structure diminishing and approaching a more stable structure (Kodikara *et al.*, 2002; Tang *et al.*, 2011). From previous studies, there seems to be a confirmation as equilibrium state tends to occur during multiple wetting and drying cycles, meanwhile this largely depend on the percentage of clay mineral in the soil. Basically samples with high plasticity required more cycles to reach an equilibrium state compare to sandy soil samples (Al Wahab and El-Kedrah, 1995; Omidi *et al*., 1996; Yesiller *et al*., 2000).

It was earlier established that crack network became more complex with wetting-drying cycles, meanwhile the reasons for the continuous breakage of cracks into more complex network than the previous homogenous system are stated below based on the observation of the Nafferton clay samples. It was observed that the initial homogeneous system was broken into further heterogeneous systems after the first drying cycle, therefore the second drying cycle treated each of the created islands as a separate homogenous system which now cracks and further subdivided depending on the flaws at the edges of the various boundary which is now been created. This goes on with cycles until it get to the smallest possible level where it cannot subdivided again that is, where further drying will only lead to evaporation and not cracking anymore. At that point, the system was stable because it had become weaken that no adequate tensile strength can develop again that will lead to further cracking, even the tensile strength of the respective segment was very low at that point. The soil had been broken down almost into aggregates, so there were no structures for tensile stress to build up again to cause cracking.

The above observation will largely depend on the size of the sample as while three cycles can completely mangle up the Nafferton samples of 400 x 400 x 75 mm, a very large sample of considerable sizes will take up to much more cycles to attain the equilibrium state as describe herein. As far as there are segments for the tensile stress formed to propagate, more cracks will keep developing as the sample continues to subdivide. With respect to Tang *et al.* (2011) equilibrium explanation at the end of three cycles, this concept of subdivision will depend on the size of starting sample that will determine the number of cycles at which it starts to equilibrate because as far as there are still a large islands of soil mass, it will still further crack. It will continue to subdivide until the whole system has become aggregated completely.

This idea was conceive from the drying Nafferton samples taking note that at the end of the drying, there are still some residual moisture content within the sample waiting to be evaporated, yet no cracking was observed anymore. This is because the surface area of the different aggregate has gotten to a smallest bearing minimum that no changes necessary will occur. This mechanism of crack propagation and equilibrium had not been seen or explained in any literature and therefore will need to be validated through further research. Figure 4.15 below explains the crack development and progression towards attaining equilibrium (concentrating on the bounding circle).

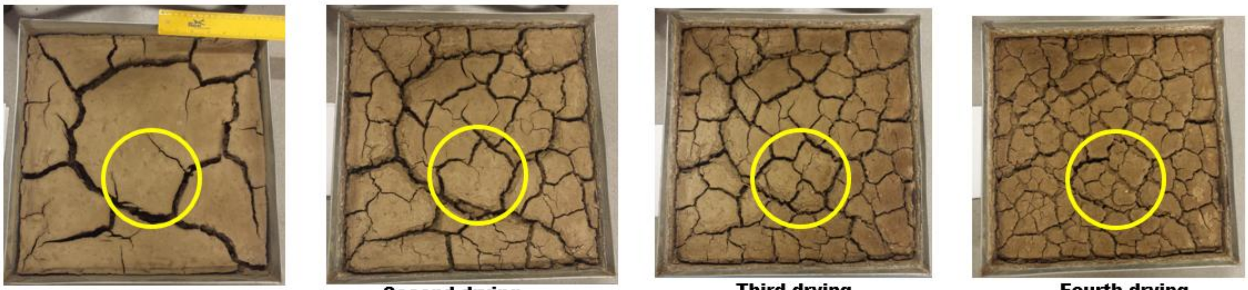

First drying **Second drying** **Third drying** **Fourth drying**

Figure 4.15: Cracks development gradually approaching equilibrium

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

4.7.7 Image analysis of Cracks

With reference to the procedure stated in the methodology section, all the crack images at the end of each cycles for every sample were analysed by the image analysis software for quantification of the surface area of the cracks. All crack parameters were calculated precisely, the data estimated from the sample images of the cracks are shown in Table 4.6.

To measure the extent of cracking, crack intensity factor (CIF) was determined which is the percentage of the surface area of the cracks to the total surface area of the samples. The images of the cracks were analysed in the imaging software (Figure 4.16 and Figure 4.17), it is interesting to observe that all the Nafferton samples have similar orthogonal crack pattern basically intersecting at an angle of 90^0.

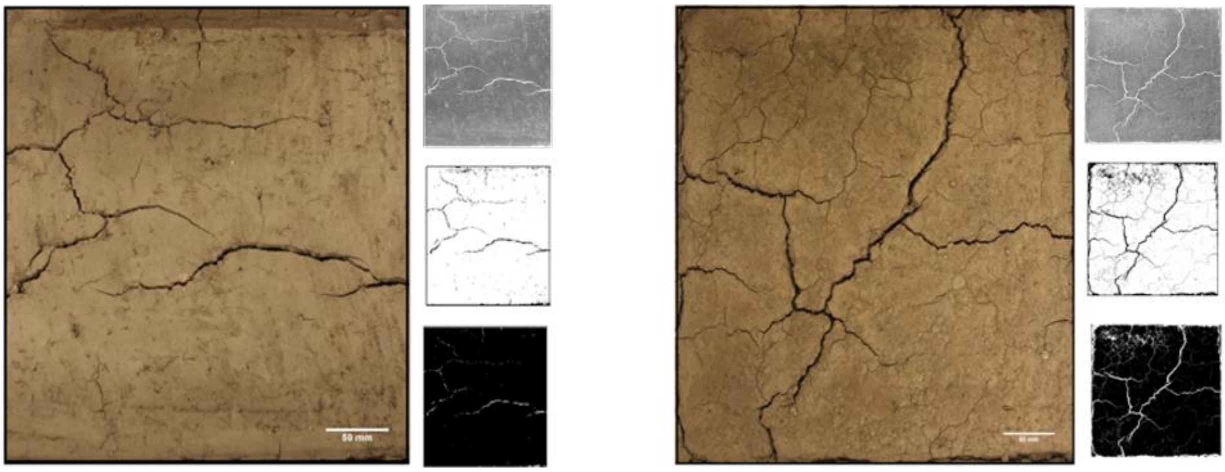


Figure 4.16: Processes involved in extracting cracks parameters (NF1 and NF2)

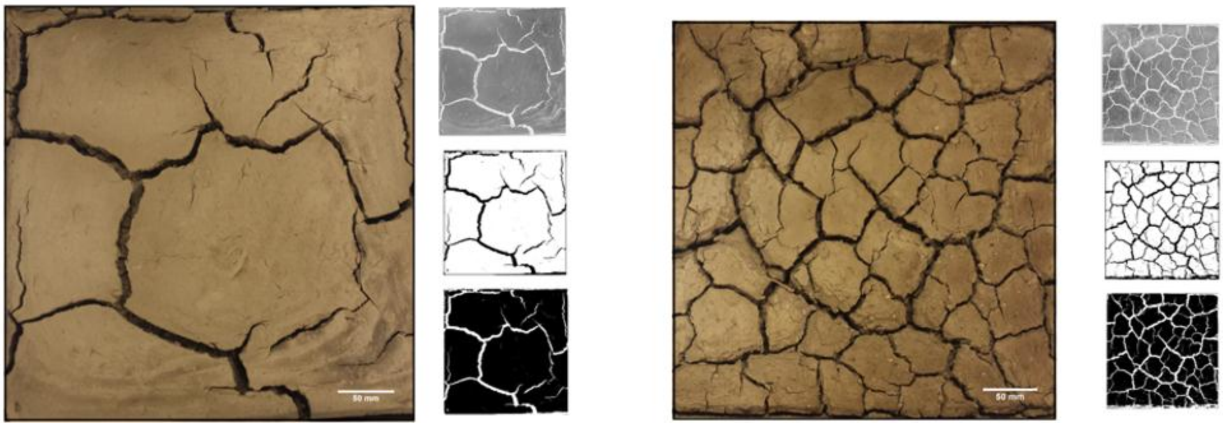


Figure 4.17: Processes involved in extracting cracks parameters (NFB1 and NFB2)

Table 4.6: Geometric parameters of cracks during each wetting-drying cycle using imaging analysis

Samples	Wet-Dry cycle	Average Width (mm)	No of cracks Intersection	CIF (%)
NF 1	First	4.34	7	4.3
	Second	6.48	10	7.0
	Third	6.93	12	7.5
	Fourth	7.27	11	8.6
NF 2	First	3.15	4	4.0
	Second	5.21	12	5.7
	Third	5.93	12	6.8
	Fourth	6.10	13	7.1
NFB 1	First	20.27	7	10.5
	Second	18.42	20	17.1
	Third	17.95	26	23.8
	Fourth	18.21	24	23.9
NFB 2	First	25.59	8	15.5
	Second	21.27	20	17.3
	Third	20.94	22	19.2
	Fourth	20.16	19	20.8

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

For the purpose of estimating the number of crack intersections using the imaging software, images of the samples at the end of each cycles were being skeletonized and a diagonal line was drawn on the images. The software was set to count the intersection of any cracks along the diagonal line (Figure 4.18).

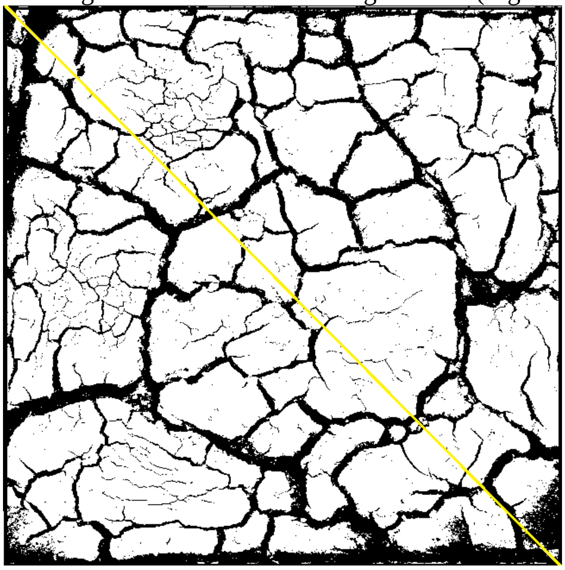


Figure 4.18: Image processing to extract crack intersection

4.8.7.1 Crack intensity factor (CIF)

In view of the fact that desiccation cracking commonly occurs in form of a system of cracks with numerous widths, length and depth, estimation of which could be hard and time consuming. Crack intensity factor (CIF) is usually calculated to basically relate to the area of cracks in an integrative manner. For the purpose of estimating and quantifying the intensity of the cracks, a crack Intensity factor (CIF) was calculated which was centred on the description by Miller *et al.* (1998) as the proportion of cracks area to the overall surface area of the drying sample mass. The accuracy of the techniques used for estimating the cracks area can significantly affect the estimated crack intensity factor values.

Though manually estimating the crack widths, lengths and depths had been considered inaccurate and therefore a much more accurate technique was used in this research which is the image analysis. After each drying cycles, the variation of the surface crack ratio was estimated using the imaging software to understand deviation of the crack area with respect to the total surface area and the results was plotted in Figure 4.19.

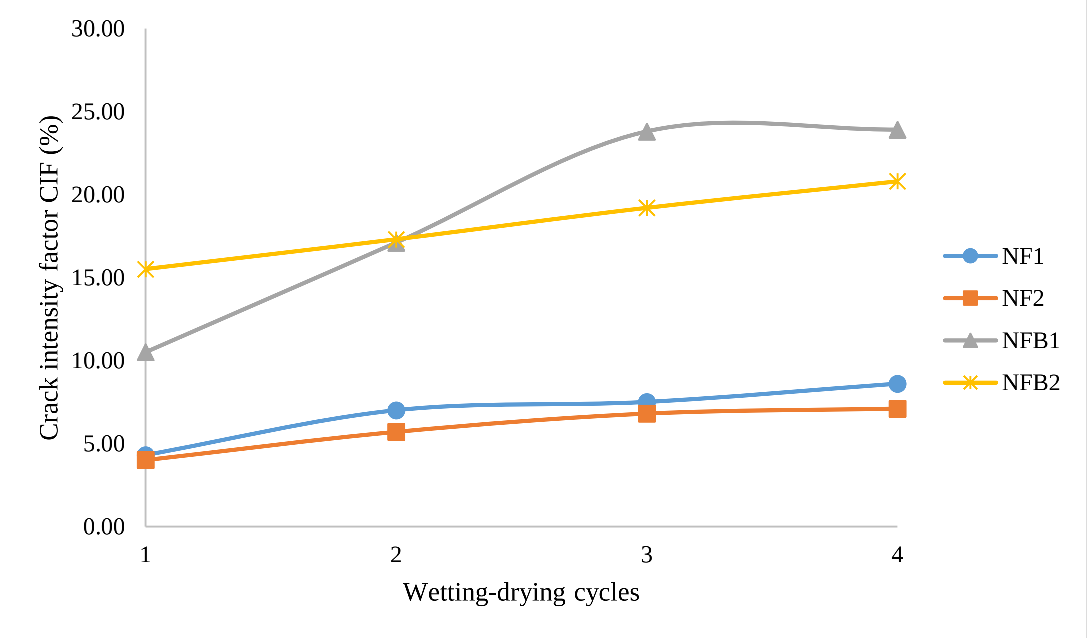


Figure 4.19: Crack intensity factor after each wetting-drying cycle

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

Figure 4.19 indicates that the CIF increases with cycles in all the samples, meanwhile the higher plasticity bentonite mix sample (NFB) has a greater crack ratio compare to the Nafferton samples. This thus confirms that material property such as plasticity index has a significant effect on the initiation and propagation of cracks. Furthermore, the method of desiccation does not significantly affect the crack intensity factor, but the rate of drying and possibly the sample thickness.

4.7.8 Repeatability and Closure

Whether cracks are repeated during of cyclic events or not have received similar attention as the issue of cracks development is concerned (Yesiller *et al*., 2000). Rayhani (2007) noticed that the hydraulic conductivity of saturated soil samples after cracking was greater than the intact sample not exposed to desiccation which suggested that the cracks did not heal completely after wetting. Yesiller *et al.* (2000) conducted experimental tests to examine the desiccation cracks of some compacted soils and found that consequent wetting cycles created some curing to the cracks that developed in the first wetting-drying cycle. However, the major primary crack kept re-occurring in subsequent cycles but with some evidences of gradual closure with respect to their widths, lengths and depths.

Consequently to the occurring of cracks of Nafferton samples in the first cycle, measure was taken to observe the cracks repeatability in the subsequent cycles.

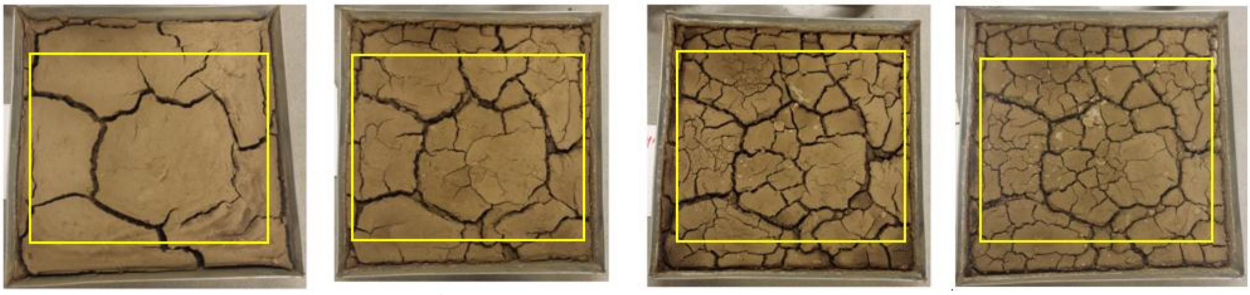


Figure 4.20: Repeatability of cracks seen in NFB 1 sample (concentration within bounding rectangle)

Concentrating on the area within the bounding rectangle, some primary cracks were identified right from the first cycle and monitored through to the fourth cycle. The observed cracks are labelled below.

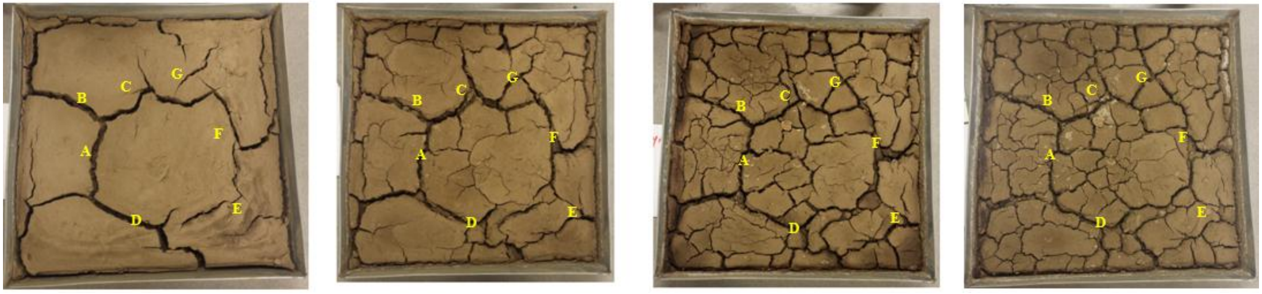


Figure 4.21: Repeatability of cracks seen in NFB sample

From Figure 4.20, it is evident that the first sets of cracks which appeared in the first drying cycle repeated themselves in subsequent cycles, but this time with some obvious evidence of healing due to the re-arrangement of the soil structure. Meanwhile during this process, the soil loses some of its thicknesses and aperture. Table 0.7 shows the widths of the measured cracks in the Figure 0.21, note how the cracks widths increased and decreased based on the initiation of other minor cracks during subsequent cycles.

Table 4.7: NFB2 sample and crack widths dimension with cycle

	Cracks Widths						
Cycles	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)	F (mm)	G (mm)
1	16	18	3	20	4	10	5
2	14	15	8	5	7	10	4
3	13	13	5	5	7	8	3
4	13	13	5	5	7	8	3

The positions of the cracks are repeatable on other cycles. The mechanisms of the repeatability of these cracks can be considered from a perception of soil behaviour and wetting approach. The soil pore structure can be classified as intra-elemental pores, intra-assemblage pores, inter-assemblage pores, and trans-assemblage pores (Collins and McGown, 1974). Usually, the adsorbed water in the intra-elemental pores is difficult to eliminate from the soils

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

especially the higher plasticity soil (bentonite mix). Cracks are the margins of different masses in a soil, the bonds within the masses are much stronger than that between the cracks segments. Therefore extra bonding produced inside the masses during a drying cycle will cause the strengthening of masses which resists the failure of the particles during subsequent wetting process. Cracks may heal due to softening of the soil or the falling in of shed off particles at the surface or edges of the cracks. Though the bonds within the cracked region are much feebler than the bond within the soil mass, thus with further drying cycles more particle masses become even and cracks tend to appear between the soil masses mainly within the earlier cracked zones. Tang *et al.* (2008) also witnessed repeatable cracks in clays soil and establish that the very first three dry/wet cycles improved soil cracking, thereby enhancing the crack intensity factor in subsequent cycles.

4.7.9 Implication of cyclic wetting and drying on ground works and slope stability

Clay soils are one of the most abundant materials within the earth crust, and also inevitable for use in any engineering construction especially within the UK. These cohesive material combined with the alternating weather pattern tend to have a significant point to worry about owing to the established behaviour of these materials to consistent moisture change. Clays are known to be fine grained which signifies their susceptibility to shrinkage and cracking, and to geotechnical engineers the long term stability of various infrastructures like embankments, motorways, bridges, dams, railway and so on is of uttermost concern. Perry *et al.* (2003) estimated that thrice as many slopes which had failed in the past are likely to fail again in the future if no preventive actions are reserved to account for the cyclic change in climate and its effects on infrastructures.

The adverse effect from series of embankment failures prompted Mishra *et al.* (2008) into broad investigation of slope movements. The outcome of the study had proven that most of the slope failures are associated with precipitation and also the properties of the soil involved. Rainfall is related to soil cracking such as providing a pathway for percolation of water thereby decreasing the slope resistance to slide. Also the moisture content within the slope rapidly increases through the cracks resulting in the decrease of effective stresses, cohesion (c) and angle of internal friction (Φ). The pore pressures which are applied within the sides of the cracks thereby decrease the slope stability. As recorded by Clarke *et al.* (2006), the region with prolong dry season, shallow slope failure results due to a considerable large surface crack which were as a result of extreme shrinking in the summer and healing rapidly in the wet period.

With all of the above implications, one of the objective of this project is to propose some measures which when followed along with other geotechnical specifications will mitigate the problem of infrastructural failures associated with soil cracking. Below there are some measures which are considerably high enough to prevent, or limit the detrimental effects of soil cracking due to the unavoidable cyclic weather pattern.

1. Material properties

The primary factor affect the initiation of cracks is the soil properties which are the expansive clay minerals which enhance the activity of the soil. According to the geotechnical specification for construction, the more the percentage of expansive clay the more problematic the clay will be and this include the shrinkage and cracking potential. Table 4.8 and Figure 4.22 indicate the activity of some clay mineral as stated by Skempton (1953).

Table 4.8: Activity values of some clay minerals (Skempton, 1953)

Clay mineral	Activity
Kaolinite	A=0.5 (low activity)
Illite	A=1.0 (medium activity)
Montmorillonite	A=7.2 (very high activity)

Note Activity $A = \frac{\text{PI}}{\%\text{clay finer than } 2\mu\text{m}}$

Where: A < 0.75 =Inactive clay, 0.75 < A < 1:25 =Normal clay, A > 1.25= Active clay

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

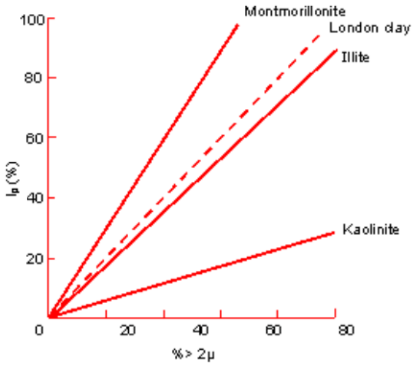


Figure 4.22: Relationship between plasticity index and percentage of clay (Skempton, 1953)

Plasticity is a direct reflection of the expansive clay minerals present within the soil mass, the plasticity index of the Nafferton clay is 19.3% while that of the bentonite mix is 21.0%. The outcome of the variation in the plasticity index of the samples used for the laboratory experiment is obvious as the bentonite mix sample have a higher shrinkage and cracking surface area compared to the Nafferton clays. According to Dyer *et al*. (2009), the soils with plasticity index higher than 25% are more prone to cracking. Also different soil types will have different tensile strength which as indicated by Yesiller *et al.* (2000) that region of considerably low strength is more prone to cracking maintaining that the properties of the weak zone within the soil imitate the strength at which cracking will occur. Therefore to avoid soil cracking, all these variables need adequate and accurate specifications to enhance a long term stability of engineered infrastructures.

2. *Compaction effect*

Several studied showed that compaction of soil invariably improves the strength parameters which in turn limits the potential for cracking. Compaction increases the soil density, reduces porosity and dissipates the excess pore pressure (Batey, 1990). As established earlier that cracking occurs when the tensile stress generated from negative pore pressure (suction) exceeds the soil tensile strength, compaction will enhance the soils tensile strength thereby reducing its susceptibility to cracking. Figure 4.23 indicates the demonstration of a compacted soil.

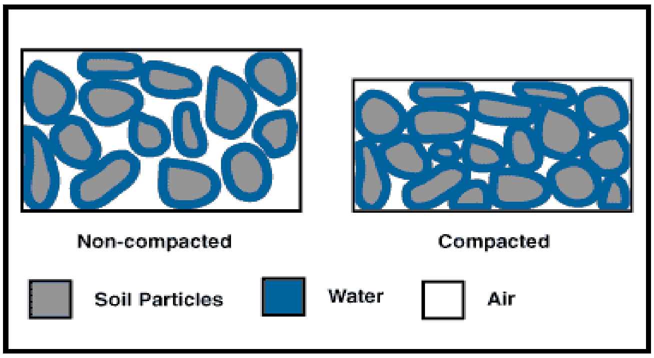


Figure 4.23: Compacted soil showing demonstration of an engineered embankment, taken from (University of Minnesota, 2001)

3. *Vegetation effects*

The rate at which moisture is lost within the soil give rise to soil suction resulting in cracks initiation. From literature, it is has been established that moisture can be lost either through evaporation or evapotranspiration. The existence of vegetation on an embankment gives rise to less cracks and also control the development of pre-existing cracks by reducing the rate of moisture loss within the soil mass. In this case, the nature of the vegetation roots also comes into plays as indicated by Smethurst *et al.* (2006). The aforementioned study observed the pore pressure and moisture content of grass protected slope in London clay over a period of 12 months and discovered that the vegetation has a significant impact on the effective stress on the topmost layer of the soil profile. In this study the influence of root types was not considered which should be the subject of further investigation on the impacts of vegetation roots on formation of cracks.

5. CONCLUSIONS

The wetting and drying effects on shrinkage and cracking were investigated on Durham boulders clays otherwise refer to as Nafferton clays. The investigation was mainly laboratory based, but aim to simulate field scenario. The desiccation rate, linear shrinkage, cracking moisture content, structural changes, cracks quantification, repeatability, closure of cracks and the implication of this cyclic event on engineered work were scrutinized. Digital imaging tools were used to analyse the images of the cracks at the end of each cycle. The overall deductions of the behaviour of the tested samples are summarized as follows:

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

- Desiccation rates decreased with cycles as observed in the desiccation curve, meanwhile this largely depends on the wetting approach and drying time.
- From the desiccation curve, it was observed that moisture content decreases with time irrespective of the desiccation approach. Two phases of water evaporation were identified, constant evaporation stage where moisture is lost at a rapid rate and the falling evaporation stage where there seems to be a decrease in moisture loss with time at it approaches a residual state.
- Oven drying at 60^0C has a higher desiccation rate compare to air drying at 1.3m/s wind speed.
- The residual moisture content is the estimated moisture content within the sample at the end of the drying phase which in the case of this project is 48 hours.
- Estimated plasticity index of the 5% bentonite mix sample was still classified as intermediate plasticity but have a higher PI compared to the Nafferton clays.
- Linear shrinkage is the estimation of the horizontal shrinkage of a sample at its liquid limit. Samples with higher plasticity have a higher shrinkage potential as observed in the bentonite mix samples.
- The cracking moisture content is the moisture content within the sample at the first crack observation.
- The structure of soil changes during cycles which initiate from the micro scale and manifested with the obvious rearrangement of the particle during wetting.
- Depending on the number of cycles and the properties of the soil, during the cyclic events the soil tend to approach an equilibrium state where consequent cycles have no or little effects on the samples.
- Crack intensity factor is the ratio of the surface area of cracks to the total surface area of the samples.
- Image analysis of the cracks surface area indicated that the crack intensity factor increases with cycles, meanwhile the variation between the third and fourth cycle was not significant in relation to the first and second cycles.
- The bentonite mix sample has a higher crack intensity factor compare to the Nafferton clay.
- The repeatability of the major cracks is evident as cracks are seen occurring again in subsequent cycles, meanwhile the dimension such as widths and depths were altered and also led to the formation of minor cracks.
- The cohesions in previously crack area are weaker than the bonds within the soil mass, thus more minor cracks were seen occurring in the earlier crack regions.
- It is clearly observed that all major cracks with significant width and depth of greater than 1.5 mm and 20 mm respectively were repeated in subsequent cycles.
- The mechanism of closure was initiated during the wetting phase but evident at the end of the subsequent drying phase. The weak materials lost their cohesion and filled the cracks space. Also the re-arrangement of the soil particle was observed during wetting especially the surface particles contribute to closure of some cracks.
- As much as this project tries to simulate field conditions, the development of cracks in the laboratory experiment is different to the field due to conditions like soil heterogeneity, desiccation approach, wetting approach, effect of boundary and time all of which are difficult to simulate appropriately in the laboratory.
- The cracking adverse effects on the prediction of extreme cyclic weather condition will be minimised with the understanding of the shrinkage and cracking mechanism.
- Understanding of the mechanism of cracking will be useful to prevent slope failure which will save the governments millions of pounds for reconstruction and compensation to the affected public.

5.1 *Achievement of the project objectives*

Within the content of this research based on the shrinkage and cracking investigation under cyclic wetting and drying, all the laid down objectives were examined and achieved. Objective one was to progress in the knowledge of the mechanism involved in the initiation of cracks, and this was achieved by comprehensive literature review. The determination of the properties responsible for altering the behavior of soil after numerous cyclic events was the focus of objective two and that was achieved by introducing series of variables such as the moisture content, plasticity, rate of drying, method of drying, and compaction (engineered soil). All these variables one way or the other have an influence on the behavior of the soil.

The geometry and dimension of the crack formed were examined and adequately investigated to understand their variations with each variables introduced with cycles. Objective three and four were accomplished by looking at these dimensions in terms of widths, thicknesses and crack intensity factor using imaging analysis. The essential focus of objective five was to actually observe the repeatability of the cracks with subsequent cyclic events and this was accomplished in discussion section. The core aim of this research is to generate an idea which can be applied in the real world to save life, properties and improve the standard of current and future infrastructures. This was achieved by evaluation the implication of cracks on engineering works like embankment, slopes, foundations etc. In addition, adequate preventive measure was provided for further studies which can be included in future specifications.

5.2 *Recommendations for further research*

The laboratory investigation of shrinkage and cracking of Nafferton clays soil has provided an understanding about the behaviour of a representative intermediate plasticity clay under cyclic wetting and drying. Moreover, more works still need to be done to fully comprehend the mechanism of cracking. Below are some area of focus for further studies:

- Cracks occur when the tensile stress developed during desiccation exceed tensile strength of the soil. Moisture content is not the main factor that led to cracking but the second derivative known as suction. Many authors seem to use water content directly to explain desiccation cracks, probably because suction is

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

difficult to measure in the soil. Meanwhile its quantification can shed more light on the mechanism of cracking, therefore it need to be investigated further.

- This project uses Nafferton and Bentonite mix clays for the cyclic experiment. Future experiments should be carried out on variety of different clays of varying material properties to understand their behaviour for comparison purpose, wider application and to have an overall behaviour of clays under cyclic events.
- More cycles of drying and wetting should be conducted to further confirm or invalidate some already known concepts whether they are still valid or not, also other variables should be introduce such as temperature, drying rate, clay mineralogy, wetting approach, compaction effect, vegetation and other worst case conditions in preparation for the future of extreme cyclic event as predicted.
- Future investigation should look at the use of image processing techniques, which would permit accurate cracks measurements at different moisture contents with greater accuracy.
- More numerical models should be setup which will at a greater length simulate field conditions.
- Since vegetation reduces the moisture within the soil due to the process of evapotranspiration, it is necessary to study and understand the rate at which this occurs and its influence on the initiation and development of cracks using different species of plants and trees.

ACKNOWLEDGEMENTS

Firstly I will like to appreciate God for his unfailing grace over my life and my family, for providing me with the wisdom and understanding all the way to the successful completion of this degree, I say glory be to His holy name. Also to my father for his love and support, you are indeed a wonderful father, I will continue to love you.

I also express my sincere gratitude to the following people for their significant contributions toward the success of this research from its inception through the laboratory experiments, critical results analysis and proper academic writing skills.

- Dr. Colin Davie, The project supervisor and a senior lecturer in Civil Engineering and Geosciences, University of Newcastle upon Tyne
- Mr Oboho Eminue (PHD research student in Geotechnical engineering, University of Newcastle upon Tyne)
- Mr Chris Davies (PHD research student in Geotechnical engineering, University of Newcastle upon Tyne)
- Mr Stuart Patterson (Laboratory Technician, School of Civil Engineering and Geoscience, University of Newcastle upon Tyne)
- Mr Fred Beadle (Laboratory Technician, School of Civil Engineering and Geoscience, University of Newcastle upon Tyne)

Also to my colleagues in the school like Serafin, Zhanna, Nihaad, Dunstan, Fei, Sarah, Ning and others. I am so grateful to you all and cannot simply thank you enough. I sincerely cherished your suggestions and encouragements, God bless you all.

REFERENCES

[1] Al Al Wahab, R.M. and El-Kedrah, M.A. (1995) 'Using fibers to reduce tension cracks and shrink/swell in a compacted clay', *Geoenvironment 2000@ sCharacterization, Containment, Remediation, and Performance in Environmental Geotechnics*, ASCE, pp. 791-805.

[2] Albrecht, B.A. and Benson, C.H. (2001) 'Effect of desiccation on compacted natural clays', *Journal of Geotechnical and Geoenvironmental Engineering*, 127(1), pp. 67-75.

[3] Anderson, M.G., Hubbard, M.G. and Kneale, P.E. (1982) 'The influence of shrinkage cracks on pore-water pressures within a clay embankment', *Quarterly Journal of Engineering Geology and Hydrogeology* 15(1), pp. 9-14.

[4] Batey, T. (1990) 'Control of compaction on the farm a personal view', *Soil technology* 3(3), pp. 225-229.

[5] Bradley, C., Mosugu, M. and Gerrard, J. (2007) 'Seasonal dynamics of soil–water pressure in a cracking clay soil', *Catena*, 69(3), pp. 253-263.

[6] Briggs, K. (2010) 'Charing embankment: climate change impacts on embankment hydrology', *Ground Engng*, 43(6), pp. 28-31.

[7] British geological survey (2012) *Shrink swell ¦ GeoSure ¦ British Geological Survey (BGS)*. [Online] Available at: http://www.bgs.ac.uk/products/geosure/shrink_swell.html [Accessed 19 June 2015].

[8] Chertkov, V.Y. (2000) 'Using surface crack spacing to predict Crack network geometry in swelling soils', *Soil Science Society of America Journal*, 64(6), pp.1918-1921.

[9] Chertkov, V.Y. (2002) 'Modelling cracking stages of saturated soils as they dry and shrink', *European Journal of Soil Science* 53(1), pp. 105-118.

[10] Clarke, G.R.T., Hughes, D.A.B., Barbour, S.L. and Sivakumar, V. (2006) 'The Implications of Predicted Climate Changes on the Stability of Highway Geotechnical Infrastructure: A Case Study of Field Monitoring of Pore Water Response', *EIC Climate Change Technology, 2006 IEEE.* IEEE, pp. 1-10.

[11] Collins, K.t. and McGown, A. (1974) 'The form and function of microfabric features in a variety of natural soils', *Geotechnique* 24, pp. 223-254.

[12] Costa, S., Kodikara, J. and Shannon, B. (2013) 'Salient factors controlling desiccation cracking of clay in laboratory experiments', *Geotechnique*, 63(1),pp. 18-29.

[13] Day, R.W. (1994) 'Swell-shrink behavior of compacted clay', *Journal of geotechnical engineering*, 120(3), pp. 618-623.

[14] Dyer, M., Utili, S. and Zielinski, M. (2009) 'Field survey of desiccation fissuring of flood embankments', *Proceeding of the ICE-Water Management*, 162(3), pp. 221-232.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

[15] Elias, E. A., Salih, A. A. and Alaily, F. (2001) 'Cracking pattern in the vertisols of the Sudan Gezira at the end of dry season', *International Agrophysics*, 15(3), pp. 151-156.

[16] Ellah, R.G.A. (2009) 'Evaporation rate at Wadi El-Rayan Lake, Egypt', *World Applied Sciences Journal* 6(4), pp. 524-528.

[17] Falkowski, P., Scholes, R.J., Boyle, E.e.a., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Högberg, P. and Linder, S. (2000) 'The global carbon cycle: a test of our knowledge of earth as a system', *science* 290(5490), pp. 291-296.

[18] Fang, H.-Y. and Daniels, J.L. (2006) *Introductory geotechnical engineering: an environmental perspective*. CRC Press.

[19] Ferber, V., Auriol, J.-C., Cui, Y.-J. and Magnan, J.-P. (2009) 'On the swelling potential of compacted high plasticity clays', *Engineering Geology* 104(3), pp. 200-210.

[20] Holtz, R. D. & Kovacs, W. D. (1981) *An introduction to geotechnical engineering*. Prentice-Hall, Incorporated, Route 9W Englewood Cliffs, NJ 07632 USA.

[21] Hughes, P.N., Glendinning, S., Mendes, J., Parkin, G., Toll, D.G., Gallipoli, D. and Miller, P.E. (2009) 'Full-scale testing to assess climate effects on embankments', *Proceedings of the ICE-Engineering Sustainability*, 162(2), pp. 67-79.

[22] Jacobson, M.Z. (1999) 'Effects of soil moisture on temperatures, winds, and pollutant concentrations in Los Angeles', *Journal of Applied Meteorology* 38(5), pp. 607-616.

[23] Kodikara, J., Barbour, S. and Fredlund, D.G. (2002) 'Structure development in surficial heavy clay soils: a synthesis of mechanisms', *Australian Geomechanics: Journal and News of the Australian Geomechanics Society* 37, 25.

[24] Kodikara, J. and Costa, S. (2013) 'Desiccation Cracking in Clayey Soils: Mechanisms and Modelling', in *Multiphysical Testing of Soils and Shales*. Springer, pp. 21-32.

[25] Kodikara, J.K., Barbour, S.L. and Fredlund, D.G. (2000). 'Desiccation cracking of soil layers', *Unsaturated Soils for Asia*, 90(5809), p. 139.

[26] Lau, J.T.K. (1987) *Desiccation cracking of clay soils*. MSc Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Canada.

[27] Li, J.H. and Zhang, L.M. (2011) 'Study of desiccation crack initiation and development at ground surface', *Engineering Geology*, 123(4), pp. 347-358.

[28] Miller, C.J., Mi, H. and Yesiller, N. (1998) 'EXPERIMENTAL ANALYSIS OF DESICCATION CRACK PROPAGATION IN CLAY LINERS1', *JAWRA Journal of the American Water Resources Association*, 34, pp. 677-686.

[29] Mishra, A.K., Dhawan, S. and Rao, S.M. (2008) 'Analysis of swelling and shrinkage behavior of compacted clays', *Geotechnical and Geological Engineering*, 26(3),pp. 289-298.

[30] Mitchell, J.K. '1993, Fundamentals of Soil Behavior, John Wiley and Sons, Inc., New York'.

[31] Morris, P.H., Graham, J. and Williams, D.J. (1992) 'Cracking in drying soils', *Canadian Geotechnical Journal*, 29(2), pp. 263-277.

[32] Nahlawi, H. and Kodikara, J.K. (2006) 'Laboratory experiments on desiccation cracking of thin soil layers', *Geotechnical & Geological Engineering*, 24(6), pp. 1641-1664.

[33] Novák, V. (1999) 'Soil-crack characteristics-estimation methods applied to heavy soils in the NOPEX area', *Agricultural and Forest Meteorology*, 98, pp. 501-507.

[34] Omidi, G.H., Thomas, J.C. and Brown, K.W. (1996) 'Effect of desiccation cracking on the hydraulic conductivity of a compacted clay liner', *Water, air, and soil pollution*, 89(1-2), pp. 91-103.

[35] Peron, H., Laloui, L., Hueckel, T. and Hu, L.B. (2009) 'Desiccation cracking of soils', *European journal of environmental and civil engineering*, 13(7-8), pp. 869-888.

[36] Perrier, E., Mullon, C., Rieu, M. and Marsily, G. (1995) 'Computer construction of fractal soil structures: simulation of their hydraulic and shrinkage properties', *Water Resources Research*, 31(12), pp. 2927-2943.

[37] Perry, J., Pedley, M., Brady, K. and Reid, M. (2003) 'Briefing: Embankment cuttings: condition appraisal and remedial treatment', *Proceedings of the ICE-Geotechnical Engineering*, 156(4), pp. 171-175.

[38] Rao, A.S., Phanikumar, B.R. and Sharma, R.S. (2004) 'Prediction of swelling characteristics of remoulded and compacted expansive soils using free swell index', *Quarterly journal of engineering geology and hydrogeology*, 37(3), pp. 217-226.

[39] Rayhani, M. H., Yanful, E.K. and Fakher, A. (2007) 'Desiccation-induced cracking and its effect on the hydraulic conductivity of clayey soil from iran', *Canadian geotechnical journal*, 44(3), pp. 276-283.

[40] Skempton, A.W. (1953) 'Soil mechanics in relation to geology', *Proceedings of the Yorkshire Geological Society* , 29(1), pp. 33-62.

[41] Smethurst, J.A., Clarke, D. and Powrie, W. (2006) 'Seasonal changes in pore water pressure in a grass-covered cut slope in London Clay', *Geotechnique* 56(8), pp. 523-538.

[42] Standard, B. '1377 (1990) Methods of Test for soils for civil Engineering Purposes', *British Standards Institution, London.*

[43] Stirling, R.A., Davie, C.T. and Glendinning, S. (2015) 'Multiphase modelling of desiccation cracking in the near surface of compacted soil', Newcastle University, Newcastle-upon-Tyne, UK.

[44] Tang, C.-S., Cui, Y.-J., Shi, B., Tang, A.-M. and Liu, C. (2011) 'Desiccation and cracking behaviour of clay layer from slurry state under wetting–drying cycles', *Geoderma* 166(1), pp.111-118.

[45] Tang, C.-S., Cui, Y.-J., Tang, A.-M. and Shi, B. (2010) 'Experiment evidence on the temperature dependence of desiccation cracking behavior of clayey soils', *Engineering Geology*, 114(3), pp. 261-266.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

[46] Tang, C., Shi, B., Liu, C., Zhao, L. and Wang, B., (2008) 'Influencing factors of geometrical structure of surface shrinkage cracks in clayey soils', *Engineering Geology*, 101(3), pp. 204-217.

[47] UKCIP02, 2002. *Climate Change Scenarios for the United Kingdom*: The UKCIP02 Scientific Report. Tyndall Centre, School of Environmental Sciences, University of East Anglia.

[48] University of Minnesota, S. C. C. a. C. (2001) *Soil Compaction Causes and Consequences.* Available at: http://www.extension.umn.edu/agriculture/tillage/soil-compaction/ [Accessed 20 June 2015].

[49] Wilks, J.H. (2010) 'Forecasting transportation infrastructure slope failures in a changing climate', *11th Young Geotechnical Engineers Symp*, University of Bristol, Bristol, Australia.

[50] Yam, K. L. and Papadakis, S. E. (2004) 'A simple digital imaging method for measuring and analyzing color of food surfaces', *Journal of Food Engineering*, 61(1), pp. 137-142.

[51] Yesiller, N., Miller, C.J., Inci, G. and Yaldo, K. (2000) 'Desiccation and cracking behavior of three compacted landfill liner soils', *Engineering Geology*, 57(1), pp. 105-121.

[52] Yong, R.N. and Warkentin, B.P. (1975) 'Soil Properties and Soil Behavior'. Elsevier, Amsterdam.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

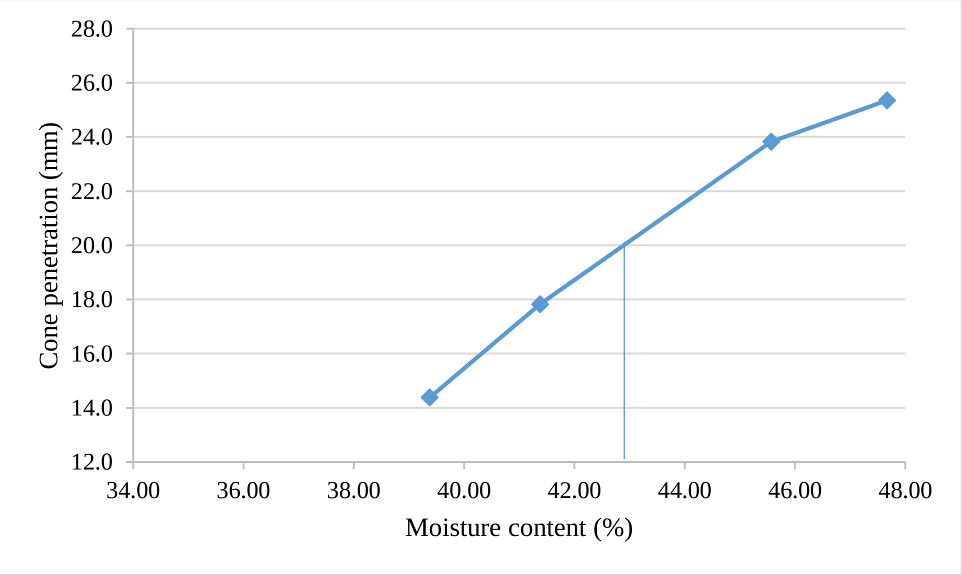
APPENDICES

Appendix A: Liquid and plastic limit test

NAFFERTON CLAY

PLASTIC LIMIT Test no.	1	2	3	Average
Container no.	C26	R2	B5	
Mass of wet soil + container g	12.09	11.75	11.73	
Mass of dry soil + container g	11.07	10.77	10.78	
Mass of container g	6.64	6.60	6.64	
Mass of moisture g	1.02	0.98	0.95	
Mass of dry soil g	4.43	4.17	4.14	
Moisture content %	23.02	23.50	22.95	23.16

LIQUID LIMIT Test No.	1	2	3	4
Initial dial gauge reading (mm)	14.4	17.7	23.8	25.6
Final dial gauge reading (mm)	14.4	18.0	23.9	25.2
Average penetration (mm)	14.4	17.8	23.8	25.4
Container no.	**E30**	**C23**	**B4**	**N3**
Mass of wet soil + container (g)	20.78	17.35	28.59	28.88
Mass of dry soil + container (g)	16.00	13.39	20.78	20.91
Mass of Container (g)	3.86	3.82	3.64	4.19
Mass of Moisture (g)	4.78	3.96	7.81	7.97
Mass of dry soil (g)	12.14	9.57	17.14	16.72
Moisture content (%)	39.37	41.38	45.57	47.67

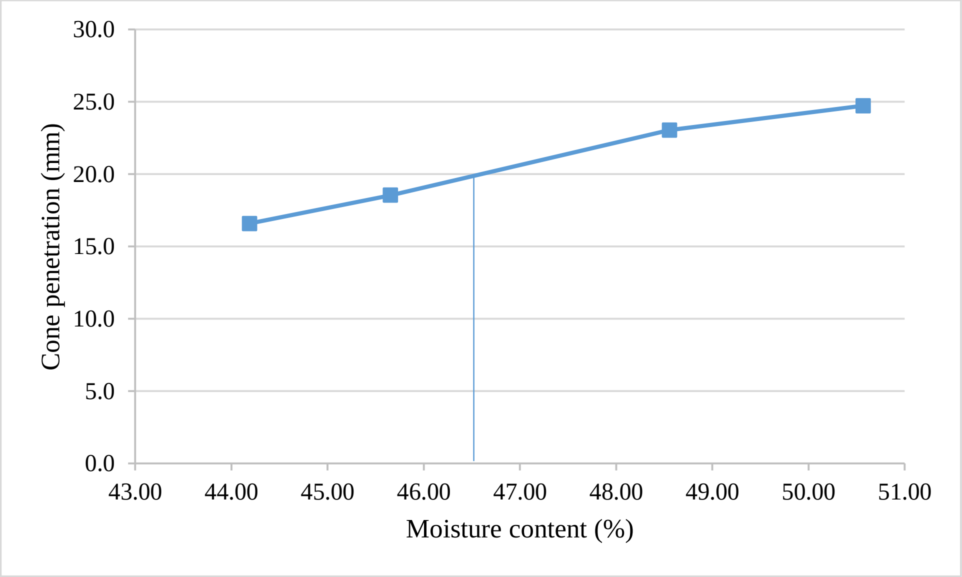


(This work is licensed under a Creative Commons Attribution 4.0 International License.)

BENTONITE MIX

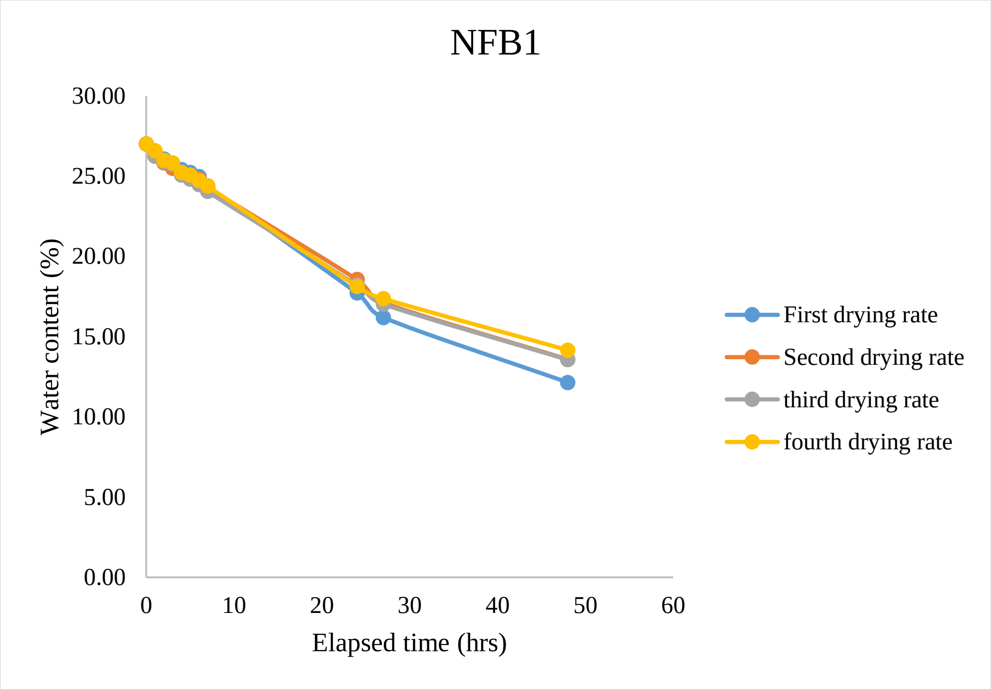
PLASTIC LIMIT Test no.	1	2	3	Average
Container no.	M6	C20	B9	
Mass of wet soil + container g	11.52	12.82	11.50	
Mass of dry soil + container g	10.49	11.51	10.51	
Mass of container g	6.47	6.51	6.49	
Mass of moisture g	1.03	1.31	0.99	
Mass of dry soil g	4.02	5.00	4.02	
Moisture content %	25.62	26.20	24.63	25.48

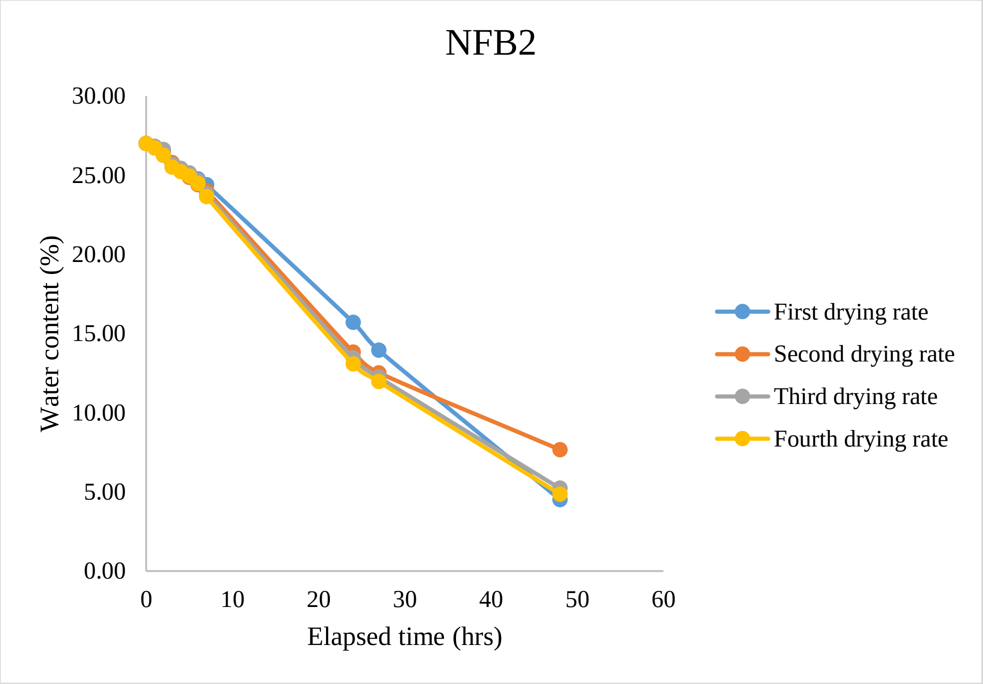
LIQUID LIMIT Test No.	1	2	3	4
Initial dial gauge reading (mm)	16.4	18.6	23.2	24.6
Final dial gauge reading (mm)	16.8	18.5	22.9	24.9
Average penetration (mm)	16.6	18.5	23.0	24.7
Container no.	**R1**	**P3**	**F2**	**E10**
Mass of wet soil + container (g)	21.79	27.20	31.79	30.10
Mass of dry soil + container (g)	16.28	19.80	22.73	21.16
Mass of Container (g)	3.81	3.59	4.07	3.48
Mass of Moisture (g)	5.51	7.40	9.06	8.94
Mass of dry soil (g)	12.47	16.21	18.66	17.68
Moisture content (%)	44.19	45.65	48.55	50.57



Appendix B: Desiccation curves for the bentonite mix samples

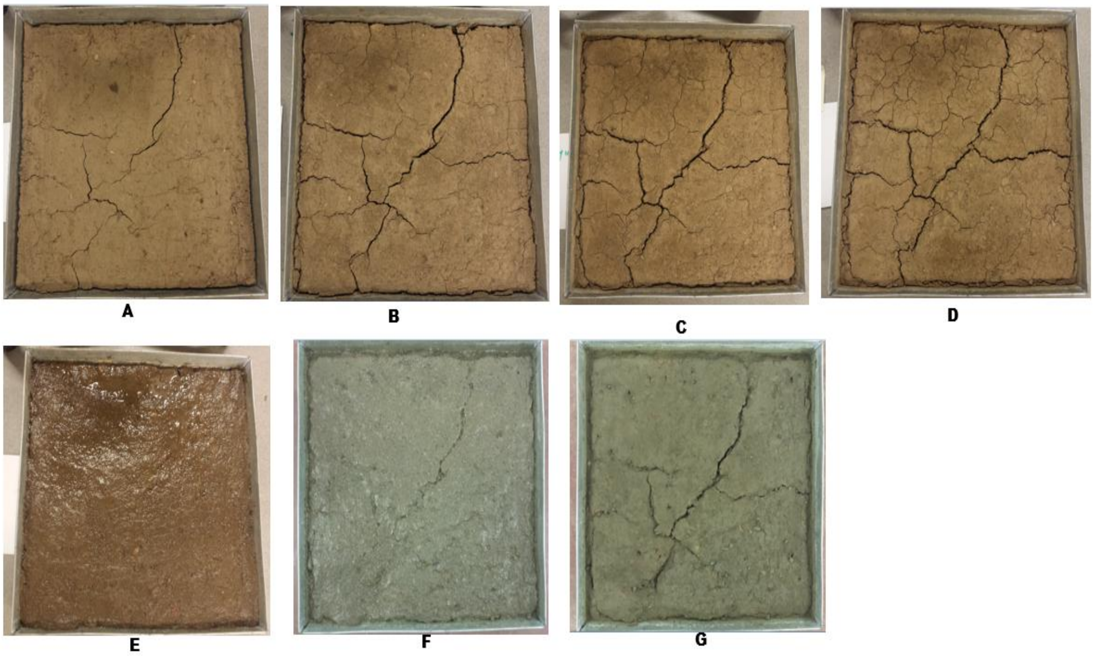
(This work is licensed under a Creative Commons Attribution 4.0 International License.)



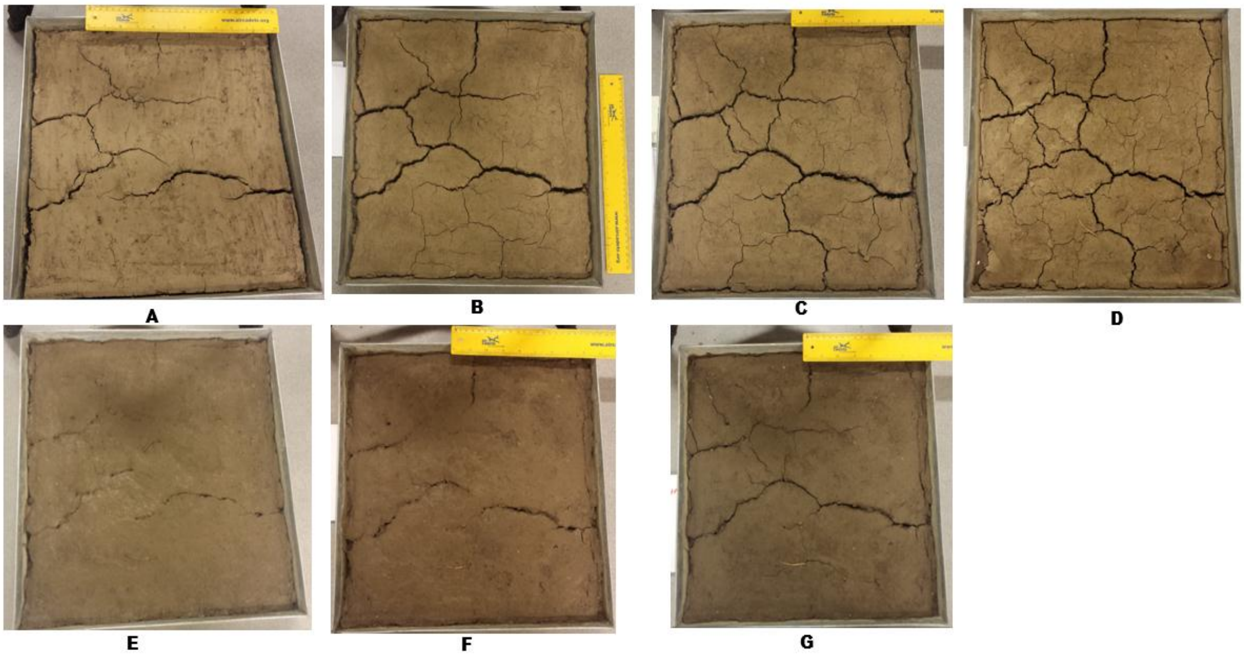


(This work is licensed under a Creative Commons Attribution 4.0 International License.)

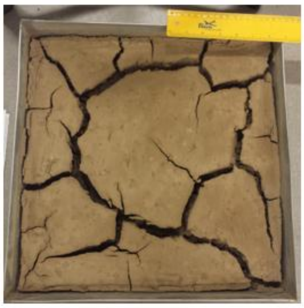
Appendix C: Images of the Nafferton and bentonite mix samples during the cyclic wetting and drying.



NF 2



NF 1


A


B


C


D


E


F


G

NFB 2


A


B


C


D


E


F


G

NFB 1

(This work is licensed under a Creative Commons Attribution 4.0 International License.)