DISAGGREGATION OF SOIL DURING SLURRY PIPE JACKING

By

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“When the spirits are low, when the day appears dark, when work becomes monotonous, when hope hardly seems worth having, just mount a bicycle and go out for a spin down the road, without thought on anything but the ride you are taking” – *Arthur Conan Doyle*

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ABSTRACT

Pipe jacking is an environmentally friendly technique for the installation of services and utilities, which leads to minimum disturbance during installation. It is an important construction method for urban environments where disruption to transport is expensive. The need to tunnel through varying geologies requiring support during tunnelling has led to the increased use of slurry tunnel boring machines. The slurry is used to stabilise the tunnel face and transport the excavated spoil to the surface.

The research detailed in this dissertation assesses the magnitude of soil disaggregation during the excavation and pumping of the arisings within the slurry to the separation plant. The two main objectives were to create a mixing test that would allow the disaggregation of the soil to be predicted prior to specification of the separation plant and to link the results of this test to typical soil properties. In addressing the second objective efforts have also been made to characterise the different mechanisms of disaggregation observed in the mixing tests. The typical soil testing methods used to classify the soil samples were; Atterberg limits, particle size distributions, unconfined compressive strength, mineralogy (XRD) and chemical analysis (XRF).

A mixing test has been designed using a Hobart planetary mixer to classify the amount of soil cuttings that disaggregate during mixing with a slurry fluid. This test was found to produce repeatable results using Speswhite Kaolin samples and then used to assess the differences in disaggregation rates of London Clay, Upper Mottled Beds and Fleetwood Silts. In total 71 mixing tests were completed during the development of the test and the classifying of the soils. The test involved mixing distilled water with 10 clay cuttings for varying times. The resulting solid particles were then sized through a series of sieves and sedimentation tests carried out to produce a particle size distribution of the resulting soil.

The mixing tests showed the Upper Mottled Beds to have the highest rate of disaggregation, with the Fleetwood Silts displaying the least. This has been attributed to the level of cementing within the soil and the microstructure of the clay and silt sized particles.

The liquidity index and initial soil strength were not found to be important factors in the predicting the rate of disaggregation of a particular soil type, but were significant for some soils. The Fleetwood Silts had the lowest unconfined compressive strengths but also produced the least amount of disaggregated soil. The soil macrofabric, although not quantified, also appeared to have an effect on the rate of disaggregation of a particular soil. An increase in discontinuities within the sample produced more cuttings larger than 4.75 mm but a lower amount of 63 μm sized fraction disaggregated.

In addition to the mixing tests carried out using water, a series of tests were completed using a polymer based slurry, HydroCut CF. This showed mixed results; The polymer prevented any clay or silt sized particles from passing through the 63 μm sieve. However, there was no overall reduction in disaggregation and a significant increase in the time it took to sieve the slurry.

DECLARATION

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DEFINITIONS OF TERMS

For the purpose of this thesis the terms pipe jacking and tunnelling are interchangeable as the topics being dealt with are predominantly the surface plant that can be scaled up for tunnel contracts.

Arisings
Spoil produced from the excavation of the tunnel.

Coagulate
The coming together of particles due to the reduction in surface particle charge.

Cake
Separated solids being re-combined within a separation process to form a solid layer. This is often referred to when describing fine aperture shakers, decanting centrifuges, filter press or belt press.

Disaggregate
Individual and aggregates of particles breaking away from the larger soil cutting (*see soil cutting)* and ending up in suspension in the slurry (*see slurry).*

Flocculate
The binding of particles with a flocculant by both charge attraction and chemical bonding.

Liquid arisings
Arisings that do not meet the following statement; "*Any waste that near instantaneously flows into a hollow in the surface of the waste*" or " *If the arisings containing more free liquid than 250litres or 10% of the arisings (which ever is less)"* (Potter & Jeffries, 2005)

Lump
See soil cutting

Mud Man
Separation plant operator in charge of monitoring and operating the separation system.

Particle
A single soil grain or an aggregate/lump of grains.

Ped
An aggregate of clay sized particles.

Sludge
A material that has a water content beyond the liquid limit but does not meet the criterion "*near instantaneously flows into a hollow in the surface of the waste*" (Potter & Jeffries, 2005).

Soil Cutting
A large gravel or cobble sized lump of excavated soil.

Slurry
A suspension of solids within a liquid. Within this document it refers to the water based transport medium used in slurry tunnelling and is historically a water and bentonite mixture but in more recent years is often just water (plus cut solids) or water and a polymer additive.

TBM
Tunnel Boring Machine.

XRD
X-ray diffraction, method of analysing and identifying soil and rock mineralogy.

XRF
X-ray fluorescence, method of analysing and identifying soil and rock chemical make up.

Symbols

A	Soil activity
D	Diameter
g	Acceleration due to gravity (9.81m/s2)
Id	Slake durability Index
IL	Liquidity Index
Ip	Plasticity Index
R	Radius
s_u	Undrained shear strength
w	Water content
W	Weight
V	Velocity
γ	Shear rate
τ	Shear stress
Ω	Rotational speed
δ	Gap between mixing attachment and bowl wall on a planetary mixer
ωL	Liquid Limit
***ω*P**	Plastic Limit

1.0 Introduction

1.1 Introduction

Soil slurry has been used as a support and transportation mechanism within tunnelling and pipe jacking since the 1970's. The development of tunnel boring machine technology and the need to install tunnels and pipe lines through an increased range of geological strata have seen an increase in slurry tunnelling. At the same time tightening of waste disposal legislation has seen the implementation of slurry separation plant become more complex and costly.

Both contractors and clients require the specification of the separation plant to be economical and in order to do that, a prediction of the percentages of soil particle sizes reaching the separation plant is required. Currently the specification of the separation plant is carried out using experience from previous tunnel drives, with no means of validating its suitability.

1.2 Background

The introduction of slurry has been influenced significantly by the oil and gas drilling industries, using both slurry additives and separation equipment developed for these fields. The slurry used in pipe jacking is water based and depending on the ground conditions bentonite and/or synthetic polymers may also be added. For efficiency and environmental reasons this slurry is reused in a closed loop system, resulting in the need to remove all excavated solids from the slurry. This is most challenging with the suspended solids having a particle size less than 63 μm.

The majority of particles larger than 63μm are removed from the slurry using a series of shaker screens and hydro-cyclones. The remaining particles require separation using primarily decanting centrifuges and flocculant treatment. In some instances filter plate presses or a belt press maybe used as an alternative. In order to specify the processing capacity of the centrifuge(s) the quantity of sub 63 μm particles should be known.

Significant advances have been made in tunnelling machine technology and the surface separation plant. However, the breakdown of the excavated solids, due to the machine action and slurry/solids interaction during transportation is not widely understood.

The industry has expressed a need to understand how varying soil types react to the processes being applied to them during slurry tunnelling, with the aim of economically specifying plant required for surface separation. Inaccurate prediction can lead to high off-site processing costs or the loss of a contract at tender stage; this has led the Pipe Jacking Association to commission this research.

1.3 Aims

The aims for this research project are to look soil cuttings and slurry interaction with reference to slurry tunnelling.

- Understand the factors determining soil disaggregation.
- Design and carry out a repeatable soil/slurry mixing test to simulate the process of transporting slurry to the surface separation plant.
- Assess the effect of using a polymer additive to the slurry.

1.4 Objectives

In order to achieve the above aims the following objectives were carried out.

- A review of current practice for predicting soil disaggregation within civil engineering and the oil and gas drilling industry.
- Carry out soil classification tests, looking at fully dispersed particle size distributions, Atterberg limits, mineralogy, chemistry and unconfined compressive strengths.
- Design a mixing test method that enables the analysis of soil cutting breakdown and can be shown to be repeatable.

- Combine the results of the mixing tests with results from soil classification and additional observations to gain an understanding of which mechanisms might affect the rate of disaggregation.
- Develop a proposal for further work in order to assess a wider variation of soil types and to correlate results to pipe jacked tunnel drives.

1.5 Summary of this dissertation

This dissertation looks at the development of a soil and slurry mixing test that aids in the prediction of soil disaggregation. To accompany the mixing test a series of standard soil classification tests have been undertaken to help gain an understanding how and why fine grained soils disaggregate at varying rates. In order to complete this, an understanding of the mechanical processes inflicted on to the soil are required and are described within Chapter 2. Along with this a review of current soil breakdown tests and possible influencing factors was assessed and described within Chapter 3. Although the tunnelling and pipe jacking industry have not implemented a testing method for disaggregation, other industries such as oil/gas drilling and mining have started to postulate ideas for rates of breakdown.

In Chapter 4 the development of the mixing test procedure is described through its multiple iterations. Along with this, the methods of testing and classifying each soil used are also described and the tests carried out to confirm the applicability of the mixing test using data collected from a pipe jacking site.

A significant volume of test data was collected during this research project, with 71 mixing tests completed, along with soil classification tests and particle size tests carried out on slurry samples from a pipe jacking site. All of the raw results are displayed within Chapter 5 and the analysis of these results is detailed in Chapter 6.

Key findings and recommendations that will aid in predicting the amount a soil will disaggregate are detailed in Chapter 7. This looks at the use of the mixing test as a prediction method for soil disaggregation, along with specific soil classification tests that help to identify potential indicators for the potential to disaggregate. Although this body of work was comprehensive, it is also the first time this problem as been addressed in detail. Therefore, there are still areas that potentially require further work, which are also described in Chapter 7.

2.0 BACKGROUND

2.1 Introduction

Within this chapter the fundamentals of the mechanical processes that occur during slurry tunnelling are introduced and how the excavated arisings are transported from the tunnel face to the surface for disposal. This includes excavation of the soil, its transportation and the separation of the soil from the slurry. Although the term slurry tunnelling will be used throughout this dissertation, the scope of the work is primarily intended for use within pipe jacking. The research project is not limited to a specific size of tunnel boring machine, with the various processes explained within this chapter.

With the growth of the urban population the installation of service and utility pipes and tunnels is often not feasible using traditional methods of 'cut and cover'. Consequently, for over half a century pipe jacking has been a desirable technique for the construction of service tunnels in urban environments. Pipe jacked tunnels are generally less than 2.5 metres outside diameter and a maximum single drive length is approximately 2.5 kilometres but often far shorter.

Current pipe jacked tunnels use very similar tunnel boring machine technology (Figure 2.1) to that used in transit and large diameter tunnelling with the main difference being how the tunnel is progressed forward. With a pipe jack the tunnel sections are full pipe sections that are pushed from a drive shaft or trench using high load capacity hydraulic jacks. The boring machine is often remotely controlled being pushed forward as it excavates from the tunnel start position. This results in the pipeline sliding through the ground. With segmentally lined larger tunnels, the tunnel boring machine manoeuvres itself forward reacting against the previously built tunnel lining immediately behind the tunnel boring machine.

In the United Kingdom mechanical excavation of pipe-jacked tunnels is now the most common method of installation. This has developed due to advances in tunnel boring machine (TBM) technologies and also the tightening of health and safety laws; limiting operatives from entering the pipe jack, due to the confined working environment. It also allows for more control of ground movements.

Tunnel boring machines have developed over the past few decades to cope with a wider range of geological conditions, including those that previously would have not been cost efficient to tunnel through. Some of the greatest advances have been with closed faced tunnel boring machines that provide more balanced face pressures reducing surface settlements and allowing tunnels to be driven under sensitive buildings.

2.2 Slurry Pipe Jacking

Slurry tunnel boring machines (STBM) (Figure 2.1) utilise a water based slurry to help provide tunnel face stability, reduce the ingress of ground water and to act as a transport mechanism to carry the excavated material to the surface. This method was first trialled in the United Kingdom during an experimental drive in New Cross, London during the 1970's (Bartlett, 1999). They can be driven in a range of geologies, but are more suited to sands, gravels and fissured weak rocks. Idealised grading curves of the ground though which slurry tunnelling boring machines can be driven are shown in Figure 2.2. The limits displayed do not necessarily apply when small diameter tunnels are being driven. This is because earth pressure balance machines (EPBM) are currently limited to tunnels greater than 1.6 metres outside diameter, due to the size restrictions of installing a screw auger and arisings removal within the tunnel. There is also a shortage of availability of EPBM machines at diameters below 2.5 metres. This leads to slurry tunnel boring machines excavating in soil with grading curves which move considerably into the silt and clay fractions, especially when water bearing.

An earth pressure balance machine differs from a slurry tunnel boring machine in that it uses an air pocket behind the face and the injection of chemical treatments that are mixed into the arisings to aid in face support. A screw auger is used to remove the mixed excavated soil. The auger pitch reduces and with the use of soil conditioning agents a homogenised paste is compressed to fill the auger before discharge. This reduction in pitch and compression of arisings allows the face pressure to be reduced down to atmospheric at the discharge point.

The use of slurry allows for safe excavation with controllable ground movements without the need for operatives to work for extended periods of time under compressed air. For non-man entry sized tunnels it also allows for pipelines to be placed in soil strata that otherwise would not be possible. A wide range of pipeline diameters can be installed using slurry pipe jacking, ranging from 250 mm to approximately 4 meters internal diameter, however typically tunnels over 2.5 meters are installed using traditional segment tunnelling techniques. In the U.K a popular pipe jack diameter is 1.2 meters.

2.3 Machine Cutter Head Variation

There are two common machine cutter actions used in pipe jacked sized tunnel boring machines. The first is the more common and is used by Herrenknecht one of the most important tunnel boring machine manufacturers. It has a centrally rotating head with a conical gap (size dependent on machine size) between it and the main head body, see Figure 2.3. The cutter head excavates the soil and slurry is fed into the cone, which is predominantly around the top sector of the cone, where it mixes with the cuttings. Cuttings are ground in a similar manner to a pepper grinder once inside the conical cone. Within the base portion of the cone there are multiple small outlet slurry ports, which slurry and cuttings are passed through before being transported back to the separation plant. The multiple small ports prevent over-sized cuttings entering the outlet pipe, with the potential to block the slurry line.

The second machine cutter action results from an eccentrically mounted cutter head, which aims to trap the soil/rock cutting between the internal head face and the main body inner cone, see Figure 2.4. This breaks rock cuttings, large gravel or cobbles through compression as the cone space reduces. On some of these machines instead of the cuttings being removed from two slurry ports towards the front of the cone, they are forced through small square gaps around the centre of the cutting head shaft at the back of the cone into a slurry chamber behind. In a clay or granular soil, face support is partially provided by the cutter head and the filling of the cone with excavated material. This limits and often prevents slurry from mixing with the ground at the tunnel face when tunnelling in a clay stratum. When tunnelling through a clay stratum the clay cuttings are remoulded before being extruded from the crushing chamber into the slurry chamber, see Figure 2.4. The most important tunnel boring machine manufacturer to use this technique is the Japanese firm Iseki.

Both head actions will have an effect on the representative particle size distribution of the solids within the slurry immediately behind the face and both will be different. The eccentric action typically would be expected to produce cuttings with a greater level of remoulding than the centrally rotating head action. The eccentric head action would however have in general a lower water content. The actions described would be difficult to model and potential changes in the in situ soil properties have not been incorporated into the test procedure. It would be necessary to retrieve samples of slurry from close to the tunnel boring machine, to assess whether some quantifiable adjustments might be applied to the laboratory test results. The exact machine type will often be specified by the contractor a significant time after the site investigation is undertaken, ensuring that any pre-tender tests would not be able to allow for this variation.

A tunnel boring machine excavates through the ground using picks, scrappers and cutting disks or grinder wheels. Often there is a mixture of these when tunnelling through the softer strata with mixed soil types. The openings at the face of the cutter head also vary in size depending on the predicted stability of the face and the size of material particles that might be encountered. Because of the large number of possible configurations this variation will not be modelled.

Due to the potential for fine grained soils to adhere to the cone of the tunnel boring machines, some contractors and tunnel boring machine manufacturers use high pressure water jets to maintain a clean cone. This will undoubtedly affect the amount of sand, silt and clay sized particles or agglomerates ending up in suspension within the slurry. The extra water also increases the volume of slurry to be treated.

Every tunnel boring machine used will have a different effect on the rate of disaggregation because the two cutter actions and cutter head dressing will interact with the soil in different ways. An idea of the variation this effect has on the cutting size and the potential for disaggregation could be obtained by sampling immediately behind the tunnel boring machine. However, this would be difficult due to the need to install sampling equipment within an active tunnel bore and confined space.

2.4 Slurry Circulation

Within the tunnel boring machine the cuttings enter the slurry and are then pumped to the surface separation plant through a steel pipeline laid close to the invert of the tunnel (varying in diameter depending on the tunnel size). This is pumped using inline centrifugal pumps, again the number required depends on the tunnel length.

It can be assumed that the length of the tunnel will affect the amount of disaggregation due to the increase in time for which soil cuttings are pumped within a slurry. So in a consistent geology the amount of disaggregation should increase as the tunnel progresses. The mechanisms causing disaggregation and the shear exerted on the slurry are examined in section 3.3 and the test has been designed to simulate appropriate shear rates as discussed in section 3.6. In addition to the time spent in the slurry, the centrifugal pumps apply a shear stress to the slurry.

2.5 Slurry Separation

Due to the nature of slurry tunnelling the excavated soil has to be removed from the slurry, so that a closed loop circuit can be operated, reusing the fluid carrying the soil. In addition waste disposal laws prohibit liquid waste from entering a landfill and consequently before leaving the site the slurry needs to become solid soil and water of sufficient quality to be returned to the circulation regime.

The separation plant is a three stage process in which there is a reduction in the size of the particles removed at each stage. Some plant variation is seen depending on the anticipated geology, both in terms of quantity and type. A systematic diagram of a typical slurry separation system can be seen in Figure 2.5.

2.5.1 Primary Separation Plant

Within pipe jacking separation plant there are two common forms of primary separation plant that typically remove particles larger than 5 mm from the slurry, although on occasion the size of particle removed may drop to 2 mm. The choice of plant may be dependent on predicted geology and the contactors opinion of the particle size distribution that will result from the tunnelling process. Often however, the plant is chosen from what a contractor owns and has available for use.

2.5.1.1 Large Aperture Shaker Screens

The first type of primary separation plant that could be used is a large aperture high-g shaker. This is typically suited to larger grained granular soils, such as sands and gravels. The slurry is fed directly onto the screen with slurry and particles smaller than the openings falling through to be carried to the second stage. The particles removed are transported along the deck in a bouncing motion caused by the eccentrically mounted high-g motors. This action helps to remove any free water from these particles. In clay soils, cut clay particles can have a tendency to stick to the screen, resulting in more solids entering the next stages of separation. This is because the deck is cleaned by scraping and washing, which applies an additional force to the cuttings. The type of screen used is dependent on the contractor’s preference; popular options are polyethylene and woven steel mesh screens which vary slightly depending on the manufacturer.

2.5.1.2 Clay Belt Separator

The second type of primary separation plant is a clay belt separator, which is commonly used when tunnelling through clay soils. It works by passing the slurry over a meshed belt, usually stainless steel chain link or a polyurethane woven material. As before the slurry passes through and the larger cuttings are carried away from the slurry output. Some times the mesh belt is passed under a blower to help remove free liquid before the cuttings retained are discharged onto the disposal pile. This method prevents extra disturbance to the clay cuttings, with the only disturbance that might lead to additional disaggregation coming from a short period when erosion of the particles will take place as the slurry passes through the belt.

2.5.2 Secondary System

The second stage of separation is generally a system combining both hydrocylones and a high-g dewatering shaker screen. The hydrocyclones remove the majority of the sand and some silt sized particles. The remaining slurry containing the majority of the clay and some silt still in suspension flows up through the top of the hydrocyclone back into the slurry tank, via a small hopper system. The solids removed by the hydrocyclones are still in a liquid form and are passed over a high-g shaker screen with a mesh aperture of between 100 and 500 μm. This dewaters these solids and they are then transported to the disposal pile. With the formation of a filter bed on the shaker screens a D_{50} of approximately 25-35 μm should be achievable.

The underflow from these shakers enters a small level controlled tank below the shaker from where it recirculates back through the hydrocylones. From this complex inner system, slurry is then passed into the main holding tank for circulation back to the tunnel face.

The primary and secondary separation stages have a variable effect on the amount of clay, silt and sand that has to be removed by the third stage of separation. This is largely due to the specification and design of the plant used. It has not been feasible to analyse the individual sections of the separation plant as part of this research project. However, although the hydrocyclones in the secondary stage apply a high shear rate to the slurry, this will have a significantly smaller effect on the effective particle size distribution produced within the slurry as the majority of the soil particles remaining as agglomerates have been removed by the primary separation stage or have a high level of bonding.

Consequently, the test focuses on modelling the actions applied to the slurry prior to the primary separation, see section 2.4.

2.5.3 Decanting Centrifuge

Running off line from the other separation plant is the clay and silt sized particle separation plant. On a pipe jacking site this tends to be at least one decanting centrifuge (Figure 2.6). Which works by continuously cleaning slurry from the main storage tank preventing the slurry density and viscosity from rising above previously designated values.

The slurry is pumped to the centrifuge and prior to entering the centrifuge is dosed with a flocculant. The decanting centrifuge exerts an acceleration of typically between 1500 and 3000 g on the slurry. This pushes the solid particles to the outside wall of the internal drum where they are removed using a screw auger. The separated liquid progresses its way to the opposite end and is fed back to the slurry tank.

This stage of separation requires constant supervision by a trained site operative and also represents a large hire or capital purchase cost for a contractor. For this reason it is important for contractors to be able to predict the volume of solids at this particle size expected from a site prior to specifying the plant and this is the driver for the research presented in this dissertation.

By the time the slurry has reached the centrifuge all particles are silt or clay sized with a maximum of 3% by weight fine sand. The centrifuge cleans the slurry producing a clear to slightly turbid centrate, so disaggregation is not a problem at this stage and does not require consideration during modelling.

Alternative plant is often used at this stage, such as filter plate presses and belt presses but predominantly on larger diameter tunnel drives where site space is not restricted.

2.6 Slurry Composition

As mentioned previously, pipe jacking operations predominantly use water to carry the soil cuttings in the slurry when tunnelling through fine grained soils and weak sedimentary rocks. The slurry pump speeds are high enough to transport the cuttings produced by the tunnel boring machine, and consequently it is often not necessary to add additional bentonite or polymer to the water to improve carrying capacity. Also due to the physical support of the tunnel boring machine, the tunnel face does not require slurry to enhance support properties. Within pipe jacking the cutter head speed is often faster than the time it takes for a filter cake to develop. This makes the slurry system easier to manage, as the operator knows that this is required to remove everything in the slurry and does not need to balance this by replenishing any additives.

However, there are a wide range of additives that have been used in the past or could be used in the future. For example traditionally, bentonite has been added to improve support and carrying capacity and more modern polymers such a xantham gum have also been used for this purpose. Polymer manufacturers have been promoting products that are designed to encapsulate cuttings, with the aim of preventing breakdown/disaggregation. There is limited understanding of the benefits or consequences of using these types of polymers, especially within the pipe jacking industry and this will be looked at in detail in chapter 3.

2.7 Alternative Application

The use of slurry as a support and transportation fluid is not unique to pipe jacking and the work carried out within this dissertation is applicable outside pipe jacking. Using slurry support is also a popular method of tunnelling for large scale tunnel projects, for example the Thames tunnels for Crossrail were constructed using slurry tunnel boring machines (Crossrail, 2013). The methodology for the use of slurry and its separation is very similar, although more emphasis is given to the support that the slurry provides at the face and the carrying capacity of the slurry in the larger transportation pipes.

In addition to large scale tunnelling, the project research is also relevant to slurry support used in diaphragm wall excavation, piling and the drilling of oil and gas wells. For all of the above excavation support is a more important factor and the slurry composition is therefore different. However, the breakdown of material when clearing a well or pile is very important to a drilling contractor and often space is also limited and separation plant is required. The different slurry composition in these applications may also have some beneficial properties in reducing cutting breakdown, which will be discussed later.

2.8 Summary

From the description of a complete slurry tunnelling excavation and separation system given above, it is evident that the soil cuttings undergo several mechanical influences prior to being removed from the slurry circuit. The mechanical processes inflicted on the excavated soil within the tunnel boring machine may have a significant effect on the disaggregated particle size distribution found within the slurry at the separation plant. This is due to the variation in size and shape of the cutting produced by the head dressing, the mechanical action of the head and whether water is injected at pressure at the tunnel face. It would be complex and beyond the scope of the research to analyse each of the individual processes described above that are found within the tunnel boring machine. Collecting samples close enough to the tunnel face and with a large enough variation of cutter head configurations, would be extremely difficult.

The mechanical actions causing disaggregation that will be focused on in this research are the shear produced by flow through the pipe and the action of the centrifugal pumps, section 3.5 and the time spent in the slurry pipe which is related to the length of the pipe and the primary separation phase. A proposed testing method should allow for these mechanical processes in assessing how much a soil disaggregates. Concentrating on this area of the process will allow for the research project to look at uniform processes and focus more on varying the soil type.

The literature review, section 3.4 and testing programme, section 4.5.4 will also include the use of different slurry compositions when excavating and pumping soils and weak rocks. This will look at encapsulation properties, swelling prevention and the possibility of a buffering effect, linking to work carried out in other areas of construction and drilling.

3.0 Literature Review

3.1 Introduction

The rate soil disaggregates during the tunnel boring machine (TBM) excavation process and the transportation of the cuttings may be affected by multiple soil properties. During the course of excavation and transportation through the slurry pipeline some of the properties that affect the rate of disaggregation may change. This chapter reviews how soil mineralogy and mechanical properties may affect the disaggregation of clays and weak rocks during the transportation of soil in a slurry tunnelling environment. It also examines how the transportation of the cuttings causes disaggregation, i.e. the effect of the soil swelling in the slurry fluid and the shear applied by the fluid as the slurry is pumped to the surface, which are covered in the first section on mechanical disaggregation.

The review of methods of testing soil properties will be limited to those not defined in a British standard, that have the potential to aid in the understanding of the soil disaggregation process. It will look particularly at how the oil and gas drilling industry assess soil breakdown and swelling, along with how they have overcome such problems in the field by varying slurry composition. The review will be limited to the drilling industry and the transportation of commodities in suspension. A variation of some of these tests maybe suitable for application to the prediction of disaggregation within slurry pipe jacking, however they all have disadvantages that prevent them being developed for this research project.

3.2 Mechanisms of Disaggregation

During the mixing or pumping of soil cuttings in slurry the disaggregation of the cuttings can be caused by different mechanisms occurring within the system and the amount of disaggregation may be dependent on the time that the cutting spent in the slurry prior to reaching the separation plant. Gillies (1991), looked at the mechanisms that may cause a cutting to breakdown. He classified these into two categories; particle breakage and surface degradation, describing particle breakage as where the particle/cutting breaks into smaller parts. This could be caused by the existence of fissures or cracks within the cutting or brittle failure due to impact forces being larger than the strength of the clay. The second mechanism is through surface erosion, where individual particles or small aggregates break away. This is caused by the movement of water over the surface or the sliding of the cutting along the pipe wall. This implies that the amount of surface erosion could also be affected by the permeability of the soil, soil strength at its surface and cutting shape or angularity.

The two mechanisms of breakdown described by Gillies (1991) are what would be expected when soil is pumped through a pipeline with impact forces from centrifugal pumps. Gillies (1991) goes on to describe the different rate and type of breakdown as the pumping time increases. He notes that initial disaggregation rates are high with cutting breakages and also the surface erosion of angular edges creating rounder, smoother cuttings. Gillies (1991) states that as time increases the rate of disaggregation decreases. Although Gillies (1991) does not provide quantitative evidence and his testing was undertaken on coal samples, his observation can be verified from visits to pipe jacking tunnelling sites and the visual inspection of cuttings.

3.2.1 Swelling

The swelling potential of clay has been identified as a possible cause for variations in the amount of disaggregation. The stability of a soil fabric can deteriorate due to swelling of a clay or weak rock exposed to water in a slurry (Mitchell, 1993). The drilling industry carry out tests on soil types that maybe encountered to understand the amount they swell. This is important because of the potential for a loss of stability in the well bore in addition to dispersion of clay cuttings due to the cutting fabric weakening (O'Brien & Chenevert, 1973).

Swelling occurs due to two mechanisms, surface hydration (crystalline swelling) and osmotic swelling. Surface swelling happens to all fine-grained materials when unloaded, but happens to different amounts depending on the change in confining pressure. However, osmotic swelling is the actual clay platelets swelling. This is caused by a concentration of surface ions on the clay. This draws water onto the clay platelet and then inside forcing the layers apart (Darley, 1969). The ability of this to happen is due to variations in metallic element levels within the clay structure. This results in Kaolinite at one end of the scale having low swelling potential (Mitchell, 1993).

The swelling potential of clay can be assessed directly using various test methods, a selection of which are:

- Oedometer test (BS1377-5:1990, 1998)
- Free swell test, using oedometer apparatus (Rauh *et al,* 2006)
- Digimatic swelling indicator (Osisanya and Chenevert, 1987)
- Methylene blue absorption test (ASTM C837-09, 2009)(Fityus *et al,* 2000)

The above tests all have both advantages and disadvantages but for the soil samples tested within this dissertation swelling was not considered to be a major factor in the degree of disaggregation seen. The effect of osmotic swelling can be assumed to have little effect due to the time spent within the slurry fluid. In the time required for the cutting to reach zero effective stress and for the water to permeate into the platelets the exposed clay would have already disaggregated. Similarly with the surface swelling, as the cutting is excavated and passed through the tunnel boring machine into the slurry pipes, the confining pressure is reduced to zero and due to the size of the lumps their potential to develop large negative pore pressures is small. The cuttings also have confining pressures removed from all directions, so when fissures open or soil swells, soil is likely to be removed by the dominant shear forces applied by the slurry fluid and pipe walls that a cutting is inflicted to within the slurry circuit. The effect of swelling can also be assessed more systematically by looking at the mineralogy of the soil to identify the proportions of different clay minerals and pore water chemistry, which affects the swelling potential, as described above.

3.2.2 Soil Fabric

Natural soil samples are not homogeneous and have anisotropic properties caused by variations in depositional and post-depositional processes applied to the soil (Little *et* *al,* 1992, Gonzáles *et al,* 2012). Post-depositional processes may be the result of a number of processes such as over-consolidation, tectonic ground movement, weathering and bioturbation (Skipper, 2016). The soil history has a significant effect on the soil fabric and structure created within a fine grained soil sample. This will determine the stacking and positioning of the clay fraction, with some soils having silt sized peds of tightly packed clay with large gaps between, allowing for larger local permeability (Skipper, 2016). The way in which these processes affect both the strength and permeability of a soil are understood to varying degrees and documented within geotechnical literature.

It is likely that these natural variations within a soil are key to the permeability of the soil cuttings and the probability that disaggregation will involve the soil cuttings breaking apart into smaller but still gravel sized lumps, rather than clay size particles. Unfortunately although the causes of the presence of structure and fabric in soils is well understood, the non-destructive characterisation of these features within a small soil sample and their effect on disaggregation are not documented.

Although in practice the fabric of a soil controls its permeability on a macro scale, the use of particle size grading to predict the permeability of a soil has been extensively studied. However the majority of this work has been carried out in relation to granular soils and these relationships are not applicable to the grading range that causes concern during the disaggregation of cuttings in slurry tunnelling. According to Mesri and Olson (1971), the permeability of clays is not only dictated by particle size, which is partially dictated by mineralogy but also other factors such as void ratio and physico-chemical variables. These control both ease of water flow but also the manner in which the individual particles aggregate. Their additional variables beyond particle size did allow a sufficiently accurate large scale estimation of permeability to be made for the clay samples used within their tests.

The variability of the measured permeability of soils and the relatively small size of the cuttings also makes it difficult to easily assess the effect of permeability. Standing and Burland (2005) give a variation in permeability within the B unit of London clay from $1x10^{-11}$m/s to $4x10^{-11}$m/s depending on the amount of erosion of the overlaying strata. More importantly though the horizontal permeabilities quoted by Hight *et al* (2003) vary by almost two orders of magnitude. CIRIA C583 (2004) gives a range of permeabilities from 5x10^{-7}m/s to 5x10^{-9}m/s for the Upper Mottled Beds and compares these to the permeability it quotes for London Clay which is 4.4x10^{-8}m/s to 2.4x10^{-10}m/s. However, Entwisle *et al* (2013) notes that the figures given for the Upper Mottled Beds are low and attribute this to the presence of sand lenses within the clay. These ranges of figures show that permeability is not a clearly defined parameter easily comparable to the potential rate of disaggregation, particularly as the fabric and soil structure produce a large variation in permeability. This is variability is magnified by the small cutting size used in a mixing test. Both macrostructure such as smaller fissures and sand/silt channels and microstructure relating to possible variations in void ratio due to the production of clay peds during deposition that provide local water paths will vary between cuttings.

3.2.3 Dispersivity

The dispersion of soil particles has been a key interest of the oil and gas industry, dam designers and agriculture in order to understand whether the soil particles will readily erode or disperse when in contact with free water. Dispersion is caused by the deflocculation of the soil due to the chemical composition of the clay and pore water, with individual or aggregates of clay particles repelling each other (Mitchell, 1993). Tests like the crumb and pinhole test have been developed to classify dispersivity and are described in section 3.3.3 and 3.3.4. Dispersion has the potential to be an important factor in defining the amount of sub 63 μm particles that end up in suspension within the slurry. However, none of the soils tested would be classified as dispersive from their mineralogy and consequently this was not a factor for the study reported here.

3.2.4 Bonding

In natural soils there is often bonding or cementing between the individual grains. This will affect both the soil strength and the likelihood that particles will disperse or be eroded as individual particles or aggregates (Mitchell, 1993). This bonding occurs over time with the changing of chemicals and minerals within the pore water. Often this can be attributed to the presence of compounds such as Calcium Carbonate and

Iron Oxide. The presence of these minerals within a sample is not however conclusive evidence of cementing, as they may just be contained within the pore water.

3.2.5 Slurry Fluid Chemistry

In the pipe jacking and tunnelling industry it is generally thought that changing the slurry fluid will affect the proportion of the cuttings that disaggregate. This effect has not been quantified and contractors are wary of the use of additives, still seeing this as a black art. The potential advantages need to outweigh the extra cost and any changes to the slurry separation process that are required. Nevertheless, the quantitative effect of some additives has been explored in both tunnelling and the oil and gas industry as described below.

3.2.5.1 Bentonite

For some slurry pipe jacks additives are added to the water to increase the carrying capacity of the water and to improve face support. Slurry additives are more common in large diameter tunnelling where the cutting size is larger and extra carrying capacity is required. Traditionally the main slurry additive has been sodium bentonite. The bentonite absorbs water between its sheet layers, swelling and producing a thixotropic fluid (Woodward, 2005).

A pure bentonite slurry acts as a Bingham fluid once hydrated, this gives the slurry a gel strength at rest. In order for the slurry to flow an initial shear stress is needed to exceed the yield point of the slurry (Lyon, n.d). Beyond this point the fluid displays a linear increase in shear stress and shear strain rate. The use of bentonite as the sole slurry additive was shown in Clark (1976) to have limited benefit to solids recovery of large cuttings (from the primary screen) compared to polymer and salt based additives.

The main disadvantages with a bentonite slurry are the quantity of dry powder that is required to be mixed, together with the difficulty of removing the bentonite quickly in changeable ground conditions. Because bentonite powder comprises well dispersed clay and fine silt sized particles, decanting centrifuges or filter presses would be required to remove it from the slurry. This is undesirable due to the cost of processing particles within this size range. Traditionally within a fine grained soil, slurry loss to the ground and enhanced carrying capacity from the slurry is not required. Consequently, because there is no evidence that adding bentonite reduces the amount of disaggregation there was no benefit in including the addition of bentonite in the test series reported in section 4.3.

3.2.5.2 Xanthan Gum

An alternative additive is Xanthan gum, which acts as a carrying agent. Xanthan gum (XC) is a polysaccharide that is created by fermenting sugars and creating Xanthomonas Campestris. Unlike bentonite it is shear thinning, with its viscosity reducing with shear rate. This ensures ease of pumping as pump speeds increase and also helps to reduce settling velocities when pumping is not taking place, keeping a large amount of solids in suspension. During pumping the required pumping energy is similar to that of a water system. Due to the small force required to pump Xanthan gum it is not the most suitable filtration control additive due to its ease in shear thinning allowing it to pass through the voids in granular soil. However with the addition of bentonite or when clay is naturally present it will reduce filtration by inducing particles to bind and start to build a filter cake (Darley & Gray, 1988).

Xanthan gum is stable in saline conditions unlike bentonite, however because of its make up it is prone to degradation due to bacteria attack. This is accelerated in warm environments, but can be reduced by having a saline slurry, high pH or the use of a bioside (Darley & Gray, 1988). For pipe jacking works in the United Kingdom due to the short drive lengths, Xanthan gum can often be used with just water and no requirement for adjusting the slurry pH or adding a bioside. However, in warmer climates or where there is a large amount of organic ground contamination this degradation can cause a problem.

The use of slurry additives traditionally used for face support and to aid in transportation may be beneficial in reducing the disaggregation of cuttings compared with just using water. They may also aid in lifting the cuttings from the invert of the pipe. This is currently not known within pipe jacking and something that requires investigation. However, there is no evidence that Xantham gum reduces disaggregation by for example encapsulation of cuttings which occurs with other polymer slurries.

3.2.5.3 Salt Based Muds

In oil and gas drilling potassium salt based muds have been used to help prevent shale swelling and breakdown since the 1960's (Darley & Gray, 1988). Potassium chloride (KCl) is added to the mud as a swelling inhibitor in sensitive clays and shales. Potassium salts inhibit swell due to the cationic exchange capacity between the Potassium salts and the negative charge on the exterior of the clay platelets. The Potassium chloride molecule is slightly smaller than the gaps in the two hexagonal tetrahedral layers of the clay, allowing it to fit snuggly and prevent the uptake of water for interlayer swelling see for example, Page & Baven, 1939, Sawhney, 1972 and O'Brien & Chenevert, 1973. Once the potassium particle has inserted itself between layers it is slow to be released due to the close fit. The use of salt muds has been shown to reduce swelling, which may also reduce the amount of disaggregation, but not in all circumstances see section 3.2.1. However, there are some disadvantages with their use, firstly they are typically a costly additive when compared to polymer based muds, it is difficult to calculate dose rates and to assess how quickly the concentration of the salt depletes as the mud circulates.

3.2.5.4 Partially Hydrolysed Polyacrylamide

Alongside potassium salts the oil and gas industry use partially hydrolysed polyacrylamide polymers (PHPA) for the prevention of swelling and in the pipe jacking industry they are often used individually as a lubricant. Partially hydrolysed polyacrylamide polymers (PHPA) are commonly believed to aid in the prevention of swelling and breakdown of cuttings by encapsulating the clay or shale (Clark, 1976). However, O'Brien and Chevnevert (1973) stated that partially hydrolysed polyacrylamide polymers used on their own have limited swelling prevention ability. They did however state, that when used in conjunction with Potassium chloride there was a reduction of swelling and disaggregation. This contradicts the common belief that the encapsulating capacity of a partially hydrolysed polyacrylamide polymer reduces disaggregation and if true would have a significant effect on the applicability of polymer slurries for use in tunnelling.

O'Brien and Chevnevert (1973) have shown that the use of Potassium chloride and a polymer can have great advantages in reducing both the swelling capacity of clays and in turn limiting the material that disaggregates. This was shown in their 2mm and 0.177mm sieve recovery results from the hot rolled jar tests described in section 3.2.5. This is a positive effect, however the cutting velocity in the hot rolled jar test is slow, leading to relatively small forces generated when cuttings impact with each other or the jar. The sliding action of cuttings surrounded by polymer slurry, could reduce the disaggregation due to the polymer acting like a protective coating. However, this effect may be limited during higher force mixing.

The use of partially hydrolysed polyacrylamide polymers (PHPA) was shown to cause problems when separating out 63 μm sized solids on shaker screens, with the potential to cause blinding of the screens thus reducing the dewatering capacity. The extra viscosity caused by the polymer additives has been seen to bridge the screen openings, even on 2mm screens (Phillips, 2012).

Liao and Siems (1990) also stated that it is difficult to monitor concentrations of partially hydrolysed polyacrylamide polymers in the slurry. Fann (2011) provides a testing procedure for the determination of PHPA concentrations within slurry, arisings or supernatant. The test is fairly easy to follow and appears easy to carry out, however it would take a mud engineer a minimum of 90 minutes to complete. This limits effectiveness of the test, as in a pipe jack the slurry would have circulated around the circuit multiple times during this period. However, more recently Lam *et al* (2014) undertook a study comparing different methods for determining the concentration of polyacrylamide in the supernatant from a decanting centrifuge. Various methods were assessed but the most consistent was shown to be the use of a viscometer. This is a quick test, which can be carried out in 5 minutes. The main drawback is that a calibration curve is required for each slurry (to account for additives and water), however, this is a simple matter of accurately mixing and testing slurries at varying anticipated concentrations. The viscosity of the supernatant can be compared to these concentrations to assess the absorption and degradation of the slurry.

The use polyacrylamide polymers in the slurry, along with the use of a decanting centrifuge with a partially hydrolysed polyacrylamide polymer as a flocculant is a subject that is not dealt with sufficiently in the literature. One issue is if the partially hydrolysed polyacrylamide polymer used in a slurry is not flocculating disaggregated particles, then particles could be assumed to be fully encapsulated preventing the separation flocculant from binding to the soil particles. This topic is an area that requires more research.

3.2.5.5 Oil Based Slurry

Oil based slurries are used by the oil and gas industry, especially in shales that are extremely vulnerable to swelling and disaggregation. However they are not a practical option for slurry pipe jacking or tunnelling due to the environmental disadvantages and cost of using such a system (O'Brien & Chenevert, 1973).

3.2.5.6 Summary

There are various options for slurry additives available for tunnelling and pipe jacking contractors. Many of these were originally developed in the oil and gas industry or adapted for piling contractors. Often these other industries require different properties from the slurry, including considerably higher carrying capacity and filter cake formation, which in fine grained soils and weak rocks are not required during tunnelling.

There are no clear reports demonstrating the benefit of using a polymer slurry and no literature could be found to prove the benefits in terms of a reduction in disaggregation within slurry tunnelling. This is an obvious area that requires significant study, with varying soil types, additive types and application in the field during slurry tunnel drives through fine grained materials or weak rocks. An extensive study is beyond the scope of this research project, however a limited initial study has been undertaken.

3.2.6 Shear rates

In order to understand fully what causes variations in the disaggregation of fine-grained soils and weak rocks. It is key to look at the mechanical forces that are imposed on the cuttings. In chapter two it was stated that the main focus of the research would be the transportation process from the tunnel boring machine to the separation plant. Consequently, the shear rate in the pipe is a key factor in the amount of disaggregation that occurs.

The shear rate in a pipe will be greatest at the pipe wall and depends on two hydraulic conditions; is the fluid Newtonian and is the flow laminar. If these conditions are assumed equation 3.1 is commonly accepted as defining the shear rate at the pipe wall as stated in Darby (2001) and Son (2007).

$$\gamma_a = \frac{8V}{D} \tag{3.1}$$

γ_a= apparent shear rate

V= pipe velocity

D= pipe diameter

This can then be developed for non-Newtonian fluids using the Rabinowitsch equation shown in equation 3.2. Non-Newtonian fluids are on occasion encountered when additives are used within the slurry (Son, 2007).

$$\gamma_w = \frac{3n+1}{4n}\gamma_a \tag{3.2}$$

Where

$$\eta = \frac{d(ln\,\tau)}{d(ln\,\gamma_a)} \tag{3.3}$$

γ_w= shear rate at the wall

τ= shear stress at the wall

η= flow behaviour index

$\eta<1$ fluid exhibits shear-thinning properties

η=Newtonian fluid

$\eta>1$ fluid exhibits shear-thickening properties

However, the flow encountered within a slurry pipe for a pipe jacked tunnel is not laminar. It is turbulent flow with a Reynolds number in the region of 300,000. This means the equations given above are not fully valid for application to a slurry transport pipe. However, for the purpose of this research and for comparison to the shear rate work carried out in section 4.3.1, this method provides a reasonable idea of the speeds and forces applied.

3.3 Breakdown and Dispersion tests

Several sections of the geotechnical and hydraulic engineering industries have looked at how soils breakdown, due to weathering and also whilst surrounded in a liquid. Some of this work has limited applicability to this research project, especially that focusing on weathering, but some testing methods have been adopted as standard practice. The suitability of these existing test methods for use in the prediction of the proportion of soil cuttings that disaggregate and are suspended in pipe jacking slurries is assessed in the following section.

The way in which shear is applied to a soil sample during these tests can be identified as shown below;

1. No mechanical forces; both water and soil static, no shear.
2. Movement/flow of water; where the water part of the test is moved and the soil sample(s) remain static.
3. Movement of the soil sample(s); the soil moves within the static water.
4. Both soil and water are mechanically moved, as occurs within a pipe jacking slurry pipeline.

In the following section, all existing tests designed to estimate soil disaggregation will be assessed in this way.

3.3.1 Slake durability

The most common breakdown test is the slake durability test (ASTM D4644, 2008) (Figure 3.1) which examines the slaking of shales and weak rocks. Slaking is the breakdown of a weak rock due to changes in environment caused by wetting and drying. The test looks at the soil's resilience to weathering and may be applicable to embankment cuttings, tunnel construction and mining where exposed surfaces of soil or weak rock are subjected to varying water contents. In the test ten 40-60 g samples are rotated around in a partially submerged drum at 20 rpm for 10 minutes. The samples are then dried and the test repeated. Drying and repeating the test could be omitted for a pipe jacking disaggregation test. This is because the mechanism of repeated wetting and drying is not applicable to the breakdown mechanisms within the slurry circuit. A 2 mm mesh allows aggregates <2 mm in diameter that break-off to enter the water bath. The slake durability index ($I_d(2)$) is then reported as the percentage of material remaining in the drum after the second cycle of drying.

The test is simple to undertake and requires minimal specialised equipment. It is a well-established standard, which allows for easy specification during a site investigation. It has the disadvantage that the mesh size of 2 mm means that material that falls through is no longer agitated. The mesh size could be reduced but this could cause the mesh to become clogged with soil.

The mechanical process within the slake durability test can be classified as type 3, where the soil samples are moving within the fluid. The drum is rotated at a slow enough speed for the soil lumps to tumble around within the drum. This slow rotational speed applies a low shear rate to the soil that is thought to be considerably lower than that in a slurry pipe. Just focusing on the initial wetting stage, the amount of slaking will be dependent predominantly on the shape of the cutting and the number of natural fissures or silt/sand lenses in the soil cutting. These are considered to be important factors when assessing the breakdown of pipe jacking soil cuttings, but the low shear rates and impact forces in the slake durability test may not activate these potential breakages.

For the above reasons carrying out slake durability tests would not be appropriate to assess clay and weak rock disaggregation within a slurry circuit. Even if the drying and second wetting stages are removed from the procedure, the mechanical processes do not inflict the same magnitude of impact forces to the cuttings and in addition sub 2 mm particles are not being agitated after passing through the drum.

3.3.2 The Saskatchewan Research Council Test

The Saskatchewan Research Council in Canada, along with other parties has carried out research on the breakdown of coal during pumping in slurry (Gillies, 1991). Several different tests have been undertaken on closed and open loop systems along with single pipeline studies. In the closed loop system (Figure 3.2) a representative slurry and coal mixture is pumped around a rectangular loop with a centrifugal pump. The pipe flow goes directly back into the pump, which is different to the open loop system where the slurry is fed into a storage hopper prior to re-entering the pump. The system can be monitored in various ways including; flow meters, nuclear density meters and pressure change apparatus (Gillies, 1991). The loop system has been shown to produce repeatable results for the breakdown of coal cuttings. It has been shown to overestimate the breakdown with respect to measurements taken in the field for single pipeline studies. This is believed to be because for the same time that the slurry is circulated through the loop system, the number of centrifuge pumps passed is considerably larger than in a straight pipeline in the field. It can be assumed that the number of direction changes is also considerably greater.

The loop system could be applied to slurry tunnelling as the mechanism of both liquid and solids being moved is the same as that which occurs in pipe jacking. The limitations are the extra pump passes and changes in direction, which are encountered during the transportation of cuttings in this test. It also requires significant space and special equipment for the tests to be undertaken. These are disadvantages when looking for a comparatively simple test that can be used for multiple and varying pipe jacking drives.

3.3.3 Crumb Test

The crumb test (ASTM D-6572, 2006) is a quick, well established soil dispersion test (as discussed in section 3.2.3) that easily generates qualitative results. The test method is of type 1 with no shear stress imposed on the soil sample. The procedure consists of carefully placing a 15 mm sample of soil at natural water content into a beaker of 250 ml of distilled water and then leaving the test undisturbed for 6 hours (Emerson, 1964). Visual assessments are taken at 2 min, 1 and 6 hours to assess the rate of dispersion.

At each assessment time the colloidal dispersive nature of the soil sample is graded and potentially photographed if future records are required. The dispersive nature of the soil is graded into four classifications, these look at the size and turbidity of the 'halo' of colloids that have broken off the soil sample (See Figure 3.3).

- Grade 1: Non-dispersive
- Grade 2: Intermediate
- Grade 3: Dispersive
- Grade 4: Highly Dispersive

Example photographs for these four grading results can be seen in ASTM D-6572 (2006). There are two test methods for the assessment of soils;

- Method A; natural soil sample
- Method B; remoulded sample

Which of the two methods used depends on the application the test is being used to assess; for example soil erosion, canal lining, dam core, etc. If used for the assessment of soils prior to slurry tunnelling, it would be recommended that both methods are carried out, as excavation and transportation through the cutter head inflicts a significant amount of remoulding to the soil. A comparison of the two results would give a more thorough insight into the potential for disaggregation.

The test only assesses a soil's potential for disaggregation into colloids, ASTM D-6572 (2006) uses the terminology 'deflocculating colloids', these terms are somewhat ambiguous as they suggest that individual sub 1 μm particles are breaking away from the soil sample. However, it would be assumed that the majority of breakdown is the breaking away of clay and fine silt aggregates because the test procedure does not apply any mechanical forces to the clay. The test may also be used to investigate the effect of pore water chemistry on dispersion or disaggregation. In a large proportion of soils it could be assumed that local cementing and true cohesion would requires extra forces to truly breakdown the soil into the individual particles. For the purpose of this research the term deflocculate is the breaking away of individual clay and silt particles.

3.3.4 Pinhole Test

Another American Standard test used to assess the susceptibility to dispersion of clay soils is the Pinhole test, ASTM D4647 (2013) (Figure 3.4). The test has been split into three methods; A, B and C. Each method for sample preparation is the same, but the potential water head, the flow rates and the classification of the cloudiness of the inserted water vary. The basic procedure is to drill or bore a 1 mm hole through a 38 mm high clay sample, either consolidated from disturbed samples or an undisturbed sample. The sample is then placed in a rig to allow the flow of water through the central hole. Initially distilled water is allowed to flow through the hole with a constant head of 50 mm for 5 minutes. During this time the discharge is assessed for turbidity and flow rate. After 5 minutes if the turbidity and flow rate are low then the head of water is increased. This routine is repeated up to a head of 1020 mm.

The test is most suitable for assessing how susceptible a soil is to erosion, as the only mechanical force is the flow of water (group 2). Although the flow rates can be of the same magnitude as those within the slurry pipe, the overall shear rate inflicted on a cutting would be significantly lower. The main advantage of the test is the simplicity and the short time period needed to gain results. Importantly the test does not consider soil structure and the effect of the shape of the cutting, both of these factors could have a large effect on the amount of soil breakdown that occurs. As with the crumb test, ASTM D4667 (2013) discusses the presence of colloids washed out into suspension.

3.3.5 Double Hydrometer Test

An adaption of the standard hydrometer test for measuring particle size distribution, the double hydrometer test looks at the percentage difference in quantities of sub 5 μm for a non-dispersed and dispersed sample. The test procedure is described in ASTM (2015), with adapted versions of various standard tests for particle size distribution (Maharaj & Paige-Green, 2013). The test comprises a standard hydrometer test, using sodium hexametaphosphate as a dispersing agent and strong agitation. This identifies the percentage of clay available, although depending on the international region the classification of this clay will range from 2-5 μm. A second sample is placed in distilled water, omitting the agitation and left with the dispersed sample for hydrometer readings to be taken at designated times.

The dispersive nature of the soil is classified as the ratio between the clay fractions in the two samples, with 0.5 and over being highly dispersive, 0.3 to 0.5 dispersive and below 0.3 non-dispersive. An example set of data obtained from this test can be seen in Figure 3.5, where Umesh *et al* (2011) show results using Suddah soil from Southern Karnataka, India. There is a 35% difference in the two clay contents, which indicates a dispersive soil. The ratios defining different levels of dispersivity represent large windows, so the actual dispersion ratio would be the most suitable method of comparison. Comparing data from an agitated test with the clay dispersed from a static sample in distilled water does raise questions of repeatability if small scale cementing and true cohesion are evident. Within these types of soils, silt sized aggregates may be dispersed, rather than significant amounts of individual clay particles.

In addition, the current test procedure only compares the clay fraction, where as a pipe jacking or tunnelling contractor would be more interested in the fraction of material sub 63 μm. However, this can easily be assessed by taking hydrometer readings at the appropriate times. The test does indicate how a soil reacts to wetting, with the clay chemistry probably dictating the amount of breakdown seen. However, it does not take into account the difference in agitation of the two soil samples and the results may not reflect the level of bonding between particles or fissures and sand lenses. This limits the tests applicability to pipe jacking, where significantly higher shear is inflicted on the cuttings during pumping.

3.3.6 Hot Rolled Jar Test

The oil and gas industry have used at least two jar methods to look at the breakdown of shales in different slurries. The test described uses cuttings varying between 2 and 3.35 mm placed in a 350 ml jar with a soil to slurry concentration of 4.55 kg soil to 159 l (1 barrel) slurry. The jars are then hot rolled for 16 hours at the temperature anticipated in the well bore (65°c used if well temperature is unknown). For tunnelling this temperature would be significantly lower than with the drilling industry, where it ranges from 10 to 30 degrees Celsius, depending on the time of year and friction in the system tunnelling system. The slurry and cuttings mixture is then allowed to cool to ambient temperature before sieving through a 2, 0.841, 0.300 and 0.177 mm sieve stack. Each sieve with its retained material is then oven dried and the mass of retained soil determined.

O'Brien and Chenevert (1973) report that this test is highly reproducible and that the test can be varied depending on the application. The testing procedure deems any material less than 0.177 mm non-recoverable for typical shaker screens on a drilling site. A pipe jacking contractor would anticipate recovery of solids from hydro-cyclones and shaker screens down to at least 63 μm, so the screen set-up may require adjustment. The test is highly adaptable with the ability to adjust time, fluid type and temperature according to the predicted circumstances that will be encountered. Using an elevated or varying temperature is not necessary with pipe jacking but this is easily omitted after carrying out baseline tests to confirm that it does not affect the accuracy of the test. The rolling action however, applies a very low to negligible shear rate to the cuttings, which is not similar to the high shear rate produced within a centrifugal pump. This could be classified as type 3 or 4 on the mechanical forces classification. This is because only relatively small amounts of movement occur to both the slurry and cuttings.

3.3.7 Mud Triaxial

The mud triaxial test simulates a drilled well by passing water or slurry through a shale specimen. This test allows a specimen to be loaded to predetermined stress levels before the slurry is circulated at 100 psi and a velocity of 4 m/s. The specimen is often prepared from drilling cuttings that have been dried, ground, rewetted and consolidated in a mould with horizontal drainage. This removes the need to drill the central hole, which the slurry is pumped through, see Figure 3.6 for a diagrammatic cut through of the equipment. The test is carried out until the test sample fails and is assessed by measuring the time to reach failure. Clark *et al* (1976) state that the high flow rate prevents a filter cake forming due to the erosion effect of the flow, this allows for increased levels of slurry penetration into the tested sample. The test can be classified as type 2 with respect to the mechanisms described at the start of section 3.3.

Because the test is assessed by measuring the time that the sample withstands the applied stresses, along with the quantity of erosion of the sample, it does not provide a single value of likelihood to disaggregate. However, it does provide the mud engineer with representative information on how the slurry chemistry affects the rate of breakdown of a soil type for comparison to previous soil or shale types and Clark *et al,* (1976) show it to be reproducible. This test does give an understanding of how a soil may breakdown but is more applicable to well wall stability and the action does not simulate what occurs in a pipe jacking situation. In particular, because the soil sample is loaded and held by a confining pressure, there will be significant differences in the way a soil would break down in this test compared to a soil cutting under zero confining stress which is being pumped. Consequently, the test procedure is not representative of soil cuttings pumped during slurry pipe jacking. It also only looks at the removal of particles by erosion on reconstituted samples, this omits any effect that you get from small fissures or weaker sand lenses found within natural soil cuttings.

3.3.8 Breakdown Test Methods Summary

From the above it is evident that significant work has been carried out to design test procedures that help predict the likelihood and degree of soil breakdown. All of the tests described above have positives and negatives in their potential application to slurry tunnelling. The most suitable test procedure would be the closed pipe loop described in research undertaken by the Saskatchewan Research Council (Gillies, 1991). This research supported theories describing how a cutting will disaggregate and the rate at which this occurs. Unfortunately the equipment required to carry out testing does not seem suitable for this research project, as it would be too large and impractical for use as a standard test by members of the pipe jacking and tunnelling industry.

The pinhole, crumb and double hydrometer tests do offer easy to use methods of assessing dispersivity of soils. However, the use of the pinhole and crumb test have also been shown to produce conflicting results for rates of disaggregation (Craft and Acciardi. 1983). Gerber and Harmse (1987) stated that the double hydrometer, pinhole and crumb test showed conflicting results when free salts were available in the pore water. This, with the inability of these tests to assess disaggregation due to fractures and discontinuities within the cuttings, limits their applicability to slurry tunnelling. These tests are also concentrated on defining the dispersive nature of a soil and consequently have less applicability to the non-dispersive soils tested, as part of this research.

The research carried out by Gillies (1991) showed that rate of disaggregation slowed with time and Gillies attributed this to a high initial rate due to the breaking of cuttings through weakness and then the rounding of the cuttings, which would be applicable to the samples tested for pipe jacking.

3.4 Summary

The literature reviewed presents current tests on soil and weak rock samples, which might be used to assess soil disaggregation. However, there are still large gaps in the understanding of this process, with no information defining what causes different levels of disaggregation, especially in the context of tunnelling and pipe jacking.

Although several methods for assessing breakdown and swelling have been reported in this chapter, none appear to be completely applicable to slurry tunnelling or pipe jacking. The most appropriate would be the closed loop pipe circuit, however it was reported to overestimate breakdown and also requires a large circuit to be specially constructed. This is something that soil testing laboratories would not have and for this reason a new test method has been designed which is described in Chapter 4.

A key criteria is to not only look at a method of applying shear that replicates the levels of disaggregation seen during slurry tunnelling, but also to investigate and hopefully classify the soil properties that cause the variation in magnitude of disaggregation. Because of this the following soil properties testing will be carried out on the soil samples tested.

Although permeability has been identified as a factor that could influence disaggregation, the difficulty of describing permeability by a single value that can be applied accurately to small variable cuttings means that it is not usable as a method of characterising the soil appropriate. However, comparing pre and post mixing test water contents may give an idea of the potential permeability of the soil. In addition, normalising data with respect to liquidity index may aid comparisons between soil types. The measurement of liquid and plastic limits will be carried out to BS1377-2:1990 (1996), with the plastic limit also being measured using the increased cone mass method (240g) (Wood &Wroth, 1978). To accompany this particle size distributions of the natural soil will be determined.

The use of slurry additives has been shown to have a long history in the drilling industries and the use of bentonite to be favoured in the tunnelling field. The use of additives is predominately required to aid in solid suspension and also bore/well stability (something less applicable to tunnelling, especially at small diameters). The effect of additives on disaggregation has been addressed predominately in the oil and gas industry, however the data presented was not conclusive. For this reason a small mixing study using a partially hydrolysed polyacrylamide polymer (HydroCut CF, manufactured by KB International Ltd) will be carried out to look at the effect of polymer slurries on disaggregation.

4.0 TEST PROCEDURE AND DEVELOPMENT

4.1 Introduction

The initial aim of the laboratory work, was the design and development of a new test, referred to as a mixing test, to examine the disaggregation that occurs in a range of different soils when subjected to wetting and shear in a slurry.

The mixing test has been designed to agitate soil samples in water or water with additives, replicating conditions similar to those experienced in the slurry pumping circuit. The test will allow the breakdown and disaggregation of different soil samples to be compared. To understand why the rate of disaggregation varies between different soil samples traditional soil classification tests have also been specified to characterise the soils tested.

Within this chapter the two stages in the development of the mixing test using a Hobart planetary mixer will be detailed and information on the soil samples provided. To validate the mixing test, the collection and testing of slurry and cutting samples from the site of a pipejack, before and after the primary screen, is also described. The unconfined compressive strength tests, Atterberg limit tests and particle size distribution tests that were used to characterise the soils tested are also detailed.

4.2 Soil Samples

The research required soil samples from a variety of geologies to be tested. These were sourced from various projects undertaken by members of the Pipe Jacking Association and the British Geotechnical Association. Bulk undisturbed samples were collected and sealed to prevent them drying out, see later for each soil type. Collection of samples was also staggered throughout the research programme to again prevent degradation of samples whilst others were tested.

The samples received were inspected and checked to ensure that they were packaged in a suitable manner for short-term storage. Mixing tests and classification tests were scheduled to make the best use of time and the samples available.

Speswhite Kaolin and seven natural soils were tested. The natural soils were collected based on availability from current construction projects but the primary factor in choosing the soils to test was to ensure a wide variation in soil properties. This would enable the results of the tests to be applied to a more comprehensive set of soils in the future. It also allows the rate of disaggregation to be correlated to a wider range of standard soil properties to gain an understanding of why soils breakdown at different rates. The state and source of all soils tested are described below.

4.2.1 Speswhite Kaolin

Speswhite Kaolin is a processed, powdered form of kaolin; Speswhite is the trade name that refers to its physical properties, which include grading and whiteness. This grade is a highly refined, ultra fine grade with a high brightness (Imerys, 2008). Kaolin is quarried in Devon and Cornwall from deposits of decomposed granite, which resulted from deep hydrothermal and surface weathering of the Feldspar in the granite (British Geological Survey, 2009). It has been used extensively in geotechnical research due to the quality and repeatable processing of the raw material.

Speswhite Kaolin has a silty, CLAY grading and exhibits a relatively high permeability when consolidated (Al-Tabbaa, 1987). To create samples for testing the powdered clay was mixed to a water content of 120% with distilled water, roughly twice its liquid limit, and consolidated in a 6” CBR mould. The clay was loaded in stages to a vertical effective stress of 500 kPa and unloaded to 250 kPa, creating an overconsolidated sample. For some of the initial tests consolidated clay was taken from centrifuge models. This had been consolidated to the same initial stress, but the models had also been accelerated to 100g, with a water table at the surface of the clay and consequently the clay may have been swelled to a lower natural effective stress than 250 kPa. The water contents at the start of each test are given in Table 5.1.

Using a processed mineral in this way allows samples to be created in a repeatable manner and for any testing to be carried out with easily comparable results. The samples created were homogeneous with no microstructure, as no notable structure present within the samples.

4.2.2 London Clay

London clay is sandy, silty, CLAY with fine sand. It was deposited in a tropical marine environment and is an overconsolidated clay. It can be categorised into eleven units all with varying particle size distributions and fissuring patterns (King, 2008). The London clay formation is found between the Bagshot beds above and a thin layer of rounded flint cobbles followed by the Reading Formation below (British Geological Survey, 2014). However, in central London the Bagshot beds and the top five London clay units are not present, resulting in the remaining lower units being overlain by either river terrace/alluvium deposits or made ground. Due to its geographical location the geotechnical properties of London clay have been significantly researched and are easy to source. It is also often tunnelled through but more commonly with open-face or earth pressure balance machines. This however does not mean that slurry tunnel boring machines do not encounter London clay, especially when small diameter pipejacks are used.

London clay is a variable unit covering a large basin area, it is a mixture of kaolinite, illite, chlorite, smectite and montmorillonite clay minerals. The proportions of these minerals vary between units and location within the London basin (Gasparre, 2005). It is reported that illite is the dominant mineral within central London, where the two samples used for these tests were taken.

(a) Tottenham Court Road Crossrail Site

A large bulk sample of London clay was taken from the construction of a caisson shaft on Great Chapel Street, as shown in Figure 4.1. The shaft was constructed by

Barhale plc and their operatives dug and collected the sample from a grab attached to an excavator. The bulk samples were made up of lumps of between 0.2-1 kg, which were stored in a sealed barrel. The clay samples were taken from approximately 11 m below ground level and from what has been interpreted as the A2 horizon, this has been hypothesised by comparing the site investigation report for the site, to that of unit descriptions in Gasparre (2005). See Figure 4.2 for comparison of the borehole log and the unit description by Gasparre (2005). The sample water contents are slightly higher than the typical unit water content when compared to data collected from multiple sources in Gasparre (2005), this is due to a reported water main leak in the vicinity of the shaft.

(b) Maida Vale Flood Elevation Scheme

A second bulk sample of London clay was taken from large cuttings from a guided auger bore being undertaken by Murphy Group. The project was in the Maida Vale area of London, see Figure 4.3 and again this consisted of 0.2-1 kg lumps stored in a sealed barrel. The sample was taken from skips containing recently excavated soil from the tunnel horizon, which was at approximately 9 metres below ground level. It is weathered London clay believed to be from the top of units B2 in the stratigraphic sequence. This classification is based on the description of the soil, the in situ water content and the Atterberg Limits compared to data in the stratigraphic sequence provided by King (1981) and Tan (2003), see Figure 4.4.

4.2.3 Mercia Mudstone

The Mercia Mudstone used is from the Gunthorpe Member and is taken from samples stored by Seward (2009). These samples were originally excavated from Ibstock brick pit, Leicestershire. The samples used were large undisturbed samples of up to approximately 15 kg, these had been wrapped in cling film, waxed and stored inside plastic storage boxes by Seward. The Gunthorpe Member is a cemented sandy, clayey, SILT. The XRD tests carried out by Seward (2009) showed a predominance of illite clays, along with some clay minerals such as illite-smectite. Chorite and kaolinites were also found in concentrations of around 5-10% from the XRD tests.

Mercia mudstone is highly variable with thin bands of inter-bedding that can vary dramatically, even within the same unit. The beds are not constant in thickness, with some only a couple of millimetres thick and others up to 5-10 centimetres. The degree of cementation is highly variable, with some beds being very stiff clay and others moderately strongly cemented claystone.

4.2.4 Fleetwood Silts

Bulk samples of Fleetwood silt were collected from site investigation works for a flood alleviation scheme in Fleetwood, Lancashire. The samples were taken from the region surrounding the horizon of the proposed pipejack, approximately 22 meters below ground level. The samples were taken by Geotechnics Ltd and made available by Donaldson Associates. The site investigation technique used to obtain the samples was cable percussion. The bulk samples were delivered in thick polythene bags, double bagged with the end twisted, folded over and cable tied firmly shut.

The samples can be described as soft, reddish brown, slightly sandy, clayey, SILT. Wilson (1990) describes the full geological history of the region. This stratum of soil is from glacial deposits of the underlying Thornton Mudstones, part of the Mercia Mudstone group. Alluvial deposits overlay the glacial clayey, SILT strata.

4.2.5 Upper Mottled clay, Farringdon Running Tunnel Enlargement

Samples of Upper Mottled clay were taken from a running tunnel enlargement dug by an excavator at Farringdon station, which formed part of the Crossrail works. This sample comprised 5-15 kg block samples, which were double bagged and stored in a plastic box. These samples were collected from Dr Sauer & Partners. The enlargement of the running tunnels was excavated using a backhoe excavator. The exact depth is not known but from face logs the Upper Mottled clays were encountered in approximately the top 1.2 m of the tunnel.

The Upper Mottled clay is part of the Reading formation and at this location sits below the London clay stratigraphy. In the location where the samples were taken the Upper Mottled clay overlies the Laminated beds (Dr. Sauer & Partners Ltd, 2014).

This clay is reported to be predominately illite and smectite, with a large proportion of chlorite and little kaolinite (CIRIA, 2004). The clay is very stiff with local fissures having extremely smooth surfaces.

4.3 Mixing Test

A mixing test was developed to model the processes that take place as the soil moves through the tunnel boring machine cutter head to the separation plant, as described in Chapter 2. The test was developed in two stages. The initial version of the test was carried out on three soil types; Speswhite Kaolin, London clay (Tottenham Court Road) and Mercia Mudstone. After the results from this initial series of tests were analysed, problems were discussed and changes made. The following section describes both the initial test procedure and the changes made to improve repeatability.

The test that has been developed involves mixing ten cut soil samples of 50-60 grams with 4.5 litres of distilled water in a Hobart planetary mixer for varying times. The mass of the soil samples has been chosen because it is similar to that produced by a 1200 mm internal diameter slurry tunnelling machine, a common mid-range machine size used by contractors in the United Kingdom and also a medium sized pipe jack, see Chapter 2. It is also the specified cutting size in the slake durability test (ASTM D4644-08, 2008). The quantity of water used was chosen partially due to ease of handling and testing and partially because it gives a similar solid to liquid ratio to that which would be expected for a 1200 mm internal diameter pipe installed at a rate of just over 2.5 m per hour (demonstrating that it represents a realistic order of magnitude).

The Hobart mixer has been used for the disaggregation test because it is a common piece of equipment in a soils laboratory. It can be set to a speed that applies a shear rate of 135 s^{-1} (as calculated below), which is of a similar magnitude to that applied within the slurry pipe and this speed can also be increased if required

4.3.1 Shear Rate in a Planetary Mixer

The method proposed to examine the disaggregation of soil cuttings was to mix these in water in a commercial planetary mixer.. The shear rates produced by a Hobart and a Kenwood food mixer were assessed by Chesterton *et al* (2011) for the whisk attachment. Both mixers rotate in a planetary motion so it is necessary to account for the varying radius and two revolutionary speeds. A planetary motion displays a non-constant velocity whilst moving through its trajectory, the paper gives the following equation 4.1 for the local linear speed.

$$V_D = \sqrt{(\Omega_R - \Omega_r)^2 R^2 + {\Omega_r}^2 r^2 - 2\Omega_r(\Omega_R - \Omega_r) rR\cos(2\pi\Omega_R t)} \qquad \textbf{(4.1)}$$

V_D= Velocity of a point on the attachment parameter (m/s)
Ω_R= Rotational speed around the attachment shaft (rad s^{-1})
Ω_r= Rotational speed around the centre of the bowl (rad s^{-1})
R= Radius of the attachment (Whisk=0.0645m, Paddle=0.086m)
r= Radius of the eccentric motion (Hobart=0.030m)

The apparent shear rate (γ_w) can be calculated from the linear speed for varying gaps between the attachment, whisk or paddle, and the bowl wall (δ). This calculation is intended for use with homogeneous dough, which is being sheared as it is mixed. However, for the purpose of this dissertation the velocity is more important because the suspended lumps are not being sheared.

$$\gamma_w = \frac{V_D}{\delta} \qquad \textbf{(4.2)}$$

The shear rate in the Hobart mixer will be constantly varying due to the change in tangential velocity denoted by the cosine function in equation 3.5. It will also vary with depth due to the changing gap distance between the mixing attachment and the bowl. The gap between the paddle and the bowl varies between 1.5mm and 15mm. The method of calculating shear rate described by Chesterton *et al* (2011) enables an understanding of the magnitude of shear rate. It is beyond the research project to check the accuracy of its application to the fluid in these tests.

From equation 4.1 it can be estimated that the maximum shear rate within the slurry pipe is 277 s^{-1}. This is based on a typical 1.2 m internal diameter pipe jack, with a flow rate of 80 m^3/hr in a 100 mm slurry pipe. This however is the wall shear rate, whereas the shear rate at the centre of the pipe is zero. This compares to a maximum shear rate of 135 s^{-1} within the Hobart mixer at speed setting one. Figure 4.5 shows the variation in shear rate depending on the height within the bowl. The change in shear rate is due to the variation in gap between the paddle and bowl wall, along with the change in distance from the centre of the paddle.

However, although the previous paragraph has discussed the comparison of shear rates, it is probably more applicable to compare flow velocities, this is because the shear rate derived from Equation 4.2 is used for a dough like structure, that is being sheared as it is mixed. However, this could be viewed as incorrect when relating to the slurry and the solid cuttings moving around together (Jefferis, 2015). For this reason future references to mixing will look at tangential velocities.

4.3.2 Initial Test Procedure

The test requires all equipment to be prepared and set-up prior to mixing in order to minimise the drying out of the cuttings. The equipment required is:

- 5.5 kg balance accurate to 0.01 grams
- Hobart Planetary mixer with paddle attachment (Figure 4.6)
- Two 5 litre measuring jugs, one for 4.5 litres of distilled water and one (of known mass) for collection of slurry
- Sieve shaker with 4.75, 1.18, 0.6 and 0.063 mm aperture sieves, 200 in mm diameter (**Procedure one only**)
- Four 200 mm diameter collection pans (of known mass)
- Adapted base pan for increased volume (Figure 4.7) (**Procedure one only**)
- 10 way cone splitter (Figures 4.8 and 4.9)

- 11 No. 500ml Pyrex beakers, 10 no. for collection of slurry using the cone splitter (of known mass) and one for wash water (500 ml distilled water)
- Stopwatch
- Wash bottle with distilled water
- Scoop for cuttings
- Soil cutting apparatus
- Cling film
- Large oven at 105-110°C
- 2 metal tins for water contents

The test procedure was as follows:

Ten soil samples approximately cubical in shape were cut with a knife or a saw and each one weighed to ensure that they were the correct size 50-60 grams and to establish the total mass of dry solids in the slurry. Two soil samples were also weighed to calculate the water content of the original soil, the water content samples ranged in mass between 30-80 grams and were tested in accordance with BS1377-2 (1996).

The test requires all the cut soil samples to be added simultaneously to 4.5 litres of distilled water in the planetary mixer, on a speed setting of '1', the slowest of three pre-set speeds. The mixing time was varied in each test, ranging from one minute to 10 minutes, in order to model the effect of extra distance pumped. Once mixed for a predetermined time period, the slurry was poured through the pre-weighed sieve stack. The mixing bowl was lightly washed using the water bottle to ensure all loose soil particles entered the sieve stack. If material was stuck to the bowl the bowl was weighed and dried post test so that the mass of dry solids left in the bowl could be determined and to account for all the dry solids tested.

The process of transferring the slurry to the sieves and setting up the shaker was accomplished within a four-minute window, this was to maintain a consistent protocol for all tests. Four minutes after the end of mixing, the sieves were shaken for one minute. This allowed particles to be sized without using a significantly greater shaking force than would be applied in the field. Because of the vertical forces applied by the shaker and because during mixing the water content shifted from the plastic limit towards the liquid limit clay started to extrude through the largest sieve. The choice of one minute was to try and minimise this effect and to represent similar shaking times to those used on site. The sieves were then placed into collection pans, weighed and placed in the oven for drying.

The slurry that was poured through the sieves was collected in the base pan and decanted into a collection jug, using a wash bottle to make sure all material was washed out. This was poured through the cone splitter, Figures 4.8 and 4.9. The jug was cleaned with 500 ml of distilled water, which was also poured through the splitter. Initially, each beaker of slurry obtained from the splitter was weighed and placed in a large oven to dry.

For each mixing test, all the test data was input into a table, as shown in Appendix A. Inaccuracies in the test are caused by loss of material or compounded errors from weighing the various components. To reduce these errors two to three soil samples were taken to calculate the water content. A range of water contents may be seen throughout the bulk sample used for testing, as shown in Tables 5.1 to 5.10. All of the soil cuttings were individually weighed and the mass of all apparatus that came into contact with the slurry weighed. This allowed the mass of dry solids, to be traced through the test and checked at the end of the test, ensuring that the change in the mass of soil between the start and end of the test is known.

4.3.3 Revised Test Procedure

During the analysis of the results from the initial set of tests areas of improvement were identified. Although the test was designed to be repeatable and straightforward to perform, there were aspects where user interpretation could change the results significantly. It was decided that the test should be adapted to remove two important elements causing variability in results.

The two areas for change that were identified were as follows:

- It was decided not to shake the sieves after pouring the slurry through them. This was because extrusion of clay through the sieves became a significant problem as the water content of the mixed samples increased. This was mainly evident on the 4.75 and 1.18 mm sieves.
- The initial gap between the paddle and the bowl was increased to prevent clay smearing on the base of the bowl and causing a significant amount of material to stick to the bowl. This lead to a significant amount of user interpretation on how much material to try and wash out. The original separation was 1.5 mm.

4.3.4 Removing Shaking from the test Procedure

Due to the extrusion of some clay during the shaking of the sieves the procedure was changed to remove shaking. The vertical shaking action is not fully representative of the forces applied during slurry separation in the field where screens are shaken in an elliptical motion. In order to check that the slurry did not back up on the finer sieves; the slurry was poured over each sieve individually. To do this, an extra 5 litre jug was required with a top diameter that allowed a 200 mm sieve to sit just inside the top edge.

Before a test was undertaken the two sieves with the largest apertures were placed on top of the two slurry jugs. During the test, the new procedure involved pouring the mixed slurry in the bowl of the Hobart mixer over the 4.75 mm sieve before carefully washing out any large lumps that did not flow out with the slurry. Special care and judgement were required not to remove material that might have been smeared during testing but just lumps that had stuck due to suction.

Once the above stage had been completed, the sieve was removed, carefully placed on the designated base pan and quickly weighed. The slurry now in the jug was poured over the 1.18 mm sieve washing all particles from the jug with the distilled water wash bottle. The sieve was then removed, placed on a base pan and weighed.

The next sieve in the sequence was now placed on the empty jug and the procedure repeated for the remaining sieves. Care was required at each stage not to spill slurry due to pouring too fast. It was also important that the jug was clean after each pour over stage. Once the slurry had been poured over each sieve, the jug of slurry was poured into the cone splitter and the original test procedure followed.

The adapted sieving procedure was checked whilst assessing the effect of varying the paddle height, described in Section 4.3.4. Although a 1.5 mm 10 minute mixing test was not carried out with just the adapted sieving procedure, the consistent results obtained when investigating a variation in paddle height and the observation that extrusion of soil no longer occurred, confirm the appropriateness of this method. Figure 4.10 shows the results from the paddle height tests along with results from the first three 10 minute mixing tests with the grading curves adjusted to remove the presumed extruded material. The result is a flatter curve between 4.75 and 0.063 mm, which correlates with the tests carried out with the adjusted paddle height, this can be seen in Section 5.3 and Figure 5.5.

4.3.5 Paddle Height Testing

The height of the paddle above the base of the bowl was varied to find the optimum height that reduced smearing to an insignificant level but also applied an appropriate velocity from the paddle to the slurry. The exact measurement used to define the gap between the paddle and bowl can be seen in Figure 4.11.

Mixing tests were carried out using the procedure described in Section 4.3.1 but with the adapted sieving procedure, described in Section 4.3.3. For each mixing test the gap between the paddle and the bowl was varied, starting with the 5 mm and increasing by 5 mm for each test from, up to 40 mm. A gap of 40 mm was large enough for all cuttings to easily pass under the paddle. The Hobart mixer used only has two paddle height settings, so to adjust the height two toolmaker clamps were carefully and tightly attached to the sliding rails controlling the height.

It was decided that a mixing time of 10 minutes was an appropriate to assess the effect of the gap between the paddle and bowl. This mixing time was chosen because at that stage 10 minutes was the longest mixing period that had been used and hence had resulted in the most smearing. It was also a balance of using a longer time to minimised any errors due to timing and small variations in the procedure, but also efficiency of time spent investigating the paddle heights effect. For this series of tests Speswhite Kaolin was tested, again for the reasons stated in Section 4.2.1.

The particle size distributions for all of the paddle height mixing tests were plotted, as shown in Figure 4.10. It can be seen that there is a large increase, approximately 25% in the amount of disaggregation when the bowl to paddle gap changes from 15 and 20 mm. This indicated that the mechanism governing the disaggregation of the cuttings changed at this point. A gap of 20 mm or larger resulted in mixing where energy is transmitted to the soil cuttings through the movement of water, rather than by smearing the cuttings to the bottom of the bowl. This action would be more representative of the type and magnitude of shear applied to the cuttings during pumping. In addition, because soil was no longer by being adhered to the base of the bowl more repeatable test results would be obtained. Consequently, the original test procedure, as described in Section 4.3.1, was changed such that all subsequent tests were undertaken with a 20 mm gap between the paddle and the bowl.

4.3.6 Sizing silt and clay sized particles

For a selection of mixing tests the particle size distribution was extended from 63 μm to 2 μm, in order to understand fully how the cuttings breakdown during mixing. Sedimentation tests were used to determine the size fractions that made up the sub 63 μm slurry. To obtain appropriate results from the sedimentation tests for the analysis of the mixing tests, the procedure given in BS1377-2 (1996) was altered by not mixing the slurry with a dispersant such as sodium hexametaphosphate. This is because the aim of the standard procedure is to completely disperse all clay and silt sized particles, whereas the aim of these sedimentation tests was to size the particles existing in the slurry.

In order to complete the sedimentation test all of the apparatus used in the ‘mixing test’ had to be prepared the previous afternoon, leaving just the mix and wash water to be weighed and the soil to be cut. This was due to the 7-8 hours required to complete the sedimentation tests, which were carried out on the same day as the mixing test. Immediately after the mixing test had been completed and all of the slurry samples from the cone splitter weighed, beaker numbers 5 and 7 were poured into two separate 500 ml sedimentation tubes and placed in the constant temperature water bath. Because the volume in each beaker was approximately 500 ml (the limit of the sedimentation tube) the slurry was passed back and forth between the beaker and the tube in order to remove all material from the beaker without adding wash water.

The sedimentation tubes often reached a constant temperature within an hour and at this point they were individually turned end-over-end 120 times in 2 minutes and placed back into the water bath. Once upright the stopwatch was started. The start point for the second test tube was delayed by two minutes to allow time to set-up for each reading. Sedimentation readings were taken for fractions 20, 6 and 2 μm in the same manner as described in BS1377-2 (1996), with the exception that any slurry that was sucked up beyond the stopcock was washed into a fourth beaker of known mass (approximately 50 ml) and kept for drying and weighing.

Once all three size fraction samples had been taken, the four small beakers, one from each time increment and the fourth which contained all the slurry overflow were placed in an oven to dry. The remaining slurry left in the sedimentation tube was then poured and carefully washed into a larger beaker (greater than 600 ml) of known mass and also placed in an oven to dry. All the material in the beaker obtained from the cone splitter has to be retained because the exact mass of material in suspension is not known before testing. It is necessary to know the amount of disaggregation that is likely to occur before carrying out the test in order to achieve a slurry sample for sedimentation with an appropriate mass of silt and clay sized particles in suspension.

As noted above, no reagents were used in any of these tests and agitation and time left in suspension were also kept to a minimum. This is necessary to prevent further breakdown of any agglomerates that are in suspension. Six sedimentation tests were completed for series two mixing tests.

4.3.7 Sizing Larger the 4.75 mm using ImageJ

As part of series two some of the mixing tests were digitally sized using the open source image processing software ImageJ (2015). The plus 4.75 mm lumps were laid out on to a clean desk after drying alongside a ruler for scale and a digital photograph taken, see Figure 4.12. The photograph was then made binary using ImageJ, a scale taken from the ruler applied and the image run through the sizing function within the software. An output comprising area, minimum feret diameter and maximum feret diameter was chosen. Using the area, the dry mass of the material retained on the 4.75 mm sieve and the specific gravity, a proportional volume and lump mass could be calculated. Each lump could then be sorted and group sized according to the chosen cut sizes, 4.75, 10, 25 mm.

Only two dimensions were available due to the 2D nature of the photographs, the lumps tended to lay with the dominant dimensions showing. In order to make sure that the summated mass of the individual lumps equalled the dry mass weighed after oven drying, a linear relationship was used to back calculate from the total dry mass. There is an unknown error in sizing the plus 4.75 mm lumps in this way, however it gives an understanding of the split within this size range that would otherwise not be easily available.

4.3.8 Variation in Slurry Fluid Chemistry

As discussed in chapter 3, although water is currently the most common base slurry fluid with, in rare circumstances, the addition of bentonite, some of the industry would like to see an increased use or understanding of synthetic slurries, similar to those often used within the oil and gas industries. Consequently, in addition to carrying out the ‘mixing test’ with distilled water, limited testing was undertaken with different slurry fluids. All tests followed the procedure described in Section 4.3.2-4.

The different slurry fluids were created by adding different proportions of the polymer HydroCut CF, manufactured by KB International Ltd. This polymer has been used as a support fluid for the excavation of diaphragm walls using hydromills. In addition to helping to suspend excavated material in the slurry, HydroCut is also designed to encapsulate the cuttings to reduce breakdown and water penetration, see Appendix B for the data sheet. Unlike many encapsulating polymers, HydroCut is designed to pass through separation screens, whereas most would bridge the screen apertures and flow over into the solids disposal pile.

Three concentrations of HydroCut, 0.375, 0.75 and 1.5 kg/m^3 were tested with Speswhite Kaolin, London clay and Upper Mottled Beds. All tests were undertaken with a 10 minute mixing time. The correct mixing and aging of polymer slurries is essential for both repeatability of testing and the performance of the polymer. For each test 5 litres of distilled water was poured into a jug and the required mass of HydroCut weighed out. The slurry was mixed by creating a vortex within the jug using a pallet knife and whilst maintaining the vortex adding the Hydrocut powder very slowly to avoid clumping (fish eyes). To mix in small quantities of powder it was best to pour the powder from a piece of folded paper, tapping it so individual particles fell into the vortex.

Once initial mixing had been carried out, the jug was placed on a magnetic stirrer and left for an hour to be gently mixed, before being aged for 24 hours. Prior to using in a 'mixing test' the slurry was mixed again with the magnetic stirrer. A Marsh funnel viscosity test was carried out on the three Hydrocut concentrations following to the procedure outlined by Fann (2013). From this point onwards the procedure is the same as the 'mixing test' with water as the fluid.

4.4 Cone Splitter Development

A cone splitter was developed to divide the slurry into manageable fractions, for both drying and assessing the total disaggregated solids, as well as creating samples for sizing through sedimentation. The smallest sieve size that the slurry can be easily passed through is 63 μm, the quantity of slurry collected in the underflow of the sieves is approximately 5.1 litres. Particles of sizes sub 63 μm are suspended within this slurry and the quantity of these must be determined in order to accurately measure the amount of disaggregation. The water content of the sieved slurry ranges from 1500-13,000% and would take too long to dry as a complete unit. Because of this it was necessary to develop a method for creating smaller samples that were representative of the slurry as a whole.

A cone splitter is commonly used in water sampling with fines contents up to 100 g/l (Ward & Harr, 1990). It is a highly accurate method of producing sub-batches of slurry. Other options were researched and the Churn splitter also considered, however Siu *et al* (2008) states that the cone splitter produced a closer split of solids concentration and also representative particle size distributions.

The cone splitter splits the slurry containing the suspended sub 63 μm particles into ten Pyrex beakers. The splitter (Figure 4.8 and 4.9) was manufactured using clear Perspex, with 10 holes accurately drilled at 45° to a 20 mm central core. The core is fed via a funnel opening out into a clear 120 mm internal diameter column with holding capacity of 4.5 litres. This was adapted by installing a further funnel on top to minimise the effect of the pouring angle from the feed jug.

The cone splitter was tested using the slurry collected from the initial mixing tests described in section 4.3. Thus, slurries of varying solids concentrations could be tested and the percentage variation at each port evaluated, whilst making efficient use of time by removing the need to mix up slurries with a range of solids concentrations from powder. Both the mass of slurry and mass of the dried solids collected in the 10 beakers have been analysed. Figure 4.13 shows the variation in slurry masses for seven of the eight kaolin tests and the four London clay tests, one kaolin test was omitted due to a port blockage caused by a small piece of paper towel.

Each port can be seen to separate out a slightly different percentage of the total slurry, however the variation for a given port was small which is the most important factor. Port two can be seen to give the largest spread equal to 2.65% by mass, and port three the most repeatable varying by only 0.81%. Dried solids were not measured for all beakers in the first test. This is because the method of analysing the repeatability of the splitter was proposed after test one had been completed.

Some variation was also seen in the mass of solids collected. It was not always the same proportion of the total slurry mass for a particular port, as would be expected. Table 4.1 shows the two errors recorded for each port, together with the compound error. The error for the dry solids was calculated as the difference in the predicted percentage of solids taken from the slurry split masses compared with the actual dry mass in the beaker after drying. As the error for the dry solids is relatively small the compound error is only slightly larger than the slurry error. The average error in the mass of dried solids measured ranged from 0.17 and 0.37%.

The cone splitter allowed the mixing tests and slurries sampled on site to be split into smaller samples. This facilitated quicker drying and easier handling of the slurry. The ports that were used following the initial tests were 3,4,6 and 8, as the error associated with these was found to be the lowest, shown in Table 4.1. Care was taken when a sample of the <63 μm portion was required for sedimentation tests, and when shorter mixing times or soil types that were not prone to disaggregate led to low concentrations of sub 63 μm particles in the slurry. In these cases samples from a greater number of ports were used.

4.5 Accuracy

Within the ‘mixing test’ there were inevitably errors associated with different aspects of the experimental method followed. Most of these errors are percentage errors associated with the measurement of parameters such as time and mass, however there are other errors which are absolute such as those related to the cone splitter. Understanding the errors associated with the test enables a better assessment of the causes of any variability in the results. In particular, whether these result from errors or were caused by natural variations in the soil.

The main errors associated with the ‘mixing test’ were with the weighing of all of the containers and soil samples. During the ‘mixing test’ one balance was used for ease of operation and consistency. The balance has a maximum capacity of 5.5 kg with the ability to read to 0.01 gram, however the accuracy of the balance could not be confirmed to be better than 0.1 gram. This was determined by weighing a range of objects on both the 5.5 kg balance and a newer balance with a resolution of 0.001

gram (up to a maximum of 220 gram). In addition, for the heavier end of the range, a variety of items of varying mass were placed on to the balance multiple times and the mass displayed was noted. It was found that the masses varied by up to 0.1 gram, but typically less.

As a percentage error this was greatest for the objects with the lowest mass, but all of the errors were compounded for each sieve size and consisted of the error in weighing the sieve, pan and dry soil. These four errors varied significantly with each sieve division, increasing with a reduction in aperture size. The error for each sieve was calculated by compiling the errors in each individual mass taken to compute the dry solids (sieve, base pan and sieve+ base pan+ dry solids). The error ranged from 0.02-9.7%, this was due to the small quantity of material often retained on the small aperture sieves. Although, 9.7% is a large error in relation to the mass of soil on one sieve, the actual difference is very small for a compiled particle size distribution, can be seen in chapter 5.

$$Percentage\ error = ({n_1}^2 + {n_2}^2 + \cdots)^{0.5} \tag{4.3}$$

n_1=percentage error 1
n_2=percentage error 2

The sub 63 μm portion of the slurry was split with the cone splitter, section 4.4. The errors were compiled using equation 4.3 and using the compiled port error shown in Table 4.1, the total error in the measurement of the mass of the sub 63 μm fraction can be calculated with the addition of the balance error. The four points used to calculate the dry solids, were ports 3, 4, 6 and 8. These were the four most repeatable ports, along with ports 5 and 7 that were used or sedimentation tests. The errors associated with the dry solids measured at the four ports were 0.82, 1.07, 1.10 and 1.03% respectively. When these errors were compiled with the balance errors, the overall error for port 6 is 1.39% (worst case). This again is small and insignificant for the mass of material retained within this fraction. For instance this relates to 0.06 grams of the total mass for a 5 minute mixing test using Fleetwood Silts.

Due to natural variation a range of water contents was often measured for the bulk samples used for a particular ‘mixing test’. This is unavoidable, however there is also an error associated with measuring the water content. The water contents are used to understand the properties of the soil being used and also to check that all soil used in a ‘mixing test’ is accounted for post testing. Because not all the material is sized due to a small amount sticking to the bowl and paddle and the slight variation in total dry weight due to variation in water contents, the particle size distributions were calculated using the total mass of solids found on the sieves only. The water content is also important in understanding the strength of the material and unknown variations in water content across the sample will have a significant effect on this.

The errors associated with the mixing test have been shown to be small and are detailed in Table 4.2. The largest effect on the results from measurable errors was associated with the cone splitter, however this was shown to only be ±0.11g. The variation in water content of the natural soil will have a more significant effect when analysing the causes of breakdown and comparing the amount of disaggregation to typical soil properties.

4.6 Pipe Jack Slurry Sampling and Testing

In order to evaluate whether the ‘mixing test’ is generating similar mechanisms of disaggregation to those that occur in the field, a comparison with pipe jacking slurries was required. Due to plant set-up, operation of decanting centrifuges and timings, not all sites are suitable for sample collection. Over the length of the project it was only possible to obtain samples of slurry from one site where a 600 mm internal diameter pipe jack was taking place in Clapham, South London. This was through weathered London clay, similar to that found in the Maida Vale flood alleviation project. The separation plant used at the site was a clay ball belt with a screen aperture size of 3 x 50 mm and a decanting centrifuge. However, the centrifuge had not been in operation at the time of sampling.

Samples were taken early in the drive, on the morning of the second day of tunnelling, at an approximate chainage of 5 m. Samples were collected from the underflow of the clay ball belt, prior to slurry being discharged into the agitated tank. A Marsh funnel jug was used to collect samples, with care being taken not to allow the jug to overflow. One litre, bottled samples were collected and quickly taken back to City University London for a particle size analysis. Approximately 1 kg of soil cuttings were also taken from the clay ball belt to use for fully dispersed particle size distributions.

Prior to carrying out the particle size analysis, the slurry was visually assessed to specify an appropriate size range for the sieves to be used in the analysis. For the London clay 250 and 63 μm sieves were used. The bottled slurry was tipped end-over-end 30 times to make sure that any settled sediment was in suspension and then poured over the stacked sieves with a base pan collecting the sub 63 μm slurry. No washing of the screens was required and the sieves were then placed in a collection pan and then in the oven to dry.

The slurry in the base pan was then carefully poured back into the bottle, ensuring all material was washed out of the pan. With the lid securely tightened the slurry was tipped end-over-end 120 times in two minutes and a 500 ml sample was then poured into a sedimentation tube and left in the water bath to equalise in temperature. The remaining slurry was then poured into a beaker of known mass and oven dried so that the total mass of solids could be calculated.

The procedure for pipette sampling to determine the proportions of silt and clay sized particles was as described in Section 4.3.5. Again, it was key that all slurry was kept and dried to calculate the solids used in the test. The specific gravity needed to complete the sampling times was initially estimated, with the exact particle sizing calculated at a later date once the exact specific gravity was known.

4.7 Crumb Test and Water Content Penetration

To investigate the effect of using a polymer based slurry on the rate of disaggregation, extra testing was required. Many drilling polymers are advertised as ‘encapsulating’ and preventing water ingress, which would imply that the inner part of a cutting should remain at a constant water content. As the water content of the sample changes, the rate of disaggregation is also likely to change.

To study this behaviour an adapted crumb test was undertaken. Two samples were used; one was submerged in distilled water and the second in HydroCut CF, the polymer used in the tests described in Section 4.3.6. The polymer slurry was mixed at 0.075%, 24 hours prior to testing. Two separate 600 ml beakers were partially filled with the separate liquids. For the test a sample of Speswhite Kaolin was used, which had been consolidated as described in Section 4.2.1. Two 38 mm cores were cut vertically from the sample. As each core was extruded the bottom 5 mm was discarded and then a 10 mm slice was taken from the core and placed in a tin of known weight. This was weighed and placed to one side. A further 75 mm of the core was extruded, cut and placed directly in one of the beakers, making sure that the level of the liquid was 10 mm above the core. A stopwatch was started immediately after placing the core and a photograph taken from above the core looking down (Figure 4.14).

Once the test was running a 10 mm slice was taken from the remaining core, as was done with the bottom slice. This was also weighed to determine a second water content. The remaining clay in the core could then be discarded. The above technique was then repeated for the second sample, which was placed in the alternate liquid in the second beaker.

As soon as the test time elapsed, a second aerial picture was taken and the sample carefully lifted from beaker. The orientation of the sample was noted and the top and bottom 10 mm were then sliced off and placed in separate tins of known mass and weighed. A smaller 20 mm diameter core was taken, vertically through the central portion of the sample and extruded into another sample tin in order to calculate the water content.

It was important to keep track of the orientation of the original core and where the water content sample came from in relation to this. Speswhite Kaolin is non-dispersive and samples should stay together, however some soils may crumble and slump. In these cases final water contents may only be applicable to the material that remains intact.

4.8 Soil Testing

To allow for a base comparison of the characteristics of the soils and weak rocks tested prior to conducting the disaggregation test proposed in section 4.3 it was important to classify the soils by properties that were thought to have an effect on their breakdown. In the early stages of the research project limited classification tests such as Atterberg limits, water contents and fully dispersed particle size distributions were carried out. However, for the second series of tests described in section 4.3.2, soils were also classified using X-Ray diffraction for mineralogy, X-Ray Flourescene (XRF) for chemistry and unconfined compression tests to determine unconfined strengths.

The dispersive properties of the soils were not investigated in detail as both results and analysis displayed in Chapter 5 and 6 show that the soils tested in this dissertation are non-dispersive.

4.8.1 Particle Size Distribution

Accurate particle sizing is key to the testing of the various soils used. The British Standard for soil testing (BS1377:2, 1996) presents two methods for measuring particle size above 63 μm. Dry sieving where there is no fine material present (sub 63 μm), this method is not applicable for this project. Wet sieving, where the sample is dispersed and washed through each sieve. Where 10 % of the soil is finer than 63 μm, BS1377:2 (1996) states that the soil should be classified down to 2 μm.

For this two standard approaches are given; the sedimentation pipette method and the hydrometer method. Both tests rely on Stokes law of settling velocity in order to determine the size of particle in suspension at a given time interval. The soils testing industry have commonly adopted the use of the sedimentation pipette method for quantifying the distribution of sub 63 μm particles within a soil, as it is widely thought to be more accurate (Clayton, Simons & Matthews, 1995). For this reason the hydrometer method was not used.

The wet sieving method for determination of particle size is simple in its approach, but there are some areas within the procedure that could lead to errors in the particle size distributions obtained. The fine particles must be completely dispersed and soil should be thoroughly washed through the sieves until the wash water is completely clear. It has been reported that errors are generated by both the potential to overload a screen or when particles with one dimension smaller than the sieve opening do not make it through (Clayton, Simons & Matthews, 1995). Both of these problems should be insignificant if samples are shaken for long enough, at least 10 minutes and because for the soils tested during this research the fraction above 63 μm is relatively low, preventing the risk of blinding the sieve.

To determine the distribution of particle sizes within the sub 63 μm range is more difficult and there are multiple factors that can affect the accuracy of the prediction of the grading in this size fraction. The sedimentation pipette method relies on the application of Stokes law to determine the size of the particles sampled after a particular time interval. This assumes that the particle is of constant density, smooth and spherical. However this is often not the case; soils are not made up of solely one mineralogy and are often agglomerates of particles with a wide range of densities. This can be exaggerated by the hydration of some clays, where the density decreases dramatically (Clayton, Simons & Matthews, 1995). This could lead to an over estimate of the percentage of particles at a certain size, an effect that will be more dominant at the finer end of the scale due to the potential hydrating and swelling effects.

In addition, the particles are often not smooth and in the case of clay particles almost never spherical, instead individual clay particles are commonly flat platelets or sometimes tubular in shape. Flat platelets will settle with the largest face perpendicular to the direction of settlement; increasing the settling time. Again, this will potentially overestimate the percentage passing any set point below 63 μm, with the major axis size being underestimated by a factor of up to two (Lu, Ristow & Likos, 2000) (Ferro & Mirabile, 2009). Data presented by Ferro and Mirabile (2009), along with Eshel *et al* (2004) show that the use of laser diffraction methods would produce closer estimates of the percentage of a given sized particle actually present in the soil, but this method has a major drawback due to the large cost of purchasing a laser diffraction machine. Although it is probable that the percentage passing a given size will be overestimated using the sedimentation pipette method, the majority of correlation work with other soil properties (soil strength, permeability, etc) in the literature has been carried out using this method and there will be consistency across all the particle size distributions obtained and presented here

For comparison with the particle size distribution produced from mixing tests, the fully dispersed particle size distributions (PSD) are required for all soils. All of the soils tested were first classified in accordance to BS1377-2 (1996). With the exception of Mercia Mudstone, all soils had a majority of particles of less than 63 μm sizes. Hence particle size distributions were obtained using the sedimentation pipette method after the soil had been sieved through mesh sizes 63 μm and 150 μm. Two samples from each soil type were tested, each approximately 12 grams in mass. Two samples were used in order to check that no errors occurred during the test, as sedimentation testing is susceptible to errors caused by small discrepancies in procedure.

A larger sample of Mercia Mudstone, 137 grams, was used and wet sieved in accordance with BS1377-2 (1996). Sieve mesh sizes of 5, 2, 0.425, 0.3, 0.15 and 0.063 mm were used and a sedimentation pipette test carried out on a sample of the sub 63 μm material. The increase in mesh and sample sizes was due to small bands of strongly cemented material running through the samples. All samples were left to soak in distilled water for at least one week before testing, with gentle hand agitation throughout the week.

All of the samples tested showed negligible signs of organic content, so the use of hydrogen peroxide was omitted from the test procedure. Due to time gaps between testing each soil fresh sodium hexametasphosphate was mixed for each test.

4.8.2 Atterburg Limits

Measuring the Atterburg Limits of a soil and comparing these to the current water content of the soil provides an understanding of the change in the mechanical behaviour of the soil with change in water content. The liquid (ω_L) and plastic limit (ω_p) give the limiting water contents at which a soil starts to change from plastic behaviour to that of a slurry (ω_L) or to a non-plastic/friable state (ω_p) (Azizi, 2007).

The main criticism of tests to determine the liquid and plastic limit of a soil is that they are carried out on remoulded samples with no original structure remaining. The maximum grain size is also 420 µm, and therefore not influenced by the medium to coarse sand fraction that may be present. The latter disadvantage of the test is limited for the soils tested because the fraction of soil greater than 420 µm is mostly negligible.

4.8.2.1 Liquid Limit

The liquid limit is the water content at which the soil starts to behave like a liquid. It can be defined by two accepted tests, the fall cone and the Casagrande method, both procedures are described in BS1377-2 (1996). The fall cone test was used here due to repeatability and the reduced influence of the operator (BS1377-2:1990, 1996).

The fall cone (Figure 4.15) test still requires care to be taken in order to achieve repeatable results. Measuring the liquid limit with the fall cone method can also provide data on the undrained shear strength (s_u). Wroth and Wood (1978) suggested that s_u=1.7 kPa at the liquid limit, although this value has been shown to vary depending on variables in the cone penetration test. However, Houlsby (1982) points out that it will give an engineer a good correlation from which to work.

4.8.2.2 Plastic Limit

The plastic limit of the soil is the moisture content when its behaviour changes from non-plastic/friable to plastic behaviour. BS1377-2 (1990) specifies the Casagrande thread rolling technique as the method to be used to determine this water content. This has been a heavily criticised technique, because it is influenced by the operator's technique and judgement. Variability can occur due to the pressure applied, geometry of the thread, technique used for rolling and speed of rolling (Sivakumar *et al*, 2009). Different test procedures to determine the plastic limit have been put forward by Whyte (1982) and Brown and Downing (2001), along with several other proposed test procedures but currently none have been widely adopted. Due to this potential for variability other methods have been developed, several of which use modified fall cone apparatus.

The increased mass fall cone method proposed by Wood and Wroth (1978) looks at the relationship between the undrained shear strengths of a soil at its liquid and plastic limits. It has been documented that at the plastic limit the undrained shear strength of a soil is approximately 100 times that at the liquid limit (Skempton and Northey, 1953, Wood and Wroth, 1978). If this relationship were to be used to determine what mass of cone should be used to find the plastic limit, the mass required would be 8kg. However, using an 8kg mass attached to the cone is impractical and also poses health and safety risks (Sivakumar *et al*, 2009). It is also difficult to place a soil with such a low water content whilst avoiding air voids.

A relationship has been described and used where the mass of the fall cone is increased three fold to 240 grams. The procedure for testing remains the same as the liquid limit fall cone test and results are plotted on the same graph as the liquid limit data. The plasticity index (I_p) can then be derived from Equation 4.4 (Wood and Wroth, 1978).

$$I_p = \frac{2\Delta W}{\log_{10}\frac{W_1}{W_2}} \tag{4.4}$$

Where:

Δw= Difference in water content between 80g data and 240g data as a percentage

W_1= Increased mass cone (240g)

W_2= Mass of liquid limit cone (80g)

With both tests easy to perform and neither time consuming, each soil was classified by both approaches, which allows for a greater understanding of the soils properties.

In addition, all the thread rolling tests were undertaken by the same operator reducing factors that may cause variation between results. (Due to the wider acceptance of the thread rolling test values using this method were used in the analysis of the results)

4.8.3 Unconfined Compression Tests

In order to try and understand how the effect of natural water content, voids ratio and the presence of any bonding or cementation affected the rate at which a soil disaggregated during the ‘mixing test’, unconfined compression tests were performed. Soil samples were cut and trimmed into shape (38 mm cylindrical sample) in accordance with BS1377-1 (1996), with a shape cutting tool and guide. Specimens were prepared in a sample preparation room with a humidifier creating a high humidity environment.

Once trimmed the specimen was wrapped and taken for testing in a standard triaxial apparatus (Figure 4.16). The specimen was cut to length (at least twice the diameter) and dimensions were measured before the sample was loaded. The unconfined compression tests were carried out in accordance with BS1377-7 (1996) and loaded at a rate of less than 2%/min, which for most samples was at 1.5mm/min.

After the specimen had failed, one of the large fragments of the specimen was placed directly in a tin of known mass and weighed, before being placed in the oven for drying for the calculation of the water content. The above test procedure was carried out for each soil sample tested individually.

For soil types where significant bedding was apparent in the natural sample, specimens were tested in both horizontal and vertical orientations. This is because when soil cuttings are transported within the slurry no specific orientation is applicable.

4.8.4 X-Ray Diffraction Mineralogy Tests

To assess the clay mineralogy of the soils tested in the series two mixing tests, a set of X-Ray diffraction tests were carried out on samples of Speswhite Kaolin, London Clay (Maida Vale), Upper Mottled beds and Fleetwood silts. The tests were carried out by Dr. Jenny Huggett using a fully automated Phillips 1820 X-ray diffractometer. Samples were scanned using Cu Ka radiation and a variable slit system, with the clay scanned at varying angles untreated, glycolated and also heated to 400°C and 550°C.

The scanning was undertaken externally due to the specialist nature of both the test equipment and the analysis of the raw data. For a full description of the methodology see Seward (2009).

4.8.5 X-Ray Fluorescence Chemical Analysis

In order to understand the possible levels of cementing within the clay samples a set of X-ray fluorescence tests (XRF) was carried out on the same samples as listed in section 4.8.4. Professor David Wray carried out the XRF tests at the University of Greenwich. XRF testing works by subjecting a sample to high energy x-rays, which in turn dislodge one or more ionized elections from an atoms inner orbital, which are then replaced by electrons from the outer orbital due to the instability in the structure. This causes the atom to expel a photon, the radiation of which can be measured by the XRF equipment. The amount of radiation released is unique to a mineral or chemical and hence the individual constituents can be identified.

One disadvantage to this method is that it only identifies whether a mineral or chemical is present within a sample, not what state it is in, i.e. acting as a cementing agent or just available in the pore water. This requires an expert analysis of the material to ascertain the likelihood of cementing (Skipper, 2016).

4.**8.6 Microscope Analysis**

Specimens taken from the three natural soils, London Clay, Upper Mottled Beds and Fleetwood Silts were all photographed through a microscope (Keyence digital microscope and Keyence RZ x500-x5000 zoom lens) at various degrees of magnification to allow for a quantitative analysis of the soil fabric and the effect of cutting. Speswhite Kaolin was not photographed because the bright white colour of the soil makes it difficult to focus on. The three samples were all cut using the same sample preparation techniques used in the mixing test, section 4.3. This used a soil knife to obtain a clean face prior to placing this face horizontally level under the microscope. Three magnifications were used at the same location on the clay surface, 500, 2000 and 4000 times and an image was taken for each magnification. The 4000 times magnification was the maximum available due to difficulties in focusing on a surface which had small but significant variations in height.

4.9 Summary

The work described within this chapter outlines the comprehensive testing undertaken, along with some of the limitations caused by measurement errors and natural variation in the soils. The 'mixing test' procedure developed has been rigorously tested and improvements made when deemed necessary. A range of tests have been carried out to characterise the soil properties that it would be reasonable to assume would affect the disaggregation of the soil cuttings as discussed in section 3.2. In addition, observations have been made to characterise the soil macro and micro fabric.

5.0 TEST RESULTS

5.1 Introduction

Results from all completed tests are presented in this chapter and will be discussed in detail in Chapter 6. The main set of tests were mixing tests as described in Chapter 4 and were carried out in two stages. In the first test series (series one) soil disaggregation was promoted by mixing with the paddle 1.5 mm from the base of the bowl. Following a preliminary analysis of results, it was decided to adapt the mixing procedure, so that the paddle was 20 mm above the base of the bowl to reduce the effect of smearing and the fraction of the clay cuttings that adhered to the bowl, see section 5.3 for series two results.

The results of the classification tests on the soils used are also described, together with results from tests where a polymer was added to the slurry and particle size distributions for the slurry taken from the site of a pipe jacking drive where a slurry tunnel boring machine was being used.

5.2 Series One Mixing Test

5.2.1 Introduction

In this series, 21 successful mixing tests were carried out on three soil types. Of the 21 tests 9 used Speswhite Kaolin, 8 used London Clay from a Crossrail shaft construction at Tottenham Court Road and 4 tests used Mercia Mudstone, see section 4.2 for the properties of these soils. As noted above in this test procedure there was a 1.5 mm gap between the paddle and the bowl. In addition, the vibrating sieve shaker was used for one minute to size the slurry following mixing.

Each test has been given a reference code incorporating the soil type, mixing series, speed of the planetary mixer, mixing time and also if it was a repeat test. The mixing series is denoted by an *S,* with 1 representing the first test procedure and 2 the second. *Sp* denotes the speed on the planetary mixer, typically this is 1, the lowest speed. Time is denoted in minutes and multiple tests with the same time are identified as *T1, T2, etc* for example, Speswhite Kaolin S1 Sp1 5min T2.

5.2.2 Speswhite Kaolin

For all mixing tests Speswhite Kaolin was used as the base soil with the intention of confirming the repeatability of the testing procedure. For the initial stages of testing Speswhite Kaolin cuttings were mixed for 1, 2, 5 and 10 minutes, with each duration repeated at least once. The basic test data is summarised in Table 5.1. Within the table there are two omissions in the results. Firstly, for the 5 minute mixing time for test 1, there is no value for the standard deviation of the water contents. This is because only two samples were put aside for calculating the water content measurements. The water content of one of the sample was calculated to be 17%, which was unrealistic and has been omitted from the results. The second gap in the table is the post mixing water content for the mixing time of 10 minutes for test 1. In this case the calculated value was unrealistically high, possibly due to a large amount of free water remaining on the sieve when it was weighed. For the first three mixing tests using Speswhite Kaolin the material left in the mixing bowl was not weighed and therefore these data are also omitted from the results.

The particle size distributions for all mixing tests for this soil have been plotted together on one graph in Figure 5.1, along with the fully dispersed particle size distribution for comparison. This will be the standard format used to display the raw data from all mixing tests.

For each mixing time the amount of disaggregation was similar for all tests at the same time interval. The level of correlation decreased with time, with the quantity of sub 63 μm disaggregated particles varying by 1.4% for both the one and two minute tests, but 15% for the 10 minute mixing time tests. The particle size distributions in Figure 5.1, show that the shape of the particle size distributions is similar, with the percentage passing both the 4.75 mm and the 1.18 mm sieve increasing with mixing time. However, the material retained on both the 600 and 63 μm sieves remained negligible. As mixing time increased typically the amount of 1.18 mm material also increased. This was attributed to extrusion of clay from the 4.75 mm sieve and was due to the increase in water content of the plus 4.75 mm cuttings, as recorded in Table 5.1. Evidence that clay was extruding through the sieve is provided in Figure 5.2, which was typical in the longer mixing tests. After analysing the initial results the test procedure was modified to remove the shaking of the sieves, preventing clay extruding. After the first three tests; S1 Sp1 1min T1, S1 Sp1 1min T2 and S1 Sp1 2min T1, it was decided that any soil left on the mixer paddle or bowl that was not easily removed with light washing should be accounted for in the dry weights. For the remaining six tests the paddle and bowl were also dried and weighed. A negligible mass of material remained on the paddle, however a notable amount was always left in the bowl, as shown in Table 5.1. This quantified the inaccuracy introduced with the procedure and helped to identify the need to adapt the procedure resulting in an investigation of the influence of the gap between the bowl and the paddle.

5.2.3 London Clay Tottenham Court Road

For series one of the mixing tests a bulk sample of London Clay was used from the excavation of a caisson as part of the Tottenham Court Road Crossrail works. In total eight mixing tests were performed with mixing times of 1 to 15 minutes. Figure 5.3 shows the particle size distributions for the mixing tests, along with the fully dispersed particle size distribution as a reference. The basic test data from these tests is summarised in Table 5.2. These curves show that the percentage passing drops between 50 and 4.75 mm and then remains approximately constant until 0.6 mm before dropping again to 63 μm, implying that some of the disaggregation produces fine sand sized aggregates, as well as aggregates larger than 4.75mm.

In contrast to the Speswhite Kaolin, the average water content of the soil cuttings varies significantly, by up to 6 % between each mixing test, as might be expected for a natural soil. This variation explains the variability of the results for a given mixing time. There is also a range of water contents for the cuttings used in a given mixing test. As mentioned above in some cases up to 27 g or 6.2% of the initial mass of soil was left stuck in the bowl, however there was no visual evidence of soil extrusion from the 4.75 mm sieve to the 1.18 mm. The water content of the soil collected on the 4.75 mm sieve is at least 10% lower than the Speswhite Kaolin.

5.2.4 Mercia Mudstone

Four mixing tests were carried out using Mercia Mudstone from the Gunthorpe member, tests were limited because it was necessary to use samples from the same horizon, see section 4.2.3 for the soil description. Mercia Mudstone is highly variable with significant changes in bedding over very small changes in depth. Figure 5.4 shows the particle size distributions for the four mixing test undertaken, it is clear that the increase in mixing time affected the amount of disaggregation. As with the Speswhite Kaolin, the amount of disaggregation of sub 63 μm particles increases steadily with mixing time. Table 5.3 again displays the key test data. For test S1 Sp1 10 min T1, the water content is significantly higher than would be expected. This is an anomaly within the results. During these tests the mass of material left in the mixing bowl was not weighed.

For these tests the lumps have disaggregated to a wider range of particle sizes, with 10 and 15 % of the disaggregated soil size between 4.75 and 0.063 mm. This may be caused by bonding structure in the soil (varying layers) leading to a greater range of sizes of aggregates of particles or the influence of larger particles shown in the fully dispersed particle size distribution.

5.2.5 Summary

Initial evaluation of the first test series showed good correlation between time and the increase in disaggregation for all soil samples tested. For the two natural samples the rate of disaggregation decreased with time, which fitted with theories and previous work carried out by Gillies (1991). Where disaggregation is greater at the start of transportation and decreases as the cuttings round off. Although there was good correlation between with the test results, whilst analysing the test routine and results it was noted that the amount of clay stuck to the inside of the bowl was undesirable. Also during the shaking process, as the water content of the clay cuttings moved towards the liquid limit there was an increase in material being extruded through the 4.75 mm sieve.

It was found that the reason that clay was sticking/smearing at the base of the bowl was due to the small gap between the paddle and the bowl which was only 1.5 mm. The movement of the cuttings with this small gap created inaccuracies in the method and in addition, the flow of cuttings and slurry was unrealistic when compared to the flow in a slurry pipe. This is due to the smearing that was seen, compared with the suspended nature of though a pipe. These points have led to the development of the test as detailed in Section 4.5.2 which significantly reduced the rate of disaggregation of the cuttings compared to the Series 1 tests and for these reasons the results from the Series 1 tests will not be analysed further.

5.3 Series Two Mixing Test

5.3.1 Introduction

After analysing the first series of tests it was decided to adjust the test method to improve repeatability and the applicability of the test to slurry pipe jacking. The adapted test method is detailed in Chapter 4. In the new method the shaking of the sieves is removed and the gap between the paddle and mixing bowl is increased. Using the revised test procedure 50 mixing tests were completed using cuttings from four soils: Speswhite Kaolin, London Clay (Maida Vale), Fleetwood Silts and Upper Mottled Beds clay. The paddle height for all tests within this series was 20 mm, the justification is given in section 4.5.2.2. Some mixing tests on Speswhite Kaolin were undertaken with a higher paddle speed, setting 2 (Paddle 196 rpm, Planetary 85 rpm), compared to all other tests where the speed setting was 1 (Paddle 107 rpm, Planetary 46 rpm).

A short series of tests was also carried out where the mixing fluid was varied by adding HydroCut CF manufactured by KB International Ltd (Appendix B). The eight tests used Speswhite Kaolin and two types of London Clay; samples from Maida Vale and Westbourne Grove. A baseline test using distilled water was carried out for each soil type for comparison against tests with varying concentrations of Hydrocut CF.

During the series two tests, additional information was logged. The numbers of lumps/aggregates larger than 4.75 mm were counted at the end of the test in most cases. Where results are missing from the tables, this is denoted by an *. The lumps/aggregates above 4.75 mm were laid out and photographed in later tests. The photographs were analysed using ImageJ version 1.48, an open source image processing software that allowed the classification of the dominant area and feret dimensions using a binary image. Using the feret dimensions given in the output from ImageJ, the material retained on the 4.75 mm sieve could be sized. The samples were then split into sub 4.75, 10 and 25 mm. The area of each group of aggregates was used to establish the proportion at a given size and hence to estimate the mass of each size. It was assumed that the aggregates were lying with their dominant dimensions facing up in the images and that the volume was linearly related to area. As noted in section 4.5.3, in selected tests the sub 63 μm material was sub-divided into coarse, medium and fine silt and clay using the sedimentation method. This was added to the particle size distributions for these tests.

5.3.2 Mixing Tests at Paddle Speed 1 (Low Rotational Speed)

The main test routine used the slowest speed setting on the Hobart mixer (Paddle 107 rpm, Planetary 46 rpm, with a varying tangential speed of 0.02-0.75 m/s), 39 mixing tests were carried not for mixing times varying from 5 to 120 minutes. The speed of the paddle was calculated using the method proposed by Chesterton *et al* (2011) and detailed in section 3.5.

5.3.2.1 Speswhite Kaolin

Laboratory consolidated samples of Speswhite Kaolin were mixed for times varying from 10 to 60 minutes. 14 tests were undertaken and are displayed in Table 5.4. Typically these were carried out in pairs to prove that the mixing test was repeatable. Initially, in two cases, mixing tests with two different mixing times (10 and 60 minutes) were carried out using the same consolidated sample. The results from these tests appeared contradictory as the tests with the 60 minute mixing time showed less disaggregation than the 10 minute mixing test. Consequently, to confirm that the testing procedure was repeatable and eliminate any possible effect of rust leaching into the samples from the CBR mould, samples were tested in pairs, two tests with the same mixing time from the same consolidated sample of Speswhite Kaolin. This resulted in close correlation between the particle size distributions produced by the pairs of mixing tests, which can be seen in Figure 5.5, thus ensuring that the test method was repeatable. The groups of mixing tests from the same sample can be identified by the nomenclature of 1/2 or 2/2 in the test number column. For later tests as explained in section 5.3.4, a stainless steel consolidation tube and platen were manufactured. The results from test S2, Sp1 10min (T6) have been included in this series, which was the reference test for the test series using polymer additive, see Section 5.3.4. This test was on soil consolidated in the stainless steel consolidation apparatus.

Figure 5.5 shows the particle size distributions for all the series 2 tests on Speswhite Kaolin. With the removal of shaking from the procedure it can be seen that the material at particle sizes between 0.063 and 4.75 mm is insignificant and no extrusion occurred. The number of post mixing lumps was typically 10 to 13, but with two outlier tests breaking down into 17 and 22 number lumps, this compares with the 10 that were present at the start of the test. Unlike series 1, comparatively little material stuck to the bowl, in the worst case 0.8% of the total mass was retained in the bowl. Sedimentation tests were also carried out on the sub 63 μm fraction of the slurry for two mixing tests; S2 Sp1 10 min T4 and S2 Sp1 60 min T4. The results have been added to Figure 5.5.

The particle size plots shown in Figure 5.5 all display the same trend, where a significant proportion (30-88%) is retained on the 4.75 mm sieve, nothing or very little is retained on the sieves below and the remaining material is dispersed in the slurry and is sub 63 μm in size. The two mixing tests to include sedimentation sizing showed similar proportional amounts of breakdown for the three sub 63 μm sizes measured. But the disaggregation was not proportional to the fully dispersed particle size distribution, also shown in Figure 5.5. The fully dispersed clay fraction is 77%, however only 52 to 57 % of the sub 63 fraction dispersed as clay sized particles. In all cases when the mixing time was extended to 60 minutes the sub 63 μm fraction was lower than that obtained after 15 and 30 minutes of mixing.

5.3.2.2 London Clay (Maida Vale)

A bulk sample of London Clay was used for the series 2 mixing tests, this was collected from a caisson shaft construction in Maida Vale. 14 tests were completed with mixing times of between 5 and 120 minutes, as shown in Table 5.5. Two tests included a sedimentation stage on the sub 63 μm fraction and for one of these tests fractions between 4.75 and 50 mm were also sized using the technique described in Section 4.3.6. Figure 5.6 shows the results from each mixing test, including the extended sizing.

It is evident from the results (Table 5.5) that for this sample of London Clay the 10 cut lumps break down into a significant number of lumps greater than 4.75 mm in size, with the range being from 31 to 82 smaller lumps. The analysis using ImageJ on London Clay test S2 Sp1 30min T3, has altered the plus 4.75 mm end of the curve slightly, with only 1.3% smaller than 10 mm. The material between 10-50 mm is evenly split across the size range. The amount of material stuck to the bowl after mixing was seen to be significantly higher than the Speswhite Kaolin mixing tests, at between 1.11 and 10.15 grams. This equates to 2.2% for the worst test, S2 Sp1 120min T2.

From the two mixing tests where the sub 63 μm fraction was sized using sedimentation, it is clear that only a very small fraction of clay-sized particles was dispersed, 0.21 and 0.43%. With a large proportion of the sub 63 μm size fraction being between 0.006 μm and 0.02 μm (approximately 70% (15-17% of the total mass)). This shows that the clay sized fraction is disaggregating as silt sized aggregates, of clay sized particles as the fully dispersed particle size distribution shows 60% clay, see Figure 5.6.

All 14 mixing tests resulted in a similar shaped particle size grading and the proportion of particles sub 63 μm increased with mixing time. However, it is noticeable that as mixing time increased the material retained on the 63 μm screen also increased from approximately 2 to 7 % of the total soil. It is also worth noting that the amount of disaggregated soil between 20 and 63 μm was only approximately 1% of the total mass or approximately 4% of the sub 63 μm fraction for the two sedimentation sized slurries, however the dispersed particle sizing showed 20% in the same fraction. This suggest that the large silts are again breaking off as sand or gravel sized aggregates and not as single particles.

5.3.2.3 Fleetwood Silts

In total five mixing tests were carried out on a bulk sample of Fleetwood Silts, which were collected from a site investigation. Mixing tests lasted between 5 and 60 minutes, as shown in Table 5.6. For all of the mixing tests a complete size analysis was undertaken between 63 μm and 50 mm, including the sizing between 4.75 and 50 mm using ImageJ. For test S1 Sp 1 30 min T2, the 63 μm size fraction was also sized using the sedimentation method.

The particle size distributions can be seen in Figure 5.7, along with the fully dispersed particle size distribution. The 10 original lumps were seen to break down into a significant number of 4.75 mm and 50 mm lumps (48 to 70), of which approximately 50 % of the original material remained in lumps larger than 25 mm. Unlike the London Clay and Speswhite Kaolin mixing tests, a larger proportion of material was retained on the 63 μm sieve. The amount of fine sand retained varied from 2.3 to 6 %, which is expected given that over 23 % of the Fleetwood Silts is sand sized. The amount of material stuck to the bowl varied considerably, but was still relatively small. The variation was between 0.08 and 1.20% of the total dry solids. From Figure 5.7 it can be seen that there was no obvious trend of increasing breakdown with time.

Mixing test S1 Sp 1 30 min T2 includes the size portions between 2 μm and 63 μm. This mixing test showed very little disaggregation of sub 20 μm particles, only 9 % of the soil disaggregated between 6 and 20 μm, with less than 0.5% disaggregating into small size fractions. The amount of disaggregation within this size range is significantly lower than the fully dispersed particle size distribution, where 26.5% is clay sized and 50% silt sized.

5.3.2.4 Upper Mottled Beds (Farringdon Station)

Five mixing tests were undertaken for times varying from 5 to 60 minutes using Upper Mottled Beds clay collected from the excavation of the Farringdon station

Crossrail platform tunnels. The test data is summarised in Table 5.7, with the particle size distributions shown in Figure 5.8. All of the particle size distributions except S2 Sp1 60 min have been sized from 4.75 to 50 mm using ImageJ and sedimentation testing was also carried out on S2 Sp1 30 min T2, to size the clay and silt sized fraction.

The number of lumps larger than 4.75 mm was the highest of the four soils tested in series 2 and ranged from 51 to 96. This resulted in a large number of lumps in the range of 10 to 25 mm, equivalent to 26-41% of the total soil. The percentage passing the 63 μm screen is also quite high, with the amount of disaggregated soil varying from 26.5 to 65.4%. The percentage of material sticking to the bowl was seen to range from 0.05 to 1.44%, which was again considered to be insignificant.

The sedimentation test carried out on mixing test S2 Sp1 30 min T2, shows a clay content of 10%. This is 33.5% of the sub 63 μm fraction and compares with the fully dispersed particle sized distribution where 61% is clay sized. For all tests the amount of material retained on the sub 4.75 mm screens was significant compared to the other three soils tested. This ranged from 0.27 to 9.8 %, however was typically between 0.8 and 3%, which is expected as the fully dispersed grading shows 5% of the material is between 63 and 600 μm. The data from the tests on the Upper Mottled Beds clay showed a trend of increased breakdown with time, except for the second 30 minute mixing test (S2 Sp1 30min T2), which generated approximately half the breakdown to sub 63 μm particles that occurred with S2 Sp1 30min T1.

5.3.3 High Mixing Speed

An additional test series was carried out to assess the effect of shear rate on the degree of disaggregation. This was limited to Speswhite Kaolin, with seven tests being carried out at 5 and 10 minutes. The paddle speed was set to speed setting 2 (Paddle 196 rpm, Planetary 85 rpm), this equates to a linear paddle speed of 0.06 to 1.38 m/s. The Hobart mixer has a third speed setting, however due to the nature of the initial mixture of water and soil lumps this was too fast, causing the liquid to splash from the bowl and resulting in potential loss of material.

The representative particle size distributions are shown in Figure 5.9, along with the fully dispersed grading for Speswhite Kaolin. As with the tests at speed setting 1, no material was retained on the three lower sieves (1.18, 0.6 and 0.063 mm). Again this is expected due to the grading of the powdered clay. Table 5.8 shows the test data and it is notable that very little material (0.01 to 0.21 %) was left in the bowl after mixing. There was also little breakage of the original cuttings, with the mixing tests only producing 10 to 12 lumps on the 4.75 mm sieve.

All the higher speed mixing tests were carried out in the early stages of series 2, and consequently there are no photographs for analysis of the plus 4.75 mm size fraction. However, due to the small amount of cutting breakage it is known that all or almost all of the retained material is larger than 25 mm. The sub 63 μm fraction was also not sized.

5.3.4 Polymer slurry Tests

Polymer suppliers and some members of the tunnelling industry have advocated the use of polymer based slurries when tunnelling through fine grained soils. They believe that it reduces the amount of disaggregation and could eliminate the requirement for separation plant that deal with the removal of clay and fine silt sized particles.

Testing was limited to a polymer based slurry using HydroCut CF manufactured by KB International Ltd, which was compared to tests carried out with distilled water. All tests were mixed for 10 minutes. From a total of four tests using HydroCut two were on Speswhite Kaolin and two London Clay from Maida Vale. For the Speswhite Kaolin all three mixing tests were carried out using the same consolidated clay sample. The two London Clay mixing tests were compared to existing 10 minute mixing tests. The concentration of HydroCut was varied from 0.15% to 0.0375% concentration by weight. The viscosity measured using a Marsh funnel for the three concentrations is shown in Table 5.12.

The particle size distribution graphs for Speswhite kaolin and London Clay can be seen in Figures 5.10 and 5.11 respectively and the results are given in Tables 5.9 and

5.10. For the first HydroCut test a concentration of 0.15% was used on the recommendation of the manufacturer (test: London Clay Maida Vale, 10 min HydroCut 0.15%). This resulted in a high viscosity slurry which would not pass through the 63 μm screen and was slow in passing the 600 μm screen. Due to the clarity of the slurry that did pass through the sieve, which clearly contained minimal suspended particles, it was assumed that the weight of the sub 63 μm particles was zero. This enabled the particle size distribution to be plotted across the same range as the basic test procedure, described in Section 4.5. It is worth noting that in the second mixing test using HydroCut at a concentration of 0.075%, the quantity of sub 63 μm material was only 0.9% of the total mass, validating the above assumption.

The particle size distributions for Speswhite Kaolin in Figure 5.10, show that the distilled water and HydroCut 0.075% mixing tests broke down into similar percentages of plus 4.75 mm material. With a concentration of 0.0375% the amount of material retained on the 4.75 mm screen increased from 87 to 94 %. The two mixing tests using London Clay and varying concentrations HydroCut, also showed similar quantities of material retained on the 4.75 mm screen when compared to a 10 minute test performed using distilled water as the slurry, see Figure 5.11. However, all of the mixing tests using HydroCut resulted in almost no material making it through the 63 μm sieve and less than 1% of material passed the 600 μm sieve during the Speswhite Kaolin mixing tests.

The HydroCut based slurries passed through the 1.18, 0.6 and 0.063 mm sieves slower than water slurry. As the aperture decreased the time to sieve the slurry increased. The slurry took over 30 minutes to pass through the 63 μm sieve. This could have possibly been reduced with mechanical shaking, although this was tested with a sample of polymer and the time was still significant.

5.3.4.1 Soil Water Content Change with HydroCut

The change in water content of the cuttings during a mixing test is potentially highly important to the rate of disaggregation, as an increase in water content will decrease strength. The use of polymer-based slurries is supposed to encapsulate the cutting, preventing free water from entering the soil. To investigate and possibly evaluate this phenomenon a slump test was carried out to examine the effect of HydroCut on the water content of cylindrical samples of Speswhite Kaolin. In the test both the internal central water content and the external water content of the clay samples was measured.

Table 5.11 shows the water contents of the ends of the samples before each test was started and the water contents throughout the cores for both the distilled water and HydroCut slump tests. It shows no difference in the change in water content of the cores for the two tests, implying that no barrier is formed.

5.4 Material Properties

5.4.1 Introduction

For all of the soils used in the mixing tests, basic soil classification tests were also performed to provide data, which might be correlated with the disaggregation potential of the soil.

5.4.2 Atterberg Limits

All soil types have been tested to determine their liquid and plastic limits using the procedure described in Chapter 4.9.2. Table 5.13 shows both the liquid and plastic limits defined using the cone penetrometer and thread rolling methods described in BS1377:2-1990 (1996). The plastic limit has also been obtained using the increased mass cone method described by Wood and Wroth (1978).

Table 5.13 shows that the soils tested have a wide range of liquid and plastic limits which can be correlated with disaggregation. The plastic limit derived from the thread rolling method will be used for these correlations (BS1377:2-1990, 1996). It is worth noting that values of the water content at the Plastic Limit obtained using the Wood and Wroth (1979) method do not have a consistent relationship with those obtained using the thread rolling method.

5.4.3 Particle Size Distributions

Particle size distributions have been carried out with both wet sieving and sedimentation testing for all soil types, testing was done in accordance with BS1377:2-1990 (1996). Prior to sedimentation testing the specific gravity of the soil was identified, are shown in Table 5.13. The fully dispersed particle size distributions are shown in Figure 5.12. These plots again show the wide range of soils that have been tested, although all soil types have a significant proportion of clay and fine silt sized particles. These are the most difficult to remove from the slurry during tunnelling and therefore soil samples with large proportions of fines are key to gaining an understanding why different rates of disaggregation occur.

5.4.4 Unconfined Compression Tests

Unconfined compression tests were carried out on specimens taken from samples of Speswhite Kaolin, Fleetwood Silts and Upper Mottled Beds used in the second series of tests. It was not possible to test the London Clay (Maida Vale) because there were no cuttings large enough at the time testing took place. Table 5.14 lists the ultimate stresses for the soils tested, along with a comparable ultimate stress for London Clay as tested by Gasparre (2005). The London clay from the Maida Vale site was weathered and considered to be on the boundary between divisions B and C in the stratigraphic sequence suggested by King (1981).

The stress/strain curves for the unconfined compression tests can be seen in Figure 5.13. Figure 5.14 omits the Upper Mottled Beds to allow for better comparison of the Speswhite Kaolin and Fleetwood silts, as their peak strengths are significantly lower. Because the Upper Mottled Beds were highly structured, it was decided to test a sample in both vertical and horizontal loading planes. This is because when a clay cutting impacts the pipe wall or pump impeller within the slurry circuit there is no defined loading direction.

5.4.5 XRD Mineralogy Tests

Four XRD tests were carried out on samples of the soils tested in the series two mixing test, Speswhite Kaolin, London Clay (Maida Vale) Upper Mottled Beds and the Fleetwood silts. Table 5.15 shows the concentrations of the four main clay minerals, with a breakdown of the illite-smectite mixed layer mineral. The London clay and Upper Mottled Beds both display similar concentrations of all four minerals., The Upper Mottled Beds contain slightly more illite (18% compared to 14%), and the London clay sample contains slightly more illite-smectite (80% compared to 73%). However, the illite concentration within the interlayer illite-smectite was 10% more in the London clay, compensating for the differences highlighted above.

5.4.6 XRF Chemical Tests

XRF tests were carried out on the four soils used for XRD tests, described above. Figure 5.15 displays the percentage of individual oxides within the soil samples (total oxides equals 100%). It can be seen that three main oxides were evident within the soil samples, silicon dioxide (47.7-64%), iron oxide (0.8-10.9%) and aluminium oxide (12.1-37.6%). The aim of the tests was to establish whether there were minerals present that could provide cement between particles and consequently , the percentage of silicon dioxide can be ignored, as it is present as a major component in rock forming minerals (Seward, 2009).

Interestingly although in comparably smaller concentrations, calcium oxide was identified in notable quantities in two of the soils. The largest concentration was found in the Fleetwood Silts (5.2%), with 1.9% found in the London Clay sample and only 0.45% in the Upper Mottled Beds. Unsurprisingly no calcium oxide was identified in the Speswhite Kaolin samples, because this has been consolidated in the laboratory from mixed powdered clay. Calcium oxide is a key chemical in the cementing of clay particles (Sherwood, 1967).

5.4.7 Microscope images

Three magnified images of each natural soil sample were taken using a microscope as described in section 4.8.6 and shown in Figures 5.16-5.24. All of the 4000x magnification images are slightly out of focus due to the extremely small focal point and the microscopic variation in surface height, however this does not render them unusable. Looking at the three London Clay images, Figures 5.16-18, the surface shows clear silica silt and fine grained sand amongst the clay matrix. Although the cut surface appeared smooth to the eye, the microscope shows the evident surface roughness, with some small voids shown as dark spots between the clay peds, evident in the 2000 and 4000x magnification pictures (Figures 5.17 and 15.8).

The images of the Upper Mottled Bed samples are shown in Figures 5.19-21 and similar to the London Clay, there is a notable quantity of silica silt/fine sand is evident and the surface roughness is also highlighted by the magnification. As in the London Clay samples, voids can be seen between the clay peds, however there appear to be significantly more of these in the Upper Mottled Beds.

Unlike the London Clay and Upper Mottled Beds, the Fleetwood Silts have an different appearance under the microscope (Figures 5.22-24), due to the obvious different particle size distribution. A significant but undulating surface roughness can be seen in the 500 and 2000x magnification pictures (Figures 5.22 and 5.23). Also due to the wider grading curve (seen in Figure 5.12) and the method of deposition (Section 4.2.4), the cut surface has fewer apparent voids than the London Clay and Upper Mottled Bed samples at the available magnification.

5.5 Site Data

To validate the mixing test and attempt to understand how a soil breaks down during slurry tunnelling, slurry samples were taken from a pipe jacking site in Clapham, London. Joseph Gallagher Limited were installing a 600 mm outer diameter concrete pipe line, using an Iseki Unclemole tunnel boring machine. The site had limited separation plant, using a single clay ball belt with a 5 mm aperture metal link belt and a Bauer decanting centrifuge.

Three 1 litre samples of slurry were taken from the underflow of the clay ball belt, before being immediately returned to City University for particle size analysis. The slurry was sampled during the excavation for the installation of the second length of concrete pipe and before the decanting centrifuge had been brought into operation. The length of the slurry pipe transporting the slurry from the face at this point in the pipe construction was approximately 25 metres, equating to an approximate transportation time of 62 seconds in the slurry pipe. Figure 5.25 shows the particle size distribution for the three slurry samples tested, along with the fully dispersed particle size distributions from two wet sieving tests carried out on large cuttings taken from the clay ball belt.

Figure 5.25 shows that very little clay sized material disaggregated during the transport of the clay cuttings. The three samples of slurry contained between 0.8 and 8.4% clay sized particles, compared to 44.6 and 52.8 % clay content measured in the fully dispersed particle size distributions. There was also relatively small quantities of soil, between 3.8 and 10.1% between 0.063 and 5 mm. Unfortunately there is no way of accurately producing a full grading curve that includes the plus 5 mm cuttings. To do this it would be necessary to design and fit a special sampling port to the contractor’s plant during site set-up. This was not possible for this site.

5.6 Summary

During the research project a significant number of mixing tests were carried out, alongside testing to obtain basic soil properties. From the various test results displayed in this chapter, the mixing test procedure was shown to be repeatable and the large amount of data collected can be analysed to understand what properties may control the disaggregation of the soil and how various soil types may break down during the tunnelling process.

The practicality of using a polymer based slurry was observed, including how the use of a polymer affects the process of separating the 600 and 63 μm size fractions using a sieve. The XRD and XRF tests provided valuable information that when combined provided the best insight into the reasons for a variation in disaggregation rates in different soils, as discussed in detail in Chapter 6.

6.0 Discussion

6.1 Introduction

The results presented in Chapter 5 will be discussed, along with further analysis of the data set that has been compiled. The aim is to describe the mechanisms by which soil disaggregates in slurries and to provide insight into the reasons for the variation in disaggregation rates of soils. The discussion will concentrate on the results taken from the second mixing test series omitting the results from series one. The series two tests provide a consistent set of data and were developed to be the most applicable to the problem at hand. Direct comparisons between the two series would not be appropriate.

A wide range of mechanisms have been identified as relevant to the magnitude of disaggregation and the way in which the soil cuttings break down. These mechanisms can be related to the soil properties obtained as part of this programme of tests and to properties taken from literature. Certain soil properties have been seen to have a dominant effect for a particular soil type, meaning that although the amount of disaggregation for a certain soil can be related to a single property this is not consistent for all soil types.

The effect of the changes to the mixing test will also be discussed. The results obtained when using a partially hydrolysed polyacrylamide slurry will be analysed and compared to mixing tests using distilled water. The effect of different paddle speeds has also been addressed, with a limited set of tests on Speswhite Kaolin assessing the potential that this factor has to create a change in rate of disaggregation.

To evaluate whether the mixing test is representative of the field process, slurry and soil samples were also collected from an active slurry pipe jacking operation. These were compared to mixing test slurries in terms of particle size distributions for the sub 4.75 mm fraction, post mixing cutting shape and water content.

6.2 Influence of Soil Type on Breakdown

The second series of mixing tests were carried out using four soil types; Speswhite Kaolin, London Clay, Fleetwood Silts and Upper Mottled Bed clays. Three of the soils tested can be classified as clay and one as silt but all with significantly different soil properties, see Section 4.2. Figures 6.1 to 6.4 show the percentage passing 63 μm normalised by the percentage passing 63 μm in the fully dispersed particle size distribution plotted against mixing time for all four soil types.

From the three natural soils tested the Upper Mottled Bed clays from Farringdon Station displayed the largest amount of breakdown. After 60 minutes mixing time, 50.8% of the available sub 63 μm fraction had disaggregated from the original lumps, this compares to 21% for the Fleetwood silts subjected to the same mixing time. These two soil samples are at either end of the spectrum of soils tested, when comparing the basic soil properties displayed in Figure 5.12 and Tables 5.12 to 5.13. The Fleetwood silt is characterised as a firm, clayey SILT with a significant proportion of sand, implying a greater permeability than the Upper Mottled Beds. The silt also had an unconfined strength lower than the Upper Mottled Beds. Because of both these properties it would be expected to disaggregate more readily, however the reverse was observed. This may be partially explained if the permeability of the Fleetwood silts is in fact dominated by the 26.5% clay fraction. However, there is a factor of 10 difference in the unconfined strengths and hence it is clear that the unconfined strength is not a good indicator of the proportion of sub 63 μm particles that disaggregate.

The four 60 minute London Clay mixing tests disaggregated to give an average of 25% sub 63 μm particles (compared to 50.8% for the Upper Mottled Beds). London Clay and Upper Mottled Beds have similar qualitative soil descriptions. Both clays being described as heavily over consolidated very stiff to hard, silty CLAYS. This shows that descriptions are not a good guide to the amount of disaggregation. Although, the unconfined strength of the London Clay was not measured, indicative values from the literature reinforce the conclusion from the comparison with Fleetwood silt that this is not a good indicator of the potential for the disaggregation of sub 63 μm particles. The effect of liquidity index, which is a different measure of strength, clay fraction, macro and micro structure are more significant, as discussed later in Section 6.4.

Speswhite Kaolin was the only laboratory prepared soil used in the testing programme. The soil was consolidated and swollen to create firm overconsolidated clay lumps. On average, 33% of available sub 63 μm particles were present in the slurry at the end of the 60 minute mixing tests. However, after 30 minutes of mixing on average 69 % of the sub 63 μm fraction was present. This rather counterintuitive effect of mixing time will be discussed in Section 6.3.

The overall rate of disaggregation can be assessed by analysing the number of lumps larger than 4.75 mm that result from the original 10 cuttings. This could affect the amount of sub 63 μm fraction that disaggregates due to the increase in surface area exposed to the slurry fluid when a cutting breaks into two or more pieces. Figure 6.5 displays the number of lumps larger than 4.75 mm plotted against the disaggregated normalised sub 63 μm fraction. Although for London Clay there is only a very small increase in sub 63 μm fraction for a large variance in lumps larger than 4.75 mm (18-58). For the London clay and Fleetwood Silts there is a general trend that as the number of lumps increases so does the sub 63 μm fraction. The Speswhite Kaolin data do not fit this trend, largely because the lumps do not break up significantly. The sample is laboratory consolidated and this process does not create fabric; bedding planes, sand/silt lenses and micro fissures or cracks along which the cuttings break. The Upper Mottled Beds cuttings break into many separate lumps, 96-51, but there is less disaggregation of sub 63 μm particles when there are more lumps so the trend is opposite to that observed for the London Clay and Fleetwood silt. This counteracts the theory that as the number of large cuttings increases so would the rate of disaggregation, because of the increase in surface area in contact with the fluid and hence subjected to swelling and shear stresses imposed by the fluid. There must be more dominant mechanisms determining breakdown to sub 63 μm particles for these soils.

In the natural soils the clay fabric varies within a bulk sample, this makes it extremely difficult to cut mixing test lumps that are identical. Whilst cutting some lumps break apart along bedding planes, fissures or structural weaknesses. Although a uniform cube cutting was aimed for, these weaknesses made it impossible to achieve. Not all weaknesses were activated during cutting but may affect how a cutting disaggregates during mixing. It is impossible to predefine the exact soil structure in an individual lump that might cause it to break apart into smaller plus 4.75 mm particles and the hence the rate of disaggregation will vary between samples. Evidence of this is provided by the Upper Mottled Bed clays and London Clay, which have the largest ranges in number of plus 4.75 mm particles. Assuming that the break up into these smaller size lumps is a function of natural discontinuities in the clay, as suggested above.

6.3 Mixing Time and Speed

6.3.1 Mixing Time

The major variable in the mixing test is the time the soil cuttings are mixed in the planetary mixer. This ranged from 5 to 120 minutes, with typical mixing times of 5, 10, 15, 30, 60 and 120 minutes. Increasing the mixing time allows more processes that should increase the amount of disaggregation that occurs, as it increases the time that shear is applied to the soil from the slurry liquid, paddle and sides of the mixing bowl. It also increases the time allowed for water to penetrate the cuttings.

For the London Clay samples, the number of particles below 63 μm after mixing did increase with time, as shown in Figure 6.2. The relationship between disaggregation and time is almost linear for testing times of 5 to 120 minutes. Although the proportion of sub 63 μm particles is still low, even after 120 minutes when proportion of disaggregated sub 63 μm particles reaches a maximum value of 35.5%. For this soil type, mixing time can be considered significant to the amount of disaggregation.

Mixing time does not appear to be significant for either the Fleetwood Silts or Upper Mottled Bed clays as shown in Figures 6.3 and 6.4 respectively. For these soil types other soil properties seem to have a more dominant effect on the amount of disaggregation. This will be discussed later in Section 6.4.

For the Speswhite Kaolin, time had a more complex effect on the amount of disaggregation seen. For mixing times of 10 to 30 minutes, the number of sub 63 μm particles increased with time. However, all four 60 minute tests showed a dramatic reduction by on average 50%, in the number of sub 63 μm particles in the slurry when compared to the 30 minute mixing tests. There is visual evidence that the lumps larger than 4.75 mm had started to collect the smaller aggregates at the surface of the clay. When looking at Figure 6.6 from the fourth 60 minute mixing test using Speswhite Kaolin, small aggregates can be seen on the outside of the lump. These aggregates appear to be varying from approximately 1-5 mm. Figure 6.7 is a zoomed in crop from the material on the 4.75 mm sieve from the fourth 10 minute mixing test, this can be compared to Figure 6.6 and it is obvious that for the 10 minute test the surface of the clay is smoother, with no noticeable material stuck to the outside. This difference was also observed between the other 60 minute tests and the 10-30 minute mixing time tests.

As the number of 4.75 mm lumps increased their size decreased as they broke into smaller plus 4.75 mm lumps, with this a lower rate of disaggregation was recorded. This reduction in sub 63 μm particles disaggregating can be attributed to the lifting within the slurry of the plus 4.75 mm lumps. As the lumps decrease in size and in turn mass, the speed of the mixing allows them to be lifted from the bottom of the bowl into suspension. This reduces their contact with the bowl and a reduction in surface erosion is seen.

6.3.2 Mixing Speed

The main body of tests were carried out at the low speed setting on the Hobart mixer (Paddle 107 rpm, Planetary 46 rpm, with a varying tangential speed of 0.02-0.75 m/s). However seven mixing tests were carried out using the medium paddle speed (setting 2, Paddle 196 rpm, Planetary 85 rpm with varying paddle speed of 0.06 to 1.38 m/s) using samples of Speswhite Kaolin. This increase in speed caused a significant increase in sub 63 μm particle disaggregation as can be seen by comparing Figures 5.5 and 5.9. The three 5 minute mixing tests resulted in 30-36% of available sub 63 μm particles suspended in the slurry. This is a significant proportion for such a short mixing time when compared to the lower speed mixing tests, where the main body of 10 minute mixing tests resulted in 12-23% of available sub 63 µm particles in the slurry.

Similarly to the 5 minute higher speed mixing tests, the 10 minute tests also produced significantly more sub 63 µm particles, 45-59%, which lies between the numbers of particles produced by the 15 and 30 minute mixing tests at the lower speed. This change in speed and consequent increase in disaggregation is significant and should be considered when deciding at what speed the slurry is pumped away from the tunnel face in practice. For the Speswhite Kaolin, the mixing speed has a larger influence on cutting breakdown than time spent at the lower mixing speed. This could influence tunnel operations or tunnel boring machine design by reducing the pumping speed used in the slurry pipes. Changes such as these would require an increase in slurry viscosity to enhance the carrying capacity of the slurry.

In certain instances the slurry will require high pumping speeds to cope with the rate of excavation and the need to move cuttings away from the tunnel face. However, this would predominantly be in coarse grained material where disaggregation of sub 63 µm particles is not a topic of interest. The hypothesis that reducing cutting speeds would help to reduce disaggregation has only been briefly touched on and prior to any site operation changes more work would be required including varying the soil type and slurry viscosity. Analysis using computational fluid dynamics may also be required to check the carrying capacity of the slurry.

6.4 Rate of Disaggregation Related to Soil Properties

Classifying the water content of each soil with respect to its liquid and plastic limits is important in understanding the state of the soil and defining a measure of the intrinsic strength of the soil. Consequently, it may also be important in determining the breakdown of the soil in a slurry. When combined with the clay fraction the activity of the soil can be calculated and an indication of mineralogy can be gained, together with the plasticity index. The plasticity index defines the water content change that will be required to move from the plastic to the liquid limit and is used with the current water content to give values of liquidity index.

6.4.1 Effect of Liquidity Index

This is probably the most important measure that can be taken from the Atterberg limits, as it gives an indication of how the soil strength varies with water content for different samples of the same soil. It is reasonable to assume that this will be a factor in determining the amount of disaggregation that occurs. It is also a way of normalising the water content of the samples, to allow for a comparison between different soil types as shown in Figure 6.8. Figures 6.9-6.12 investigates the importance of liquidity index for the four soils tested. In Figures 6.1-6.4 the liquidity index is also given for each point plotted.

Figure 6.8 shows clearly that the only soil where liquidity index varied significantly was Fleetwood Silts, which has a very low plasticity index, with small variations in water content leading to significant changes in liquidity index values. Although this is a limited data set, it appears that for soils with zero or positive values of liquidity index, i.e. water contents above or equal to the plastic limit, there is a very slight trend of an increase in the percentage of particles sub 63 μm with an increase in liquidity index, particularly if a certain mixing time is considered, for example the 10 minute tests. However, the data shows that in general liquidity index is not a significant factor in determining the magnitude of disaggregation of the sub 63 μm particles and as discussed below, for some soils there appears to be a trend of decreasing disaggregation with increasing liquidity index.

As discussed in Section 6.3, the disaggregation of Speswhite Kaolin is not related to mixing time by a simple linear or exponential relationship, hence it is unlikely that the liquidity index would have the same effect for all mixing times. From Figure 6.9 both the 10 (omitting test SP1, 10min T1) and 15 minute mixing tests display a trend of decreasing normalised percentage of sub 63 μm particles with increasing liquidity index. The relationship for the 30 minute mixing tests is less clear, as liquidity index varied very little. There is a greater change in liquidity index for the 60 minute tests and a slight increase in the normalised percentage of particles finer than 63 μm. This could be due to the extra mixing and wetting time during the longer mixing tests such that these factors have a greater influence of the disaggregation process.

The longer mixing times help to give a fuller picture of how the cuttings breakdown, however for typical pipe jacks the time cuttings spend in the slurry is significantly less and a tunnel drive would have to be several km long for the slurry/cutting interaction to be longer than 15 minutes. The Speswhite Kaolin is a reconstituted clay and consequently there is no bonding/cementing material to prevent particles disaggregating when effective stresses are low/zero, so it may be that the inherent strength of the soil is not affecting breakdown except to ensure that particles are just disaggregating at the boundaries of the cutting. Consequently, the only influence of liquidity index is on the permeability of the cutting, which will be of marginal effect.

The London clay sample from Maida Vale (Figure 6.10) has a large range of data points to compare to the Speswhite Kaolin. The water contents of the London Clay samples are very close to the Plastic Limit, with a very small liquidity index range of less than 0.05, making the identification of any trends very difficult for a given mixing time. No relationships between amount of disaggregation and liquidity index were identified. The behaviour of the London Clay may well be dominated by soil properties such as structure and cementing/bonding, both of which are discussed later in this section.

The liquidity indices of soil used in the mixing tests carried out on Fleetwood Silts had a large range of between 0.07 and 0.64. As noted above, this large range is due to the small plasticity index, as the water content variation across all tests on this soil was only 5.3%. Figure 6.11 shows a trend of increasing disaggregation with increase in liquidity index for the 10 minute tests, which differs from that seen for the Speswhite Kaolin mixing tests shown in Figure 6.9. However, there were only two 10 minute mixing tests and five tests in total carried out using Fleetwood silts, so this trend cannot be confirmed. Similarly the tests on Upper Mottled Bed clays show little to no effect of liquidity index. As with the London clay the range of liquidity indices is very small at 0.05 and all tests were on samples with water contents below the plastic limit.

The values of normalised sub 63 μm fraction were also plotted against plasticity index for the four soils tested. If the plasticity index is lower, there is the potential for a larger reduction in strength under the small water content changes that occur in the mixing tests and hence there might be a correlation with amount of disaggregation. However, as seen in Figure 6.13, no such relationship was evident.

If the action of the slurry is to wet the surface of the lumps allowing the soil at the surface to swell and reach zero effective stress then the permeability of the soil is significant and changes in water content during the mixing test will be an effective measure of the relative permeability of the soils. These have been normalised by plasticity indices to look at all soils together as a high plasticity soil will have a lower permeability if fissures and coarser lenses are disregarded. Normalising by plasticity index makes a change in water content become a change in liquidity index. Figure 6.14 shows change in liquidity index against normalised percentage of sub 63 μm and Figure 6.15 shows change in liquidity index against number of lumps. From Figure 6.14 it can be seen that an increase in the liquidity index of the mixed material corresponds to an overall increase in the percentage of sub 63 μm particles in the slurry. This is not necessarily related to mixing time, but a function of each individual soil sample; its structure and local permeability.

As discussed in Section 6.2, disaggregation into many lumps larger than 4.75mm did not appear to affect the rate of soil wetting, as there is a smaller change in liquidity index when there are more lumps larger than 4.75mm, as seen in Figure 6.12. This is contrary to the comment that as more lumps are produced there is an increase in surface area, leading to an increase in the water content. The permeability of the soil should be very similar for each mixing test on a given soil type. This is because the soil comes from one bulk sample, which should be fairly homogeneous if any small local silt/sand lenses that may be present are excluded. An explanation for the smaller increase in liquidity indices could be attributed to the differences between the surface area of cut soil and the surface area produced by the breaking of lumps along discontinuities. The cutting of the soil will produce local surface shear stresses where local suctions might be produced and also some surface drying. The breaking along discontinuities however could be assumed to have a far smaller effect on the change in pore water pressures and would have been in a wet environment. The surface area produced by breakages would be proportionally larger as the number of lumps increased but the rate of surface wetting was reduced. This is an area that requires more investigation by future researchers and/or once a larger field of data has been collected from a broader spectrum of soil types.

6.4.2 Effect of Clay Content

In addition to determining the clay content of the fully dispersed soils, the grading of the sub 63 µm fraction left in the slurry was determined in a limited number of mixing tests for each of the four series two soils. This measures the silt and clay fraction that was disaggregated during the mixing test, which can be compared to the available silt and clay fractions from the fully dispersed particle size analyses. In total six sedimentation tests were completed, all showed a reduced percentage of clay sized particles in the disaggregated sub 63 µm fraction compared to the percentage clay in the fully dispersed soil (see Figures 5.5-5.8). In the London Clay and Fleetwood silt slurries there was less than 0.5% dispersed clay.

Significant clay size fractions were recorded for both the Speswhite Kaolin and the Upper Mottled Bed slurries. For Speswhite Kaolin a 10 and 60 minute mixing test were sized down to the clay fraction with 11.5% and 20.2% recorded respectively and the Upper Mottled Bed test mixed for 30 minutes contained 9.7% clay. Hence, the four soils can be divided into clay and non-clay dispersing and this phenomenon compared to the overall disaggregation of the soil.

Although there is no obvious link between the fully dispersed clay fraction of the soils and the proportion of sub 63 µm particles in the slurry, there is a link between the proportion of sub 63 µm particles and the percentage of clay particles generated during the mixing tests (see Figures 5.5-5.8). Both the London Clay and Fleetwood Silt samples showed the lowest amounts of disaggregation of sub 63 µm particles, a maximum of 34.5% and very low percentages of clay in the sub 63 µm fraction, less than 1%. The Upper Mottled Bed clays and Speswhite Kaolin disaggregated into significantly greater percentages of sub 63 µm particles, up to 69.9% and higher percentage clay in the sub 63 µm fraction, as much as 20.18%. This can be best seen in Figure 6.13 for three 30 minute mixing tests. The comparatively similar fully dispersed particle size distributions of the London Clay and Upper Mottled Beds produce significantly differing amounts of dispersed clay sized fraction after the mixing test. This link could be attributed to the amount of natural cementing and bonding within the soil samples. It is known that the Speswhite Kaolin sample has no cementing due to its manufactured state, it is also known that Kaolinite has a weak surface electro bonding, when compared to other clay minerals (Çelik, 2004). This will enable clay sized particles to disperse, although it is clear that many clay particles are still breaking away as aggregates. Upper Mottled Beds were laid down in a marine environment, which would result in a flocculated structure and the potential for cementing to occur. However, due to erosion causing over-consolidation of the soil, cementing can be broken down due to stress relief and swelling of the soil. This is often most evident at the surface of the clay unit (Entwisle *et al,* 2013), where this sample was taken from.

As discussed above, both the Speswhite Kaolin and Upper Mottled Beds samples displayed the greatest amount of disaggregation of sub 63 µm sized particles during the mixing tests. The increase in sub 63 µm sized particles can clearly be linked to the clay bonding, with the amount of disaggregated clay sized particles seen to increase dramatically compared to the London Clay and Fleetwood silts. This is down to cementing of clay and silt sized particles creating larger aggregates within these two soils and reducing the permeability between the clay particles. Although there will be some particle attraction forces helping to hold the clay sized particles together, this can be partially ruled out due to the similar mineralogy of the London Clay and Upper Mottled beds when comparing data shown in Table 5.15 and confirmed with data for London Clay in Gasparre (2005) and Upper Mottled Beds (Entwisle *et al,* 2013).

6.4.3 Effect of Mineralogy, Chemical and Microscope Analysis

The mineralogy data from the XRD tests is shown in Table 5.15 and the results of the chemical analysis carried out using XRF are presented in Figure 5.15. The main purpose of these tests was to clarify the composition of the soils tested and gain a greater understanding of the reasons underlying the variation in soil disaggregation rates. In addition to the XRD and XRF tests samples of cut clay were observed under an optical microscope, at magnifications of 500, 2000 and 4000, see section 5.4.7. The XRD data shows that the London Clay and Upper Mottled Bed samples have similar proportions of Illite, Smectite and Kaolinite, with the Upper Mottled Beds having 4% Smectite, which has the largest swelling potential. However, this is bound in Illite-Smectite interlayering which has a lower overall swelling potential than Smectite on its own (Chabrillat & Goetz, 2006). The main difference between the two clays was the amount of calcium oxide, a key cementing mineral. The London Clay sample contained 1.85% compared with 0.45% in the Upper Mottled Beds sample (Figure 5.15). This significant concentration of calcium oxide coupled with the minimal clay sized particles dispersed during the mixing tests shows that cementing has occurred between the clay platelets in the London clay.

The Fleetwood Silt sample has a predominately Illite mineralogy confirming that it does not have a highly dispersive nature. The amount of inter particle cementing has proved to be a key factor predicting the rate of disaggregation and 5.23% calcium oxide was identified from the XRF test. This is considerably more than that found within both the Upper Mottled Beds and London Clay and the low magnitudes of disaggregation of sub 63 μm particles can partially be attributed to this cementing. Interestingly, the photographs taken through a microscope for the Fleetwood Silts (Figure 5.22-24) also show a reduced number of open pores when compared to the microscopic analysis of the London Clay and Upper Mottled Bed samples (Figures 5.16-21). These open pores originate from the method of deposition and processes imposed on the soil since deposition.

The Fleetwood Silts display a wider grading curve, when compared to the London Clay and Upper Mottled Beds, this will effect the overall permeability of the soil. The local permeability on a micro scale may be more varied in the two clay soils. As described above a larger number of small voids between clay peds were identified in the magnified images of the London Clay and Upper Mottled Beds. This would allow water to penetrate quickly between the clay peds at the cutting boundary, reducing the local soil strength and allowing for easy removal due to erosion. This is particularly evident in the Upper Mottled Beds, which can be seen to have the largest number of voids between the peds of clay. Together with the low level of cementing in the Upper Mottled Beds this would explain why the cuttings disaggregated quicker and why a significant amount of clay sized particles disaggregated.

Surprisingly the Speswhite Kaolin has notable quantities of both Illite and Illite/Smectite with 14% and 12% respectively and this variation in clay mineralogy may be why a surprising amount of clay aggregates were disaggregated during the mixing test, rather than individual clay platelets. This is because during consolidation, Van der Waals attraction forces are available, with the Illite and Illite/Smectite having a larger net charge to bond with other clay particles.

The XRD, XRF and microscope analysis provide significant additional information which helps to explain why the soils tested disaggregate at varying rates. This demonstrates the importance of considering both the micro and macro structure particularly where permeability is likely to be critical together with inter-particle bonding at very low effective stresses. However, measurements of the percentage of disaggregated clay, and changes in water content related to plasticity indices also help to build a picture of the key mechanisms that are taking place in the slurry and allow contractors to build a more detailed picture of the likelihood of a soil disaggregating into sub 63 μm particles.

6.5 The Effect of Adding a Polymer to the Slurry

The use of polymer based slurries is still a new and relatively untested concept within pipe jacking and tunnelling. The four tests using KB International Ltd Hydrocut were carried out on both Speswhite Kaolin and London Clay. The concentration was varied between 0.15 and 0.0375% and all mixing tests were carried out for 10 minutes. The data sheet for HydroCut can be seen in Appendix B and it is described in Section 4.5.4, it is a partially hydrolysed polyacrylamide, with the aim of encapsulating the lumps with polymer to prevent breakdown.

In all four tests as presented in Section 5.3.4, the presence of the HydroCut almost eliminated material passing through the 63 μm sieve, which can be seen in Tables 5.9 and 5.10. However, at the recommended concentration of 0.15% the polymer also prevented the slurry passing through the sieve, by blinding the screen. With the lower concentrations the slurry did eventually make it through but extremely slowly, as mentioned in section 5.3.4 it took approximately 30 minutes for the slurry to pass through the 63 μm sieve and up to 5 minutes for the 600 μm sieve. Due to this significant increase in viscosity, future work is required by contractors to analyse the ability of site-specific dewatering screens and hydrocyclones to separate and dewater the arisings between 4.75 mm and 63 μm when using slurry with a polyacrylamide additive. This is not easily replicated in the laboratory and a contractor will require reassurance that the plant can produce arisings with a water content suitable for transportation off site.

The amount of material retained on the 4.75 mm screen only increased in the tests on Speswhite Kaolin with a concentration of 0.0375% polyacrylamide slurry. In the other three tests there was very little difference between the amount of plus 4.75 mm material in the HydroCut tests and the corresponding sizes in the distilled water tests, as shown in Figures 5.10 and 5.11. This demonstrates that the theory proposed by Gillies (1991), which suggests bentonite slurry reduced the amount of disaggregation by providing a cushioning effect to the cuttings, does not apply to HydroCut. It also demonstrates that the encapsulation theory often quoted by manufacturers does not prevent material breaking away from the boundaries of the cuttings. Instead it was the grading between 4.75 mm and 63 μm that altered when the HydroCut was added to the mixing tests.

For the Speswhite Kaolin mixing tests with HydroCut, some material was retained on both the 1.18 and 0.6 mm screens. Between 1.2 and 4.5 % material was retained on the 1.18 mm screen and 0.5 to 11% on the 0.6 mm screen (see Figure 5.10). In both cases the material retained is fairly small, however this a significant increase compared to the approximately 0.1% retained on these screen sizes when using distilled water.

The London clay mixing tests using HydroCut yielded a similar trend for the particle sizes between 63 μm and 4.75 mm. However, slightly higher amounts of disaggregation were seen in the London Clay (see Figure 5.11). With 15.2 and 21.1% for London Clay compared 5.7 and 13.0% for Speswhite Kaolin. In the London Clay tests there was again a significant increase in soil retained on the 0.063, 0.6 and 1.18

mm screens, the proportion of the total sample retained on each sieve ranged between 2 and 15.6%, again a significant increase when compared to the distilled water mixing tests which across the same set of particle sizes only accumulated 0.6 to 1.0% of the sample.

Both soil types displayed similar breakdown behaviours such that there were no sub 63 µm particles present in the slurry after it had been through the 63 µm sieve. For three of the four mixing tests using HydroCut the amount of material larger than 4.75 mm was similar to that when using distilled water. The mixing test using the smaller concentration of HydroCut (0.0375%) did show a reduction in material passing through the 4.75 mm sieve, which is unexplained because it had a lower viscosity and significantly lower concentration than that recommended by the manufacturer.

The material retained on the on the sub 4.75 mm screens was rounded aggregates with a floc like structure. This would be expected as partially hydrolysed polyacrylamide is a flocculant. Due to the flocculated structure, it can be assumed that these aggregates formed from silt sized particles and aggregates, with a similar size to the sub 63 µm grading found from testing with distilled water. Figure 6.16 shows an example of the material retained on the 1.18 mm sieve from the London Clay 10 minute mixing test using a 0.15% HydroCut slurry. This shows rounded aggregates of varying sizes between 1.18 mm and approximately 3 mm. It appears that small flocs were formed and the mixing gathered multiple flocs together, creating large flocs. The flocs are rounded because they are soft and are being mixed in suspension in a highly viscous environment.

The water content of the material retained on the 4.75 mm was greater than the equivalent tests using distilled water for all of the HydroCut mixing tests. The increase in water content observed varied from 7 to 10%. This can be attributed to the polymer sticking to the surface of the clay cuttings in a thick surface layer. The increase in water content may reduce with mechanical shaking, however this was not tested and could be something for future work.

The HydroCut did not reduce the internal water content of the Speswhite Kaolin crumb tests detailed in Section 4.8. In the results given in Table 5.11 both the distilled water and HydroCut tests display the same increase in water content for the middle portion of the cored samples, an area that is not in contact with the surrounding water in the beaker.

6.6 Site Collected Samples

Both slurry samples and tunnel boring machine cuttings were collected from a pipe jacking site in Clapham, London. Section 5.6 outlines the findings seen on site, with very little clay sized fraction found in the slurry from the tunnel boring machine. Figure 6.17 shows the grading of the soil found in slurry samples that had passed through the primary screen, along with the sub 4.75 mm grading curves for two London clay mixing tests. Although, the mixing test grading curves and the site collected data do not have a close fit in the range 0.006-0.2 mm, they do have similar percentages of clay sized particles. In the two sets of sedimentation tests similar percentages of suspended clay and material between 63 μm and 4.75 mm were measured. The site samples having 0.6 to 8.4% disaggregated clay and mixing tests 0.8 to 1.9%, in both these cases the amount of clay is relatively insignificant compared to the 50 to 60% that is available to disaggregate. This indicates that the mixing tests are applying similar shear and wetting to the cuttings as occurs in the field particularly with respect to the disaggregation of finer particles.

In both the site data and mixing tests there were similar proportions of 63 μm and 4.75 mm sized particles, with all the tests producing between 5 and 10 % material within this size range. However, this material was mainly seen to be a mixture of both fine sand particles and fine sand sized aggregates, with virtually no material larger than 0.6 mm. In the equivalent mixing tests 73 to 76% by weight of the material was removed by the 4.75 mm screen. From this it can be assumed that the lumps are breaking at weaknesses within the cuttings and then eroding away from the outside as the cuttings are mixed. A similar assessment can be made with the site data when looking at the material coming off the clay ball belt, seen in Figure 6.18.

Comparing the two images in Figure 6.18 it can be seen that the shape, size and rounding of the lumps greater than 4.75mm in size formed from the cuttings is similar to those seen from the mixing test. This also shows that there are two mechanisms of disaggregation. The breaking of cuttings and erosion around the outside removing mainly silt sized particles, with increasing sand sized particles as the sand content increases in the fully dispersed grading.

The comparison of the site and laboratory data is limited, due to the lack of access to site works. It does however indicate that the mechanisms for disaggregation are the same in both the mixing test and site data.

6.7 Summary

A large database of soil mixing test results and soil properties have been gathered and displayed within both in this chapter and Chapter 5. From the data a clearer insight into the causes of the disaggregation of soils have been discovered. Firstly, mixing time has an effect on the amount of disaggregation that occurs, however it can be seen that the pattern of the change in disaggregation with time is unique for a given soil and dependent on details of the soil properties. This can be seen particularly where soil in mixing tests of shorter durations apparently breaks down more than soil in longer tests on the same soil type.

It is thought that the dominant factor determining the rate of disaggregation is the level of micro or particle scale cementing, this was evident in the London Clay and Fleetwood silts, where little or no clay sized material ended up in the slurry, demonstrating that clay particle bonds were present. Calcium oxide was found in both soils in the XRF tests, confirming the presence of a potential source of cement. In addition, there was significantly less disaggregation of sub 63 µm particles than in the samples of Upper Mottled Beds and Speswhite Kaolin, which also produced more clay sized particles (9.7-20.2%).

The link between the disaggregation of clay sized particles and sub 63 µm particles appears to be key to predicting the volume of sub 63 µm particles that will disaggregate in a slurry. Therefore, it is recommended that repeat tests at one mixing time, 10 minutes would be suitable, be carried out, with particle sizing down to 2 µm.. Although carrying out mixing tests which include sedimentation testing requires more time and careful planning, it can be seen that understanding what is happening to the clay sized fraction is important. Clay mineralogy was not seen to have a large effect within the soils tested in this dissertation, however this could a contributing factor if the concentration of Smectite increased.

The other factor that appears to be important is the soil matrix resulting from depositional effects, including the formation of clay/silt peds separated by micro voids. As the number of these voids increases, the rate of disaggregation also increases because the water can permeate around the clay peds or aggregates. This is may not necessarily be picked up by looking at the bulk permeability of the soil.

Confirming the importance of permeability to the disaggregation of sub 63 μm particles, for each soil the change in liquidity index between the *in situ* state of the soil to its post mixing test state increased with the magnitude of the sub 63 μm sized fraction. This is due to the softening and weakening of the exterior of the cuttings. It was unexpected that as the number of lumps greater than 4.75 mm increased, the increase in liquidity index was lower than in mixing tests that produced fewer lumps greater than 4.75 mm. This was unexpected due to the increase in surface area that is exposed to the water when the cuttings break into lumps. However, this can be explained by the zero effective stress along the edges of breakages where there were existing discontinuities. This area would have had very little sucton from negative pore water pressures when compared to the edges that were cut.

The effect of using polymer slurries was the subject of a preliminary study in order to assess previous claims of a reduction in disaggregation. There was no change in the number of lumps greater than 4.75 mm removed from the slurry. However, less than 1% of the solids passed through the 63 μm sieve.

To partially evaluate the success of the mixing test in simulating disaggregation in pipe jack slurries in the field, slurry and cuttings from the primary screen were collected from a pipe jacking site in Clapham, London where a contractor was tunnelling through London Clay. The grading of the sub 4.75 mm site slurry was similar to the mixing test results. It was not possible to grade the plus 4.75mm cuttings, but similarities in size and shape to the mixing test plus 4.75mm lumps were noted.

7.0 Conclusion and Further Work

7.1 Introduction

The aim of the research project was to gain a greater understanding of the mechanisms that contribute to the rate of disaggregation of soils in slurries and in particular the disaggregation of sub 63 µm sized particles. Given this greater understanding, the aim was to predict the amount that a soil will breakdown. The understanding of which is key for pipe jacking contractors in order to specify the correct separation plant required for slurry tunnelling drives.

The work presented looks at the development of a mixing test to simulate the pumping of tunnel arisings in slurry. The mixing test was performed using three soil types initially and then developed further with four soil samples (Speswhite Kaolin being common to both test series). The mixing test was also performed using a polymer based slurry to quantify the effect of varying the slurry type. To determine why a variation in breakdown occurs and to characterise the tested soils, a range of soil property tests were also completed. The individual tests are detailed in Section 4.8.

In this chapter all of the key test results are summarised and conclusions drawn from the data available. Areas requiring further work are identified that would build on the work presented within this dissertation.

7.2 Conclusions

From the large number of findings discussed in Chapter 5, these conclusions will focus on those outcomes that solely affect the pipe jacking industry, as they have the largest practical application to the sponsors of the research. In this section the design and use of a mixing test to predict the rate of disaggregation will be summarised, linking the amount of breakdown to known soil properties.

- The amount of cementing between clay and silt sized particles is key in understanding the potential for a soil to disaggregate. It was seen that as the quantity of the clay sized fraction increased in the mixing test so did the overall levels of sub 63 µm disaggregation. An indication of the level of cementing can be obtained by using sedimentation to size the sub 63 µm fraction from the mixing test or/and by carrying out chemical XRF tests on soil samples to identify cementing minerals.

- The way a soil is deposited and the natural processes that have occurred since deposition have a significant effect on the potential for disaggregation. This was seen with the large number of micro voids between clay peds in the Upper Mottled Beds. These voids allow water infiltration at a local level and reduce the surface soil strength allowing for the clay peds or aggregates to be eroded. This results in an increase in clay size particles ending up in the slurry fluid when there is a weak level of cementation and is also evidenced by a greater increase in disaggregation with time spent in the slurry.
- The mixing test described in section 4.3.2 has been demonstrated throughout this dissertation to be a means of understanding the rate of disaggregation for fine grained soils during slurry tunnelling. The use of a planetary mixer enables relatively quick, repeatable tests to be undertaken with a variety of soils, mixing times and slurry fluids.
- The speed of the paddle and hence the velocity of the slurry was seen to effect the amount of disaggregation significantly. The increase in paddle speed to speed 2 was equivalent to increasing the mixing time by 5 minutes. This indicates the need to consider the hydraulic design of the transport system; pipes, pumps and slurry to minimise flow velocities, whilst still enabling tunnel cuttings to be transported in suspension. This could be assisted by an increase in slurry carrying capacity, provided the slurry and solids can still be separated, see above point.
- From the large base of mixing tests carried out, it is recommended that contractors specify mixing tests of samples of soil at the tunnel horizon prior to construction. A full range of mixing times are not necessary, however it is recommended that 10 and 30 minute mixing tests are carried out to give an understanding of how time affects a particular soils breakdown. Two tests at each mixing time are advisable to allow for any natural variation in soil, such as fabric and discontinuities.

- The sizing of the soil after mixing should be carried out according to the method in section 4.3.2. The sizing of the sub 63 μm fraction should also be carried out, as it will give an indication of the likelihood of disaggregation. It will also help the contractor understand the potential fraction that may be removed using the hydrocyclones and secondary shaker screen.
- The use of Hydrocut CF (partially hydrolysed polyacrylamide) almost eliminated any soil particles passing through the 63 μm sieve. It did not however increase the amount of soil retained on the 4.75 mm sieve. The time it took the slurry to pass through the 600 and 63 μm sieves increased from seconds or tens of seconds to several minutes.

The conclusions listed above demonstrate both the applicability of the mixing test in predicting the likelihood of disaggregation and also how it provides an understanding of the amount a soil might disaggregate by the comparison to different mixing tests results. The use of chemical testing to predict the bonding of clay and silt sized particles was also helpful in giving an indication of the likelihood of a soil disaggregating. There is however further work that should be carried out to back up the findings and suggestions reported in this dissertation, which are detailed in section 7.5.

7.3 Recommendations

From the research it can be recommended that the mixing test be carried out prior to the specification of the separation plant on the anticipated soils at the tunnel horizon. As concluded above, two mixing times of 10 and 30 minutes should be used and each time repeated. This is to reduce any uncertainty in how the cuttings disaggregate. For the majority of UK contractors to estimate the required sized decanting centrifuge the results can then be compared to the London Clay test data displayed in Figure 5.6 and their previous works carried out in London Clay. If a contractor has no experience within London Clay, a baseline test using a soil sample where they have significant experience should be used.

Along with testing prior to plant specification, notes should be taken on apparent percentage splits of arisings across the three stages of separation. This should be compared with the mixing test after a tunnel drive and a database of soil types, separation plant and mixing test results kept for future plant specification.

7.4 Limitations of Results and Implications

The mixing test has been designed to simulate the rates and mechanisms of disaggregation, it is however limited by the planetary motion of the mixer which does not directly simulate the more linear flow that would occur within a slurry transportation pipe. However, results displayed in section 5.6 show a good correlation between the sizes of soil particles found in slurry from a pipe jacking tunnel drive and those from a similar soil used in a series of mixing tests.

The conclusions detailed within this dissertation are also based on findings found from four different fine grained soils. The soils were chosen as they display a range of properties, however a larger range of soil may aid in linking soil properties that affect the rate of disaggregation.

The tests are also limited to the use of distilled water and HydroCut CF for the all of the mixing tests carried out. This was to eliminate any variability due to water chemistry. It is however understood that the chemistry of the water used as the slurry base on site will vary considerably between sites and this may have an effect on the potential for disaggregation. Where possible water from the proposed site water source should be used alongside distilled water, to allow for a comparison to previous results.

7.5 Recommendations for Further Work

Although a comprehensive study was performed and documented within this dissertation, there are still areas that would benefit from further research. This is inherent with most research, especially when studying problems for the first time. The recommended further work has sections that would be best carried out within a research environment and other parts by best carried out by contractors with results compiled by the Pipe Jacking Association.

Four soil types were studied using the mixing test procedure described in section 4.3.2, although these soils had varying soils properties a wider selection of soil types would allow pipe jacking contractors a wider database for comparison when tendering or specifying separation plant for a slurry pipe jack. A database on this scale would be best compiled for the United Kingdom by the Pipe Jacking Association, with member contractors undertaking mixing tests for each slurry pipe jack in fine grained soils or weak rocks. This could be accompanied by post construction remarks on the separation plant used and its appropriateness when compared to the mixing test results. Care would be required not to remove any competitive edge for contractors and would be something the Pipe Jacking Association would need to manage.

Slurry samples were collected from one pipe jacking construction site at the start of a tunnel drive. However, to further validate the mixing test results it would be beneficial for more inline slurry sampling and particle sizing to take place. This could include sampling as close to the tunnel face as possible to characterise the size and shape of cuttings using various cutter head configurations and soil types. Sampling prior to the slurry reaching the separation plant would also give a greater understanding of the effect that time within the slurry has on disaggregation. If carried out through the duration of the drive, a time profile for the change in rate of disaggregation could be plotted. Care will need to be taken when designing the sampling and test procedure so that the analysis of the results accounts for changes in geology through the tunnel drive.

One of the conclusions was that a reduction in disaggregation was seen as the number of lumps larger than 4.75 mm increased. One of the supporting theories for this was that as this size fraction of cuttings broke up, the decrease in individual cutting size allowed for cuttings to be lifted off the bottom of the bowl and be mixed in suspension. Further work could be carried out to analyse the lump size that will remain in suspension during mixing. This could be carried out both experimentally and also using computational fluid dynamics.

An idea that was postulated for causing a reduction in the increase in water content due to an increased number of lumps larger than 4.75 mm, was due to the permeability and effective stresses at the boundaries of the cuttings. To validate this theory fully some method of laboratory testing could be carried out to analyse how the local permeability varies within a lump of soil, both cut/trimmed to produce clean faces and also broken along discontinuities within the lumps.

Limited work was carried out using one type of partially hydrolysed polyacrylamide with some positive but also negative effects, detailed in section 6.5. More work should be carried out to look at various manufactured drilling polymers to gain an understanding of variation within the market. In addition, more work is required to confirm the applicability of these polymers for use in slurries where solids have to be separated by screens. It will have to be confirmed that the arisings removed from the slurry are both stable and disposable within the waste regulations current in the United Kingdom. If confirmed, there may be no need for clay and silt sized separation plant.

References

AL-TABBAA, A. (1987) *Permeability and stress-strain response of Speswhite Kaolin,* PhD Thesis, University of Cambridge

ASTM (2008) *Standard test method for slake durability of shales and similar weak rocks,* ASTM D4644-08, ASTM Pennsylvania

ASTM (2009) *Standard Test Method for Methylene Blue Index of Clay*, ASTM C837-09, Vol. 15.02, ASTM, Pennsylvania

ASTM (2006). *Standard Test Method for Determining Dispersive Characteristics of Clayey Soils by the Crumb Test*, ASTM D6572 Vol. 04.08, ASTM , Pennsylvania

ASTM (2011) *Standard test method for dispersive characteristics of clay soil by double hydrometer*. ASTM D4221-11, Vol 04.08, ASTM, Pennsylvania

AZIZI, F. (2007), *Engineering Design in Geotechnics,* Self Published

BOHLIN REOLOGI AG, (NO DATE), *Technical manual for the Bohlin Visco 88 BV,* Bohlin Reologi, Lund , Sweden (accessed on the 10/11/14)

BS1377-1;1990 (1996) *Methods of test for soils for civil engineering purposes- Part 1 General requirements and sample preparation*, BSi, London, UK

BS1377-2;1990 (1996) *Methods of test for soils for civil engineering purposes- Part 2 Classification tests*, BSi, London, UK

BS1377-7;1990 (1996) *Methods of test for soils for civil engineering purposes- Part 7 Shear strength tests (Total strength)*, BSi, London, UK

ÇELIK, M.S. (2004) *Electrokinetic Behaviour of Clay Surfaces,* Interface Science and Technology, Vol.1, PP. 58-59

CHABRILLAT, S. AND GOETZ, A.F.H., (2006) *Chapter 15, Remote sensing of expansive soils, Use of hyperspectral methodology for clay mapping and hazard assessment, Expansive Soils: Recent Advances in Characterization and Treatment* Edited By, Al-Rawas, A.A. AND Goosen, M.F.A, Taylor & Francis, London

CHESTERTON, A.K.S. MOGGRIDGE, G.D. SADD, P.A. AND WILSON, D.I. (2011) *Modelling of shear rate distribution in two planetary mixers for studying development of cake batter structure,* Journal of Food Engineering, Vol. 105, Iss. 2, PP. 343-350

CIRIA, (2004) *Engineering in the Lambeth Group,* Report No. C583, CIRIA, London

CLARK, R.K. SCHEUERMAN, R.K. RATH, H. AND VAN LAAR, H. (1976) *Polyacrylamide-Potassium Chloride Mud for Water Sensitive Shale,* Journal of Petroleum Technologies, Vol. 261, PP. 719-727

CLAYTON, C.R.I. SIMONS, N.E. AND MATTHEWS, M.C. (1995) *Site investigation, A handbook for engineers,* 2nd Edition, Wiley-Blackwell, Oxford

CRAFT, D.C AND ACCIARDI, R.G. (1984) *Failure of pore water analysis for dispersion,* Proceedings of the American Society of Civil Engineers, Journal of Geotechnical Engineering Division, Vol. 110, Issue 4, PP 459-472

DARLEY, H.C.H. (1969) *A laboratory investigation of borehole stability,* Journal of Petroleum Technology, Vol. 21, No. 7, PP. 883-892

DARLEY, H.C.H. AND GRAY, G.R. (1988) *Composition and Properties of Drilling and Completion Fluids*, Gulf Professional Publishing, Housten

DR. SAUER & PARTNERS LTD, 2014, Private document

ENTWISLE, D.C, HOBBS, P.R.N, NORTHMORE, K.J, SKIPPER J, RAINES M.R, SELF, S.J, ELLISON, R.A. AND JONES, L.D. (2013) *Engineering Geology of British Rocks and Soils - Lambeth Group,* British Geological Survey, Nottingham

ESHEL, G. LEVY, G.J. MINGELGRIN, U. AND SINGER, M.J. (2004) *Critical Evaluation of the Use of Laser Diffraction for Particle-Size Distribution Analysis,* Soil Science Society of America Journal, Vol. 68, No. 3, PP 736-743

EMERSON, W.W. (1964) *A classification of soil aggregates based on their coherence in water,* Australian Journal of Soil research,

FANN, (2011) *PHPA Polymer Concentration Test Kit Instruction Manual Revision D,* Fann, Houston, USA

FANN, (2013) *Marsh funnel viscometer instructions Rev. B,* Fann, Houston, USA

FERRO, V. AND MIRABILE, S. (2009) *Comparing particle size distribution analysis by sedimentation and laser diffraction method,* Journal of Agricultural Engineering, Vol 2, PP 35-43

FITYUS, S.G., SMITH, D.W. AND JENNAR, A.M. (2000) *Surface area using methylene blue adsorption as a measure of soil expansivity,* Geo2000 conference, Australia

GASPARRE, A. (2005) *Advanced Laboratory Characterisation of London Clay,* PhD Thesis, Imperial College London, University of London

GERBER, A. AND HARMSE, H. J, von M. (1987) *Proposed procedure for identification of dispersive soils by chemical testing,* The Civil Engineer in South Africa, Vol. 29, Issue 10, PP, 397-399

GILLIES, R.G. (1991) *Chapter 12: Particle size degradation in slurries*, *Slurry Handling*, edited: BROWN, N.P. & HEYWOOD, N.I., Elsevier Applied Sciences, London

GONZÁLEZ, N. A., ROUAINIA, M., ARROYO, M. AND GENS, A. (2012) *Analysis of tunnel excavation in London Clay incorporating soil structure*, Geotechnique, Dec 2012, Vo. 62 No. 12, PP. 1095-1109

HIGHT, D.W., MCMILLAN, F., POWELL, J.J.M., JARDINE R.J. AND ALLENOU C.P. (2003). *Some characteristics of London Clay*. Proc. Conf. Characterisation and Engineering, National University Singapore. Balkema, Vol. 2, PP. 851-907.

JEFFERIS, S.A. (2015) *Private communication*

KING, C. (1981) *The stratigraphy of the London Clay and associated deposits.* Tertiary Research Special Paper No.6. Backhuys, Rotterdam

KING, C. (2008) *The London clay formation and Harwich formation of the London area, A practical guide to their identification, subdivision and logging,* Geological Workshop 2009, Tideway-Thames Tunnel

IMERYS (2008) *Speswhite,* 8th Edition, Imerys, Cornwall

LAM, C. AND JEFFERIS, S.A (2014) *The use of polymer solutions for deep excavations: lessons from Far Eastern experience,* HKIE Transactions, Vol. 21, Issue 4, PP. 262–271

LAM, C. MARTIN, P.J. JEFFERIS, S.A. and GOODHIL K.G. (2014) *Determination of Residuel Concentration of Active Polymer in a Polymetric Support Fluid,* Geotechnical Testing Journal, 2014, Vol. 21, NO 1, PP 46-59.

LIAO, W.A. AND SIEMS, D.R. (1990) *Absorption characteristics of PHPA on formation solids,* IADC/SPE Drilling conference, Houston, Texas, PP. 297-308

LITTLE, J.A., MUIR WOOD, D., PAUL, M.A. AND BOUAZAA, A. (1992) *Some laboratory measurements of permeability of Bothkennar clay in relation to soil fabric*, Geotechnique, June 1992, Vol.42, No. 2, PP. 355-361

LU, N. RISTOW, G.H. AND LIKOS, W.J. (2000) *The Accuracy of Hydrometer Analysis for Fine-Grained Clay Particles,* Geotechnical Testing Journal, 2000, VOL 23, NO 4, PP 487-495.

LYON, J. (n.d) *CETCO Europe Drilling Manual,* CETCO (Colloid Environmental Technologies Company) internal report

MAHARAJ, A. AND PAIGE-GREEN, P. (2013) *The SCS double hydrometer test in dispersive soil identification*, Proceedings of the 18th international conference on soil mechanics and geotechnical engineering, Paris, France, PP. 389-392

MAHARAJ, A. VAN ROOY, L. AND PAIGE-GREEN, P. (2015) *Revised test protocols for the identification of dispersive soils*, Journal of the South African Institute of Civil Engineering, Vol 57, No. 1, PP. 31-37

MITCHELL, J.K. (1993) *Fundamentals of oil behavior,* Second edition, John Wiley & Sons, Inc, New York

MESRI, G. AND OLSON, R.E. (1971) *Mechanisms Controlling the Permeability of Clay,* Clay and Clay Minerals, 1971, Vol. 19, PP. 151-158

O'BRIEN, D.E. AND CHENEVERT, M.E. (1973) *Stabilizing sensitive shales with inhibited, Potassium based drilling fluids,* Journal of Petroleum Engineers, VOL. 25, NO. 9, PP. 1089-1100

OSISANYA, S.O. AND CHENVERT, M.E. (1987) *Rigsite shale evaluation techniques for control of shale-related wellbore instability problems,* SPE/IADC Drilling Conference, New Orleans

PAGE, J.B. AND BAVEN, L.D. (1939) *Ionic size in relation to fixation of cations by colloidal clay,* Proceedings Soil Science Society of America

PHILLIPS, N.S. (2012) *The optimization of slurry separation within pipe jacking*, MSc Thesis, University of Leeds

POTTER, A.D. AND JEFFERIS, S.E (2005) *Management of process arisings from tunnels and other earthworks: A guide to regulatory compliance*, Pipe Jacking Association, London

RAUH, F., THURO, K. AND SPAUN, G. (2006) *The powder swelling test-advantages and limitations,* The 10th IAEG International Congress 2006, Nottingham, Paper 472

SAWHNEY, B.L. (1972) *Selective sorbtion and fixation of cations by clay minerals: A review,* Clays and clay minerals, VOL. 20, PP. 93-100

SEWARD, L. (2009) *The Effect of Continuous Flight Auger Pile Installation on the Soil-Pile Interface in the Mercia Mudstone Group*. PhD Thesis, City University, London.

SHERWOOD, P.T, (1967) *The mineralogy and phase equilibrium of Keuper Marl,* Quarterly Journal of Engineering Geology, Vol.1, PP. 47-55

SIU, C.S.Y. PITT. R. AND CLARK, S.E. (2008) *Errors associated with sampling and measurement of solids: Application to the evaluation of stormwater treatment devices*, 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK,

SKIPPER, J. (2016) *Private communication*

STANDING, J.R. AND BURLAND, J.B. (2005) *Investigating variations in tunnelling volume loss , a case study*, Proc. Int. Conf. Geotechnical Aspects of Underground Construction in Soft ground, Amsterdam, Balkema, PP. 305-311

TAN, T.S, PHOON, K.K, HIGHT, D.W. AND LEROUEIL, S. (2003) *Characterisation and Engineering Properties of Natural Soils,* Vol. 2, A.A. Balkema Publishers, Lisse

UMESH, T.S, DINESH, S.V. AND SIVAPULLAIAH, P.V. (2011) *Characterization of dispersive soils,* Material Sciences and Applications, Vol. 2, PP. 629-633

WARD, J.R. AND HARR, C.A. (1990) *Methods for Collection and Processing of Surface-Water and Bed-Material Samples; for Physical and Chemical Analyses,* [Open file report] No. 90-140, U.S. Geological Survey

WILSON, A.A. (1990) *Blackpool. Memoir for sheet E66,* British Geological Survey

WOOD, D.M. AND WROTH, C.P. (1978) *The use the cone penetrometer to determine the plastic limit of soils,* Ground Engineering, Vol 11, No. 3, PP. 37

WOODWARD, J. (2005) *An Introduction to Geotechnical Processes,* Spoon, Abingdon

Websites

BARLETT, J. (1999) *New Cross Bentonite TBM Trials,* New Civil Engineer (NCE), London, (http://www.newcivilengineer.com/new-cross-bentonite-tbm-trials/838907.fullarticle) (accessed on; 10/11/2012)

BRITISH GEOLOGICAL SURVEY (2009) *Mineral Planning Factsheet, Kaolin,* (http://www.bgs.ac.uk/mineralsUK/planning/mineralPlanningFactsheets.html) British Geological Survey (accessed on 5/4/2013)

BRITISH GEOLOGICAL SURVEY (2014) *BGS lexicon of named rock units-London clay formation,* http://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=LC (accessed on; 17/12/2014)

CROSSRAIL (2013) *Thames Tunnel, Plumbstead to North Woolwich* (www.crossrail.co.uk/construction/tunnelling/thames-tunnel-plumstead-to-north-woolwich/) Crossrail Ltd, London, (accessed on; 19/01/2015)

IMAGEJ (2015) *http://imagej.nih.gov/ij/* National Institutes of Health (downloaded 15/2/15)

MATEST (2015) *Slake durability equipment* (http://www.matest.com/en/Products/agregados-rocas/Macro-Category/OTHER-PRODUCTS-FOR-TESTS-ON-AGGREGATES-AND-ROCKS-/a130-slake-durability-apparatus-0) (accessed on; 7/1/16)

SASKATCHEWAN RESEARCH COUNCIL (2014) *Saskatchewan research council closed loop pipeline*, (http://blog.src.sk.ca/wp-content/uploads/2014/12/Shook-Gillies-17.jpg) (accessed of 8/1/16)

TABLES

Port	Slurry Error (%)	Solids error (%)	Compiled Errors (%)
1	2.02	0.61	2.11
2	2.65	0.18	2.66
3	0.81	0.13	0.82
4	1.06	0.15	1.07
5	1.60	0.23	1.62
6	1.10	0.06	1.10
7	1.35	0.11	1.36
8	1.01	0.21	1.03
9	1.72	0.22	1.73
0	2.60	0.24	2.61

Table 4.1 Variation in solids mass at each port from cone splitter

Item Associated with Error	Specific Item	Percentage Error	Typical Mass variation (±grams, unless stated)
Cone Splitter	Port 3	1.18	0.07
	Port 4	1.36	0.08
	Port 5	1.83	0.11
	Port 6	1.39	0.08
	port 7	1.60	0.10
	Port 8	1.33	0.08
Dry Material Retained on Sieve	4.75 mm	0.02	0.05
	1.18 mm	0.69	0.02
	0.6 mm	8.78	0.09
	0.063 mm	9.66	0.10
Water Content	Water Content	0.058	0.015 (%)

Table 4.2 Errors associated with the mixing test

Soil type	Test No.	Time (min)	Mass of soil (dry g)	Average water content (%)	Water content range (± %)	<63 µm (%) (fully dispersed)	Clay %	Water content of 4.75 mm sieve (%)	>4.75 mm (post mixing)(g)	< 63 µm (%) (post mixing)(g)	Material left in bowl (g)
Speswhite Kaolin	**S1 Sp 1, 1min (T1)**	1	390.52	42.8	0.3	100	77.2	49.8	72.5	1.3	N/A
Speswhite Kaolin	**S1 Sp 1, 1min (T2)**	1	395.20	44.1	0.1	100	77.2	50.2	79.8	10.2	N/A
Speswhite Kaolin	**S1 Sp 1, 2min (T1)**	2	381.50	42.9	1	100	77.2	52.6	70.8	21.0	N/A
Speswhite Kaolin	**S1 Sp 1, 2min (T2)**	2	389.10	43.0	1.6	100	77.2	51.9	52.8	24.5	8.25
Speswhite Kaolin	**S1 Sp 1, 5min (T1)**	5	394.90	44.2	*	100	77.2	58.2	34.3	50.7	9.43
Speswhite Kaolin	**S1 Sp 1, 5min (T2)**	5	391.60	43.9	0.9	100	77.2	56.7	25.1	54.2	6.99
Speswhite Kaolin	**S1 Sp 1, 10min (T1)**	10	382.10	43.3	2.7	100	77.2	58.7	7.0	81.2	12.97
Speswhite Kaolin	**S1 Sp 1, 10min (T2)**	10	400.40	44.2	0.8	100	77.2	**	1.4	94.1	9.72
Speswhite Kaolin	**S1 Sp 1, 10min (T3)**	10	398.70	44.4	1	100	77.2	72.4	4.1	89.0	7.49

Table 5.1 Speswhite Kaolin series one mixing test results

** Water content 112%, exceptionally high and not a believable result

Soil type	Test No.	Time (min)	Mass of soil (dry g)	Average water content (%)	Water content range (± %)	<63 µm (%) (fully dispersed)	Clay %	Water content of 4.75 mm sieve (%)	>4.75 mm (post mixing)(g)	< 63 µm (%) (post mixing)(g)	Material left in bowl (g)
London Clay Tottenham Court Rd	**S1 Sp 1 1min (T1)**	1	444.63	31.0	3.6	88.2	49.1	39.2	73.4	17.3	N/A
London Clay Tottenham Court Rd	**S1 Sp 1 2min (T1)**	2	430.72	31.7	2.2	88.2	49.1	39.6	56.5	33.5	11.24
London Clay Tottenham Court Rd	**S1 Sp 1 2min (T2)**	2	428.70	27.2	1.7	88.2	49.1	35.6	73.6	18.6	12.60
London Clay Tottenham Court Rd	**S1 Sp 1 2min (T3)**	2	437.76	32.4	6.3	88.2	49.1	39.5	66.5	27.7	1.61
London Clay Tottenham Court Rd	**S1 Sp 1 5min (T1)**	5	450.0	26.6	9.0	88.2	49.1	37.3	34.6	51.7	27.70
London Clay Tottenham Court Rd	**S1 Sp 1 10min (T1)**	10	426.63	29.8	8.4	88.2	49.1	44.6	17.7	64.5	26.27
London Clay Tottenham Court Rd	**S1 Sp 1 10min (T2)**	10	430.37	32.6	4.1	88.2	49.1	47.1	17.4	66.6	2.66
London Clay Tottenham Court Rd	**S1 Sp 1 15min (T1)**	15	421.01	28.5	1.2	88.2	49.1	49.4	19.4	66.2	7.00

Table 5.2 London Clay Tottenham Court Road series one mixing test results

Soil type	Test No.	Time (min)	Mass of soil (dry g)	Average water content (%)	Water content range (± %)	<63 µm (%) (fully dispersed)	Clay %	Water content of 4.75 mm sieve (%)	>4.75 mm (post mixing)(g)	< 63 µm (%) (post mixing)(g)	Material left in bowl (g)
Mercia Mudstone	**S1 Sp 1, 1min (T1)**	1	529.78	10.0	1.6	82.8	22.0	18.8	64.7	26.0	N/A
Mercia Mudstone	**S1 Sp 1, 2min (T1)**	2	509.58	10.6	1.7	82.8	22.0	21.5	52.5	36.1	N/A
Mercia Mudstone	**S1 Sp 1, 5min (T1)**	5	486.51	12.3	1	82.8	22.0	22.0	30.6	54.9	N/A
Mercia Mudstone	**S1 Sp 1, 10min (T1)**	10	498.67	15.5	1.7	82.8	22.0	71.9*	17.0	69.4	N/A

Table 5.3 Mercia mudstone series one mixing test results

Soil type	Test No.	Time (min)	Mass of soil (dry g)	Average water content (%)	Water content range (± %)	<63 µm (%) (fully dispersed)	Clay %	Water content of 4.75 mm sieve (%)	>4.75 mm (post mixing)(g)	< 63 µm (%) (post mixing)(g)	Material left in bowl (g)	Number Of lumps	Clay % after mixing
Speswhite Kaolin	**S2 Sp 1, 10min (T1)**	10	386.25	45.3	1.3	100	77.2	53.0	64.1	35.8	3.25	*	
Speswhite Kaolin	**S2 Sp 1, 10min (T2) (1/2)**	10	405.07	43.6	0.9	100	77.2	53.9	82.3	17.5	1.14	10	
Speswhite Kaolin	**S2 Sp 1, 10min (T3) (2/2)**	10	396.61	43.5	1.1	100	77.2	55.5	79.3	20.5	2.08	10	
Speswhite Kaolin	**S2 Sp 1, 10min (T4) (1/2)**	10	376.04	42.9	0.5	100	77.2	55.3	76.2	23.6	1.05	12	11.53
Speswhite Kaolin	**S2 Sp 1, 10min (T5) (2/2)**	10	387.77	43.1	0.4	100	77.2	56.8	78.5	21.4	0.95	12	
Speswhite Kaolin	**S2 Sp 1, 10min (T6)**	10	370.82	44.7	0.4	100	77.2	58.7	87.5	12.5	1.99	22	
Speswhite Kaolin	**S2 Sp 1, 15min (T1) (1/2)**	15	385.82	44.6	0.5	100	77.2	56.4	54.7	45.1	0.85	11	
Speswhite Kaolin	**S2 Sp 1, 15min (T2) (2/2)**	15	401.90	43.6	0.9	100	77.2	53.4	51.8	48.1	1.26	*	
Speswhite Kaolin	**S2 Sp 1, 30min (T1) (1/2)**	30	387.56	43.4	1.9	100	77.2	65.7	34.6	69.6	0.25	*	
Speswhite Kaolin	**S2 Sp 1, 30min (T2) (2/2)**	30	393.74	43.1	0.2	100	77.2	67.7	29.7	69.9	0.65	*	
Speswhite Kaolin	**S2 Sp 1, 60min (T1) (1/2)**	60	397.06	43.3	1.6	100	77.2	62.8	67.8	31.7	1.17	10	
Speswhite Kaolin	**S2 Sp 1, 60min (T2) (2/2)**	60	397.13	44.1	2.8	100	77.2	58.6	70.7	29.1	2.83	13	
Speswhite Kaolin	**S2 Sp 1, 60min (T3) (1/2)**	60	402.65	44.4	1.7	100	77.2	63.9	63.6	36.2	6.3	*	
Speswhite Kaolin	**S2 Sp 1, 60min (T4) (2/2)**	60	388.90	43.8	0	100	77.2	58.3	64.8	34.9	6.15	17	20.18

Table 5.4 Speswhite Kaolin series two mixing test results

*Missing results

Soil type	Test No.	Time (min)	Mass of soil (dry g)	Average water content (%)	Water content range (± %)	<63 µm (%) (fully dispersed)	Clay %	Water content of 4.75 mm sieve (%)	>4.75 mm (post mixing)(g)	< 63 µm (%) (post mixing)(g)	Material left in bowl (g)	Number of lumps	Clay % after mixing
London Clay Maida Vale	S2 Sp1 5 min (T1)	5	448.97	30.8	0.7	99	59.3	43.7	86.9	12.6	7.44	*	
London Clay Maida Vale	S2 Sp1 5 min (T2)	5	444.64	29.5	1.6	99	59.3	42.8	82.3	17.5	9.48	42	
London Clay Maida Vale	S2 Sp1 10 min (T1)	10	445.28	29.6	4.1	99	59.3	41.8	86.3	13.1	4.27	32	
London Clay Maida Vale	S2 Sp1 10 min (T2)	10	439.17	30.3	2.1	99	59.3	43.3	82.0	17.3	4.55	42	
London Clay Maida Vale	S2 Sp1 10 min (T3)	10	439.95	29.5	0.4	99	59.3	43.3	80.4	18.6	9.89	49	
London Clay Maida Vale	S2 Sp1 30 min (T1)	30	446.38	29.8	1.0	99	59.3	43.3	82.1	17.3	4.43	*	
London Clay Maida Vale	S2 Sp1 30 min (T2)	30	443.42	29.9	1.5	99	59.3	45.6	81.7	16.8	0.77	36	
London Clay Maida Vale	S2 Sp1 30 min (T3)	30	441.74	29.5	2.1	99	59.3	48.4	76.9	21.8	5.56	57	0.43
London Clay Maida Vale	S2 Sp1 60 min (T1)	60	434.38	30.3	1.2	99	59.3	49.5	84.9	14.0	1.11	23	
London Clay Maida Vale	S2 Sp1 60 min (T2)	60	445.75	30.6	0.5	99	59.3	52.8	76.1	22.4	4.07	40	
London Clay Maida Vale	S2 Sp1 60 min (T3)	60	447.65	28.9	1.1	99	59.3	52.1	65.9	30.9	7.11	41	
London Clay Maida Vale	S2 Sp1 60 min (T4)	60	439.05	29.5	0.7	99	59.3	49	73.1	24.4	7.37	85	0.21
London Clay Maida Vale	S2 Sp1 120 min (T1)	120	454.62	28.9	2.7	99	59.3	54.5	66.8	30.1	10.15	31	
London Clay Maida Vale	S2 Sp1 120 min (T2)	120	437.92	29.8	1.1	99	59.3	56.4	62.4	34.9	5.19	*	

Table 5.5 London Clay Maida vale series two mixing test results

*Missing results

Soil type	Test No.	Time (min)	Mass of soil (dry g)	Average water content (%)	Water content range (± %)	<63 µm (%) (fully dispersed)	Clay %	Water content of 4.75 mm sieve (%)	>4.75 mm (post mixing)(g)	< 63 µm (%) (post mixing)(g)	Material left in bowl (g)	Number of lumps	Clay % after mixing
Fleetwood Silts	S2 Sp1 5min	5	464.54	18.8	8.1	76.3	22.0	30.7	85.5	11.8	0.37	48	
Fleetwood Silts	S2 Sp1 10min (T1)	10	459.49	21.2	1.0	76.3	22.0	26.2	74.8	18.9	5.33	70	
Fleetwood Silts	S2 Sp1 10min (T2)	10	480.82	18.8	2.3	76.3	22.0	27.9	81.4	14.0	0.98	54	
Fleetwood Silts	S2 Sp1 30min	30	460.97	18.7	2.9	76.3	22.0	25.2	85.6	12.5	5.51	64	0.37
Fleetwood Silts	S2 Sp1 60min	60	441.42	24.0	1.9	76.3	22.0	32.9	79.4	15.5	3.93	68	

Table 5.6 Fleetwood Silts series two mixing test results

Soil type	Test No.	Time (min)	Mass of soil (dry g)	Average water content (%)	Water content range (± %)	<63 µm (%) (fully dispersed)	Clay %	Water content of 4.75 mm sieve (%)	>4.75 mm (post mixing)(g)	< 63 µm (%) (post mixing)(g)	Material left in bowl (g)	Number of lumps	Clay % after mixing
Upper Mottle Beds	S2 Sp1 5min (T1)	5	465.87	22.5	0.6	95.2	61.2	33.0	69.7	26.5	0.65	86	
Upper Mottle Beds	S2 Sp1 10min (T1)	10	476.18	21.6	0.3	95.2	61.2	33.0	56.2	38.7	0.23	62	
Upper Mottle Beds	S2 Sp1 30min (T1)	30	471.62	21.5	1.1	95.2	61.2	39.8	33.1	60.8	0.88	51	
Upper Mottle Beds	S2 Sp1 30min (T2)	30	479.28	20.9	1.6	95.2	61.2	31.8	61.5	28.4	6.91	96*	9.69
Upper Mottle Beds	S2 Sp1 60min (T1)	60	470.55	21.5	1.9	95.2	61.2	42.2	31.8	62.3	1.42	72	

Table 5.7 Upper Mottled Beds Farringdon station series two mixing test results

* Multiple aggregates of lumps, the figure could vary by ± 5 lumps

Soil type	Test No.	Time (min)	Mass of soil (dry g)	Average water content (%)	Water content range (± %)	<63 µm (%) (fully dispersed)	Clay %	Water content of 4.75 mm sieve (%)	>4.75 mm (post mixing)(g)	< 63 µm (%) (post mixing)(g)	Material left in bowl (g)	Number Of lumps
Speswhite Kaolin	S2 Sp 2, 5min (T1)	5	381.73	42.2	0.1	100	77.2	51.5	64.3	35.5	0.8	*
Speswhite Kaolin	S2 Sp 2, 5min (T2)	5	393.81	44.2	1.6	100	77.2	52.8	70.1	29.8	0.3	10
Speswhite Kaolin	S2 Sp 2, 5min (T3)	5	405.83	43.5	1.1	100	77.2	52.0	68.8	32.1	0.2	*
Speswhite Kaolin	S2 Sp 2, 10min (T1)	10	392.17	43.7	1.1	100	77.2	54.9	42.1	57.8	0.08	10
Speswhite Kaolin	S2 Sp 2, 10min (T2)	10	399.92	43.5	0.4	100	77.2	54.1	46.8	53.0	0.05	12
Speswhite Kaolin	S2 Sp 2, 10min (T3)	10	398.81	42.5	0.7	100	77.2	51.1	55	44.8	0.14	11
Speswhite Kaolin	S2 Sp 2, 10min (T4)	10	403.50	43.7	0.3	100	77.2	51.1	51.5	48.3	0.11	11

Table 5.8 Speswhite Kaolin Speed setting 2 mixing test results

*Results missing

Soil type	Test No.	Time (min)	Mass of soil (dry g)	Average water content (%)	Water content range (± %)	<63 µm (%) (fully dispersed)	Clay %	Water content of 4.75 mm sieve (%)	>4.75 mm (post mixing)(g)	< 63 µm (%) (post mixing)(g)	Material left in bowl (g)	Number of lumps
Speswhite Kaolin	S2 Sp 1, 10min (T6)	10	370.82	44.7	0.4	100	77.2	58.7	87.5	12.5	1.99	22
Speswhite Kaolin	S2 Sp 1, 10min (hydrocut 0.075%)	10	372.10	48.5	100	100	77.2	69.0	94.3	0.5	1.43	13
Speswhite Kaolin	S2 Sp 1, 10min (hydrocut 0.0375%)	10	365.43	46.0	100	100	77.2	68.6	87.0	0.2	5.88	15

Table 5.9 HydroCut mixing tests Speswhite Kaolin

Soil type	Test No.	Time (min)	Mass of soil (dry g)	Average water content (%)	Water content range (± %)	<63 µm (%) (fully dispersed)	Clay %	Water content of 4.75 mm sieve (%)	>4.75 mm (post mixing)(g)	< 63 µm (%) (post mixing)(g)	Material left in bowl (g)	Number of lumps
London Clay Maida Vale	**S2 Sp1 10 min (T1)**	10	445.28	29.6	4.1	99	59.3	41.8	86.3	13.1	4.27	32
London Clay Maida Vale	**S2 Sp1 10 min (T2)**	10	439.17	30.3	2.1	99	59.3	43.3	82.0	17.3	4.55	42
London Clay Maida Vale	**S2 Sp1 10 min (T3)**	10	439.95	29.5	0.4	99	59.3	43.3	80.4	18.6	9.89	49
London Clay Maida Vale	**10 min (Hydrocut 0.15%)**	10	433.13	29.0	0.6	99	59.3	50.4	84.9	0*	9.3	44
London Clay Maida Vale	**10 min (Hydrocut 0.075%)**	10	410.96	29.3	2	99	59.3	54	78.9	0.9	9.58	17

Table 5.10 HydroCut London Clay Maida Vale

*Limited slurry passed through 63 µm sieve, the slurry that did pass through had very limited solids within

Distilled Water			**Average**
Starting water content	47.9	45.7	46.8
Post Test			
Top	54.3		
Middle	52.3		
Bottom	52.3		

HydroCut 0.075%			**Average**
Starting water content	46.0	47.4	46.7
Post Test			
Top	54.5		
Middle	52.4		
Bottom	51.7		

Table 5.11 HydroCut crumb test

	Marsh Funnel (seconds)		
Concentratrion	**Test 1**	**Test 2**	**Test 3**
0.15	103	91	85
0.075	46	46	47
0.0375	49	51	50

Table 5.12 HydroCut marsh funnel viscosity

Soil type	**Liquid Limit (WC %)**	**Plastic Limit (thread method) (WC %)**	**Plastic Limit (Fall cone method) (WC %)**	**Average water content**	**Percentage clay (%)**	**Sub 63 µm (%)**	**Specific gravity**
Speswhite Kaolin	64	34	40	43.9	77.2	100	2.6
London Clay Tottenham Court Road	58	24	39	29.8	49.1	88.2	2.7
Mercia Mudstone	32	20	22	12.1	22.0	82.8	2.9
London Clay Maida Vale	77	30		29.7	59.3	99.0	2.8
Fleetwood Silts	27	16	19	20.3	26.5	76.7	2.7
Upper Mottled Beds	62	27	46	21.6	62.1	95.2	2.8

Table 5.13 Soil properties for soils tested

(missing London Clay plastic limit because the fall cone method failed to produce believable answers in multiple tests)

Test/Soil Type	Peak load (N)	H (mm)	A $(m^2)(10^{-3})$	V $(m^3)(10^{-5})$	ΔH (mm)	Ultimate stress (kN/m^2)	Water Content (%)
UMB Vertical	629	78.03	1.14	8.90	5.4	513	19.9
UMB Horizontal	803	76.49	1.13	8.63	1.1	701	20.4
Fleetwood 1	87	70.39	1.16	8.16	18.5	55	18.9
Fleetwood 2	109	78.91	1.14	8.98	14.8	78	16.5
Kaolin 1	81.5	81.5	1.11	9.04	7.3	67	47.5
Kaolin 2	92.5	80.17	1.11	8.9	6.6	76	47.5
London Clay	N/A	N/A	N/A	N/A	N/A	200**	24**

Table 5.14 Unconfined Compressive Strengths

** Data extracted from Gasparre (2005)

	Illite	Illite/Smectite (Smectite rich)	Chlorite	Kaolinite	
Upper Mottled Beds	18%	73%	0%	9%	40% illite in illite-smectite
London Clay Maida Vale	14%	80%	0%	6%	50% illite in illite-smectite
Fleetwood Silt	51%	0%	15%	14%	
Speswhite Kaolin	14%	12%	0%	73%	

Table 5.15 X-Ray diffraction results

FIGURES

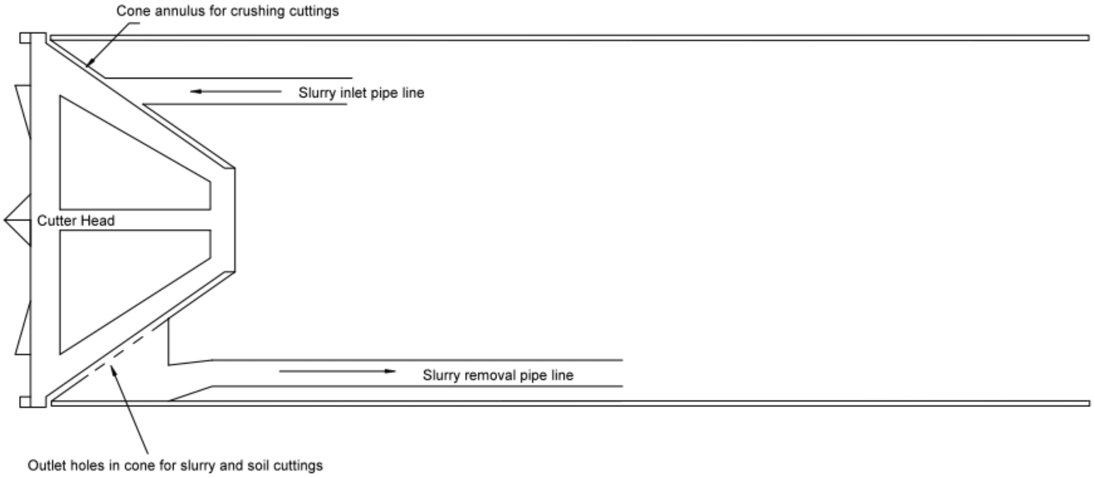


Figure 2.1 Diagram of a slurry tunnel boring machine

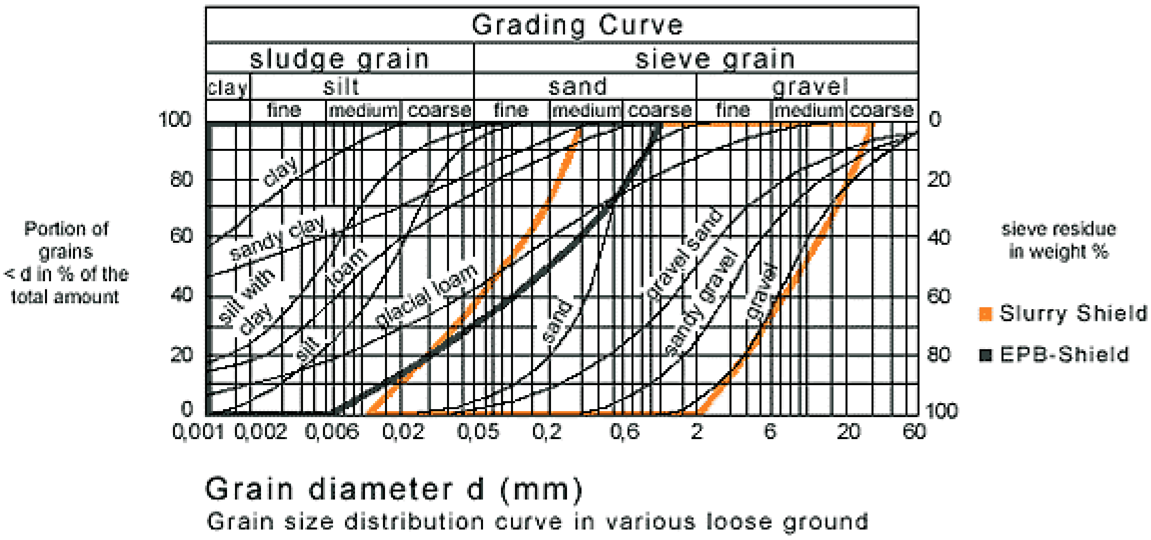


Figure 2.2 Grading curve for selection of Slurry and EPB shield tunnelling machines (Herrenknecht, 2010)

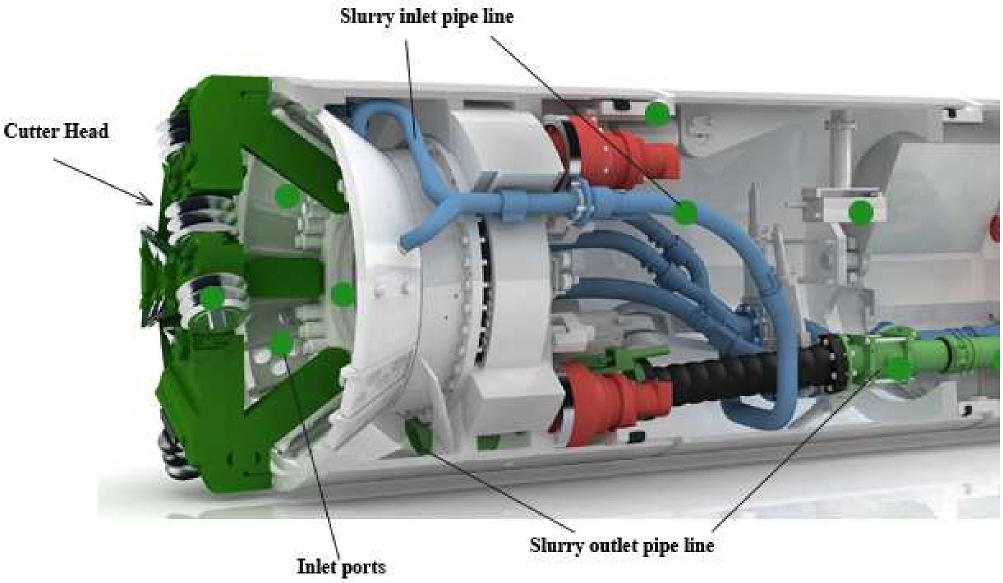


Figure 2.3 Schematic diagram of a Herrenknecht AVN slurry pipe jacking tunnel boring machine (Herrenknecht, 2013)

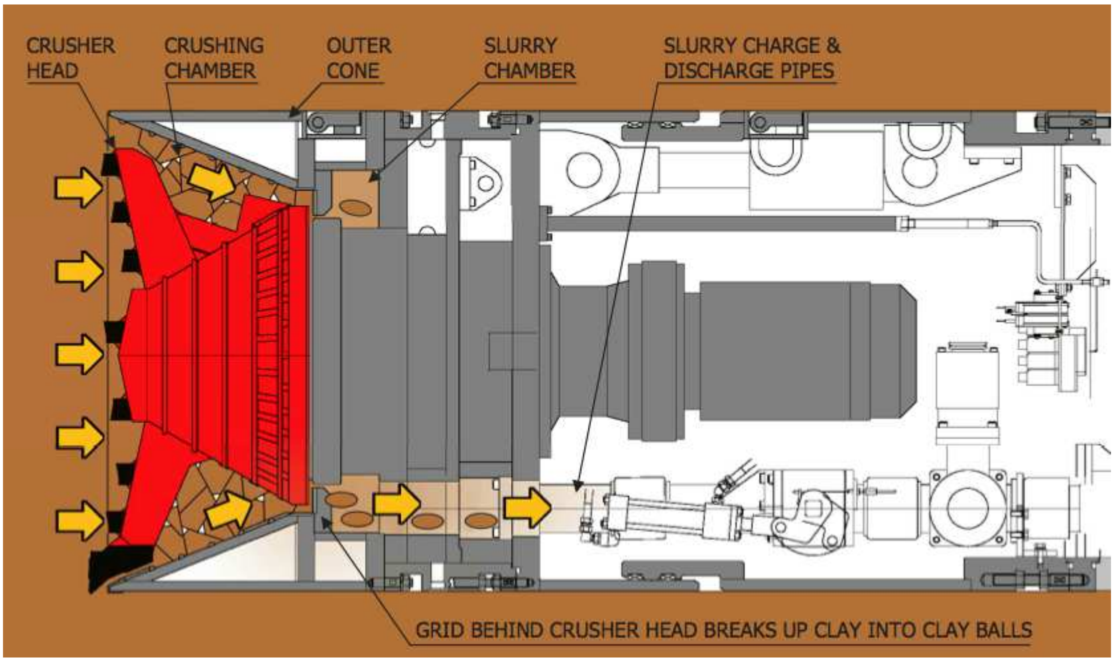


Figure 2.4 Schematic diagram of a Iseki Unclemole slurry pipe jacking tunnel boring machine and how it processes clay soils (Iseki, 2013)

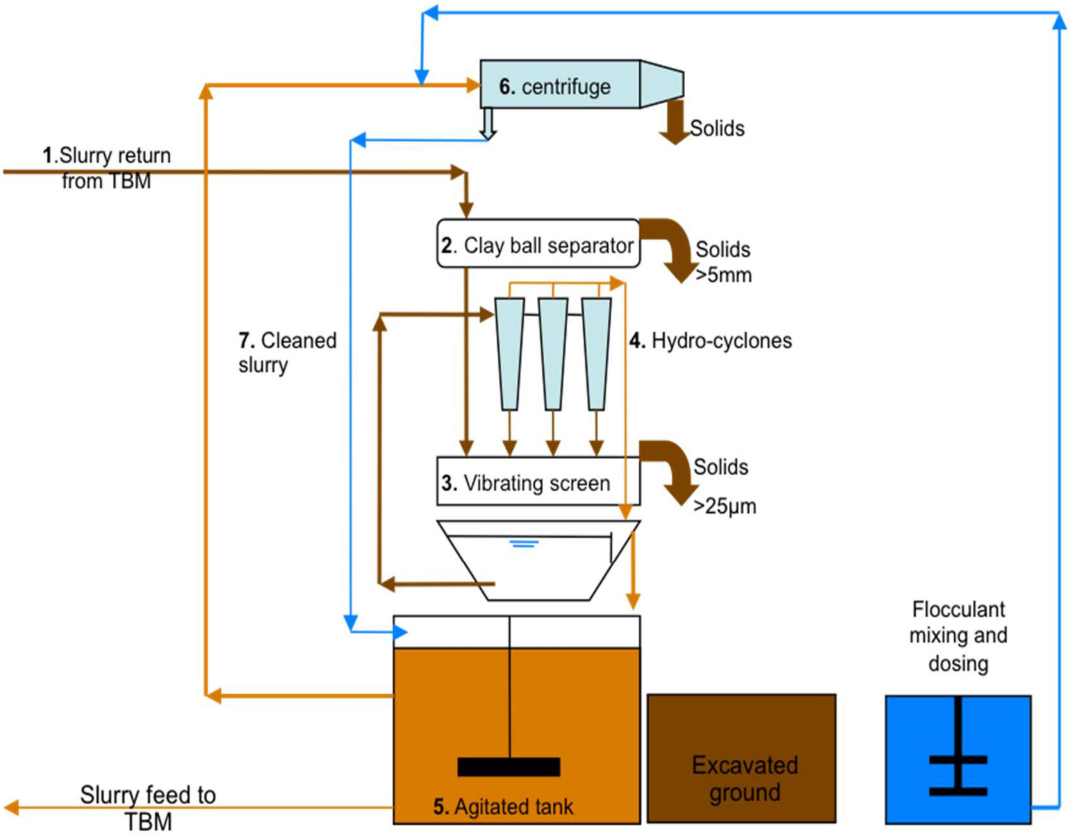


Figure 2.5 Schematic of a typical slurry separation system

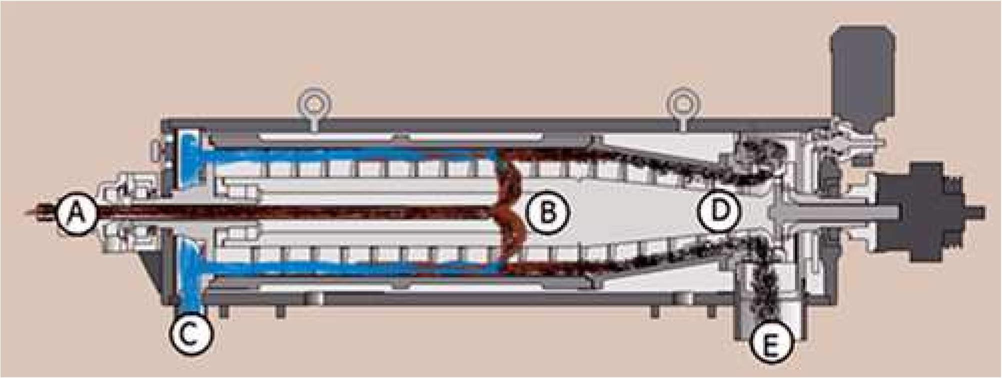


Figure 2.6 Internal schematic diagram of a decanting centrifuge (Baioni Environmental, 2013)

A: Inlet pipe: The slurry is pumped through a pipe in the centre of the end bearing. Prior to this the slurry is dosed with a flocculant.

B: Internal discharge/ liquid-solids separation point: The flocculated slurry is released from the centre of the centrifuge. The horizontal position can sometimes be varied depending on particle sizes and solids concentration.

C: Centrate discharge: The separated liquid stage of the slurry is discharged over a weir to minimise solids being carried with the liquid.

D: Solids dewatering stage: The inner bowl reduces in diameter to allow for further solids dewatering, also know as the beach.

E: Solids discharge: Dewatered solids are discharged.

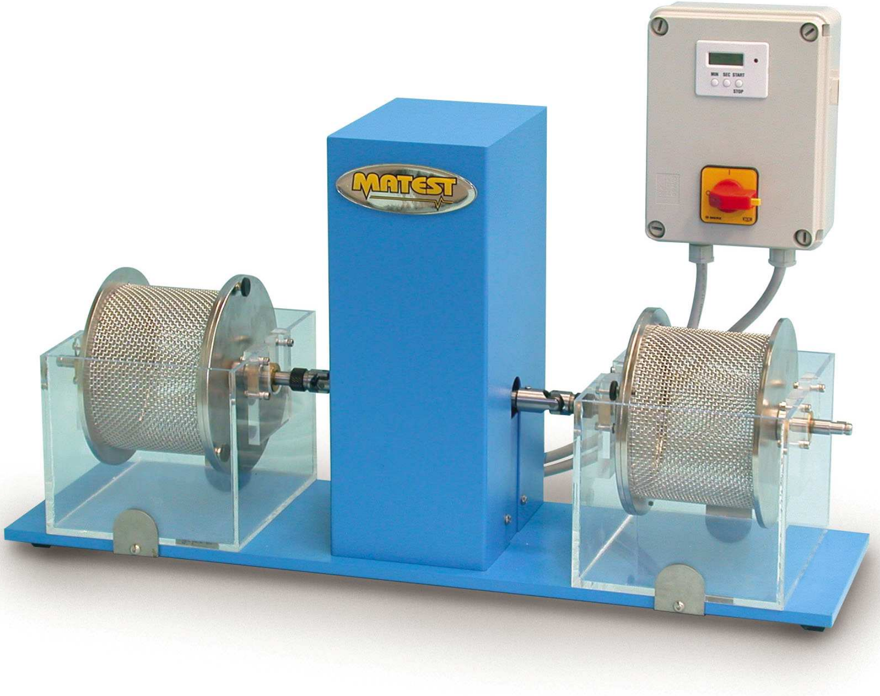
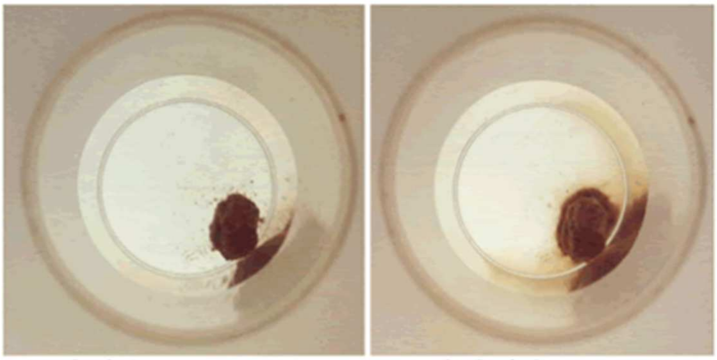
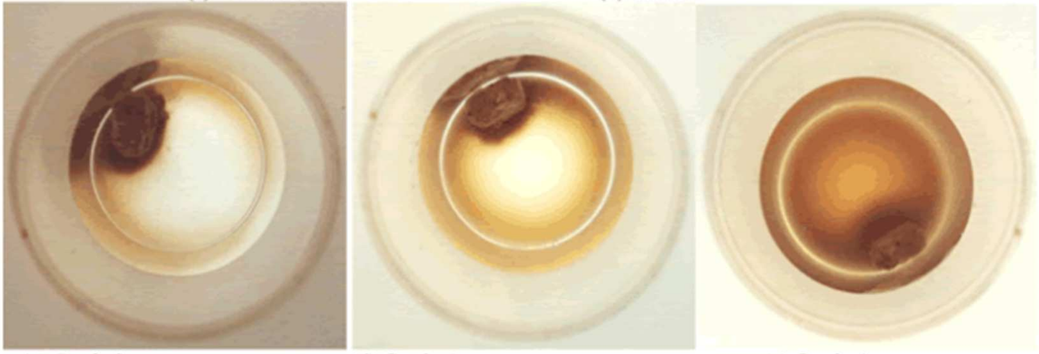


Figure 3.1 Slake durability test (two basket model) (MATEST, 2015)

Figure 3.2 Closed loop pumping system (SASKATCHEWAN RESEARCH COUNCIL, 2014)



(a) Grade 1 (b) Grade 2



(c) Grade 3 (d) Grade 4 (e) Grade 4

Figure 3.3 Grading system for dispersivity using the crumb test (ASTM, 2006)

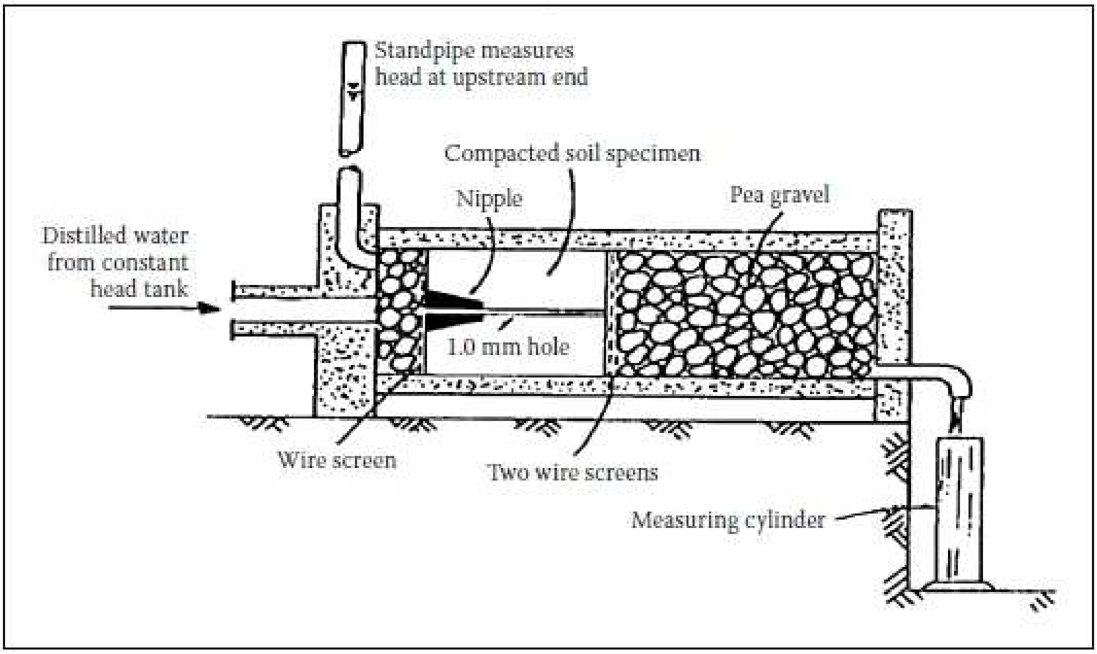


Figure 3.4 Pin hole test apparatus (Maharaj, Van Rooy & Paige-Green, 2015)

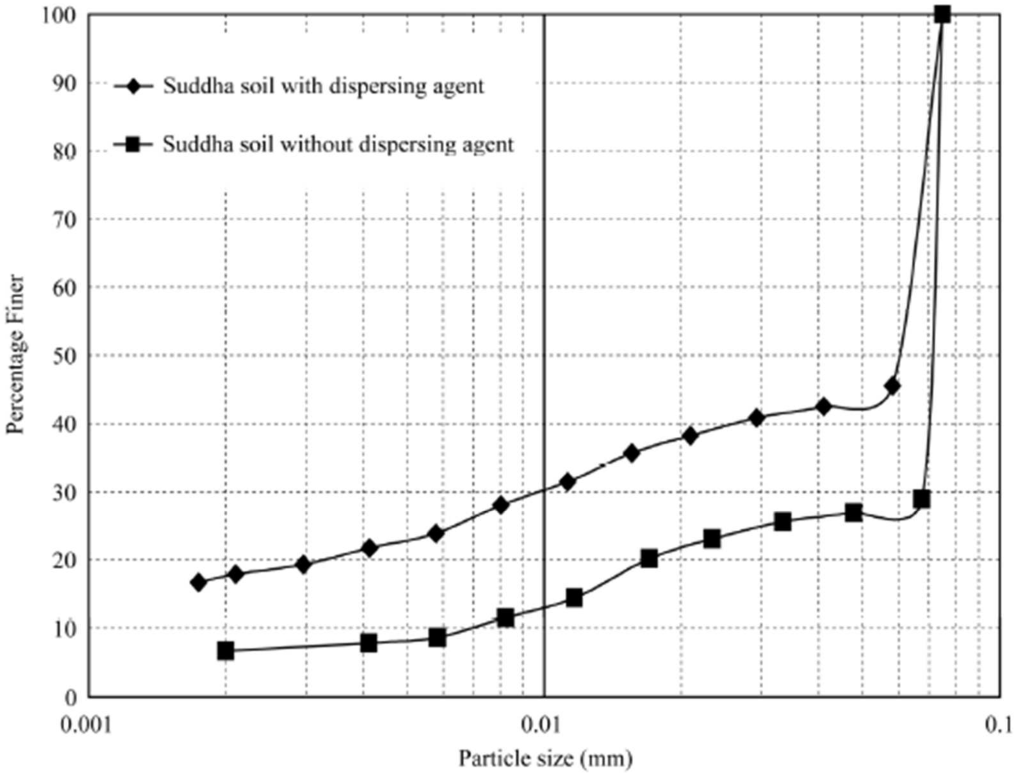


Figure 3.5 Example data for the double hydrometer test (Umesh et al, 2011)

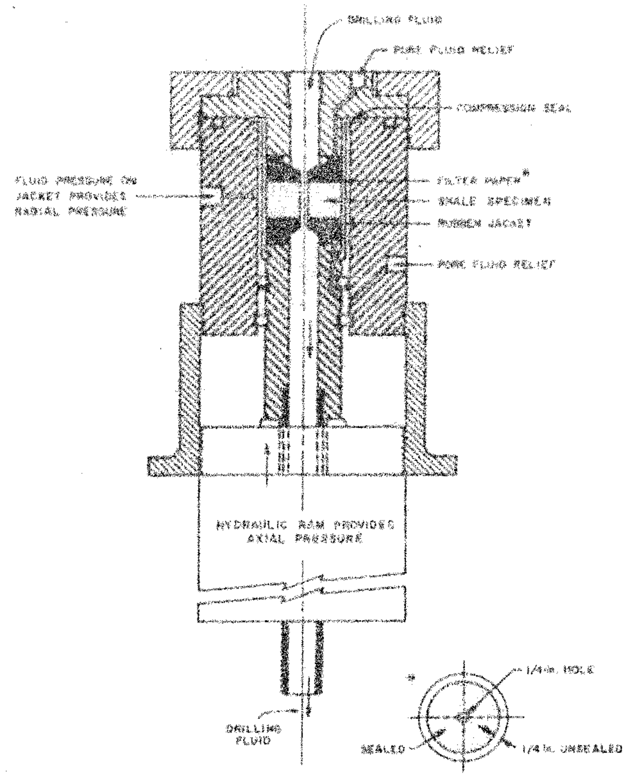


Figure 3.6 Cut through of a Mud Triaxial test (Clark *et al*, 1976)

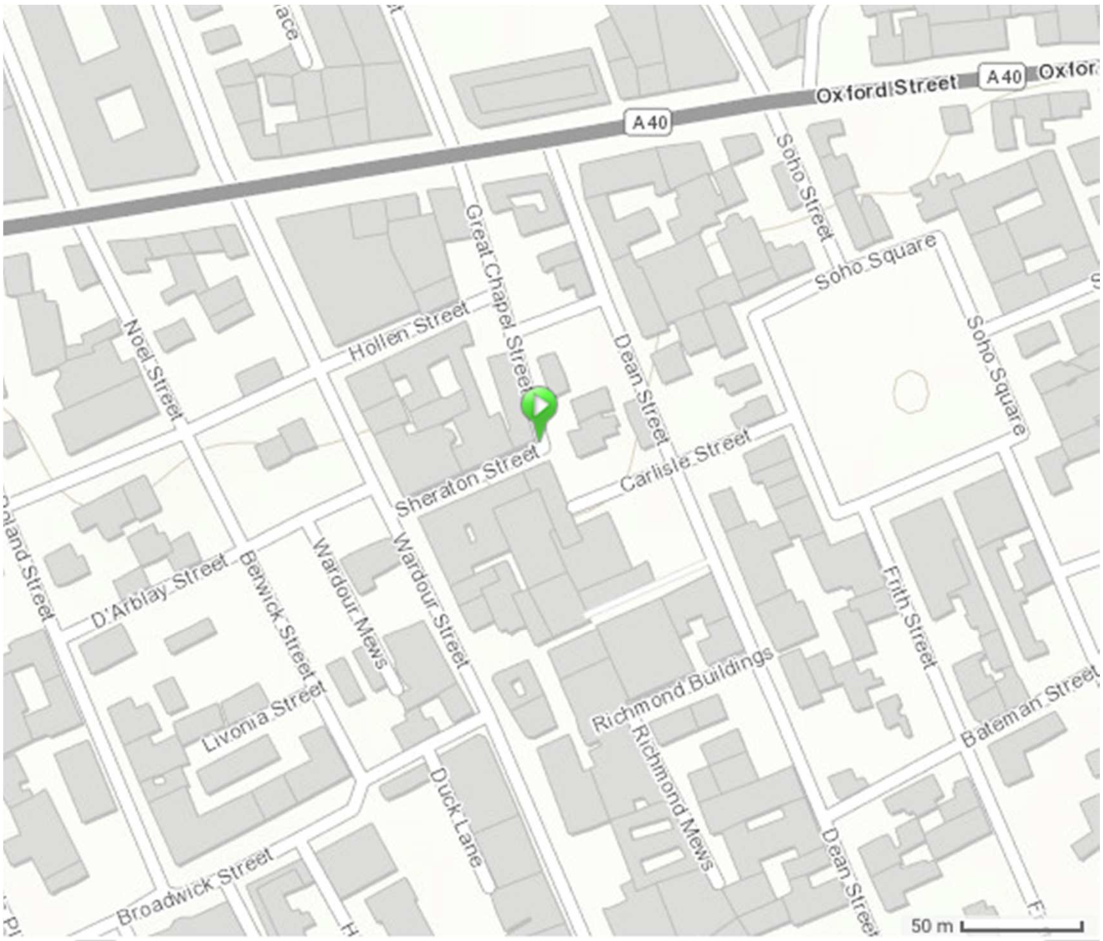
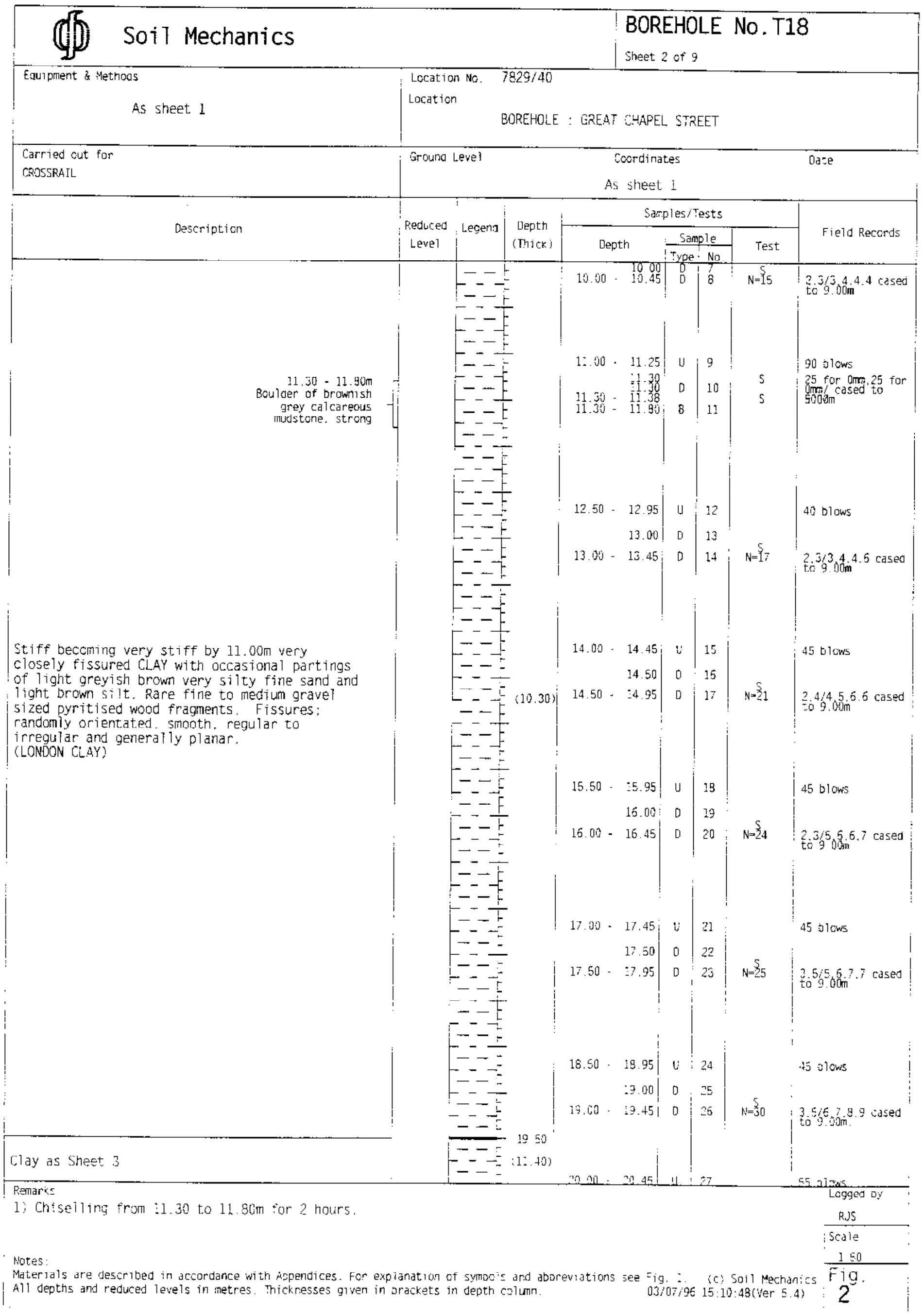


Figure 4.1 Location of shaft for London Clay Tottenham Court Road sample



Soil Mechanics

BOREHOLE No.T18

Sheet 2 of 9

Equipment & Methods: As sheet 1

Location No. 7829/40

Location: BOREHOLE : GREAT CHAPEL STREET

Carried out for: CROSSRAIL

Ground Level

Coordinates: As sheet 1

Date

11.30 - 11.80m
Boulder of brownish
grey calcareous
mudstone, strong

Stiff becoming very stiff by 11.00m very closely fissured CLAY with occasional partings of light greyish brown very silty fine sand and light brown silt. Rare fine to medium gravel sized pyritised wood fragments. Fissures; randomly orientated, smooth, regular to irregular and generally planar.
(LONDON CLAY)

Clay as Sheet 3

Depth (Thick)	Samples/Tests Depth	Sample Type	Sample No.	Test	Field Records
	10.00	D	7		
	10.00 - 10.45	D	8	S N=15	2.3/3,4.4.4 cased to 9.00m
	11.00 - 11.25	U	9		90 blows
	11.30	D	10	S	25 for 0mm,25 for 0mm/ cased to 5000m
	11.30 - 11.38			S	
	11.30 - 11.80	B	11		
	12.50 - 12.95	U	12		40 blows
	13.00	D	13		
	13.00 - 13.45	D	14	S N=17	2.3/3,4.4.6 cased to 9.00m
	14.00 - 14.45	U	15		45 blows
	14.50	D	16		
(10.30)	14.50 - 14.95	D	17	S N=21	2.4/4,5.6.6 cased to 9.00m
	15.50 - 15.95	U	18		45 blows
	16.00	D	19		
	16.00 - 16.45	D	20	S N=24	2.3/5,5.6.7 cased to 9.00m
	17.00 - 17.45	U	21		45 blows
	17.50	D	22		
	17.50 - 17.95	D	23	S N=25	3.5/5,6.7.7 cased to 9.00m
	18.50 - 18.95	U	24		45 blows
	19.00	D	25		
	19.00 - 19.45	D	26	S N=30	3.5/6,7.8.9 cased to 9.00m.
19.50					
(11.40)					
	20.00 - 20.45	U	27		55 blows

Remarks
1) Chiselling from 11.30 to 11.80m for 2 hours.

Logged by RJS

Scale 1:50

Notes:
Materials are described in accordance with Appendices. For explanation of symbols and abbreviations see Fig. 1. (c) Soil Mechanics
All depths and reduced levels in metres. Thicknesses given in brackets in depth column. 03/07/96 15:10:48(Ver 5.4)

Fig. 2

A2 description “It is non-calcareous, poorly sorted with a high percentage of silt, and has occasional wood fragments and pyrite nodules and contains no claystones. There are numerous partings and lenses of silt and fine sand. Sandy clays and silty clays with diffuse boundaries alternate, reflecting minor sea level changes.” Gasparre, 2005

Figure 4.2 Great Chapel Street Borehole for selected horizon with soil description for London clay

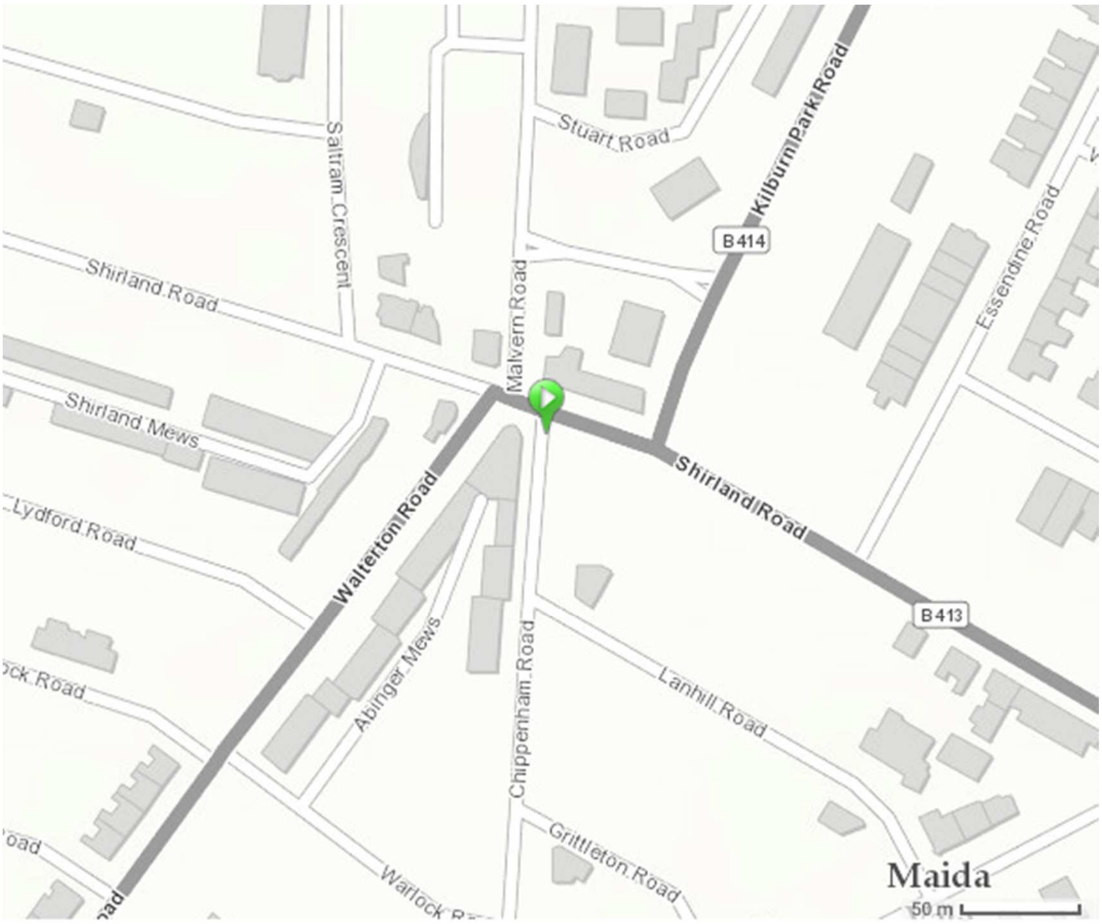


Figure 4.3 Map of Maida Vale shaft location for second sample of London clay

Borehole Log

ESG Environmental Scientifics Group

Drilled PW **Logged** NS/SW **Checked** GH	**Start** 17/12/2012 **End** 18/12/2012	**Equipment, Methods and Remarks** D3000 Hand dug inspection pit from GL to 1.20m depth. Cable percussion boring from 1.20m to 35.00m depth.	**Depth from** 0.00m **to** 35.00m **Diameter** 150mm **Casing Depth** 2.70m	**Ground Level** +26.14 mOD **Coordinates National Grid** E 525129.92 N 182410.90 **Chainage**

Samples and Tests

Strata

Depth	Type & No	Records	Date Casing	Time Water	Description (Continued from Sheet 1)	Depth, *Level* (Thickness)	Legend	Backfill/ Instruments
		*			spaced, planar and smooth with bluish grey gleying on surfaces. Occasional coarse sand to fine gravel sized selenite crystals. (LONDON CLAY FORMATION)			
5.70	D 18							
5.70-6.15	U 19	23 blows	2.70	dry				
6.15-6.20	D 20				6.15 m Occasional bluish grey gleying on fissure surfaces.	(3.00)		
6.20-6.50	B 21							
7.20	D 22	*						
7.20-7.65	U 23	21 blows	2.70	dry	7.20 m Occasional medium to coarse gravel sized pockets of medium to coarse sand of selenite crystals and yellowish brown silt. No gleying on fissures.			
7.65-7.70	D 24	*			Stiff fissured brown CLAY. Fissures are randomly orientated, closely spaced, planar, smooth, with yellowish brown silt on surfaces. Occasional coarse sand to fine gravel sized selenite crystals. (LONDON CLAY FORMATION)	7.65 *+18.49*		
8.00-8.50	B 25							
		*						
8.70	D 26							
8.70-9.15	U 27	25 blows	2.70	dry				
						(2.75)		
9.15-9.20	D 28	*						
Depth	Type & No	Records	Date Casing	Time Water	Stratum continues to 10.40 m			

Groundwater Entries

No.	Struck (m)	Post strike behaviour	Depth sealed (m)
None observed (see Key Sheet)			

Depth Related Remarks *

From	to (m)	
5.20		UXO Magnetometer test undertaken.
7.20		UXO Magnetometer test undertaken.
7.70		UXO Magnetometer test undertaken.
8.20		UXO Magnetometer test undertaken.
9.20		UXO Magnetometer test undertaken.

Chiselling

Depths (m)	Time	Tools used

Notes: For explanation of symbols and abbreviations see key sheet. All depths and reduced levels in metres. Stratum thickness given in brackets in depth column.

Scale 1:25

BH11 426.4826/04/2013 13:22:13 AGS

Project Maida Vale

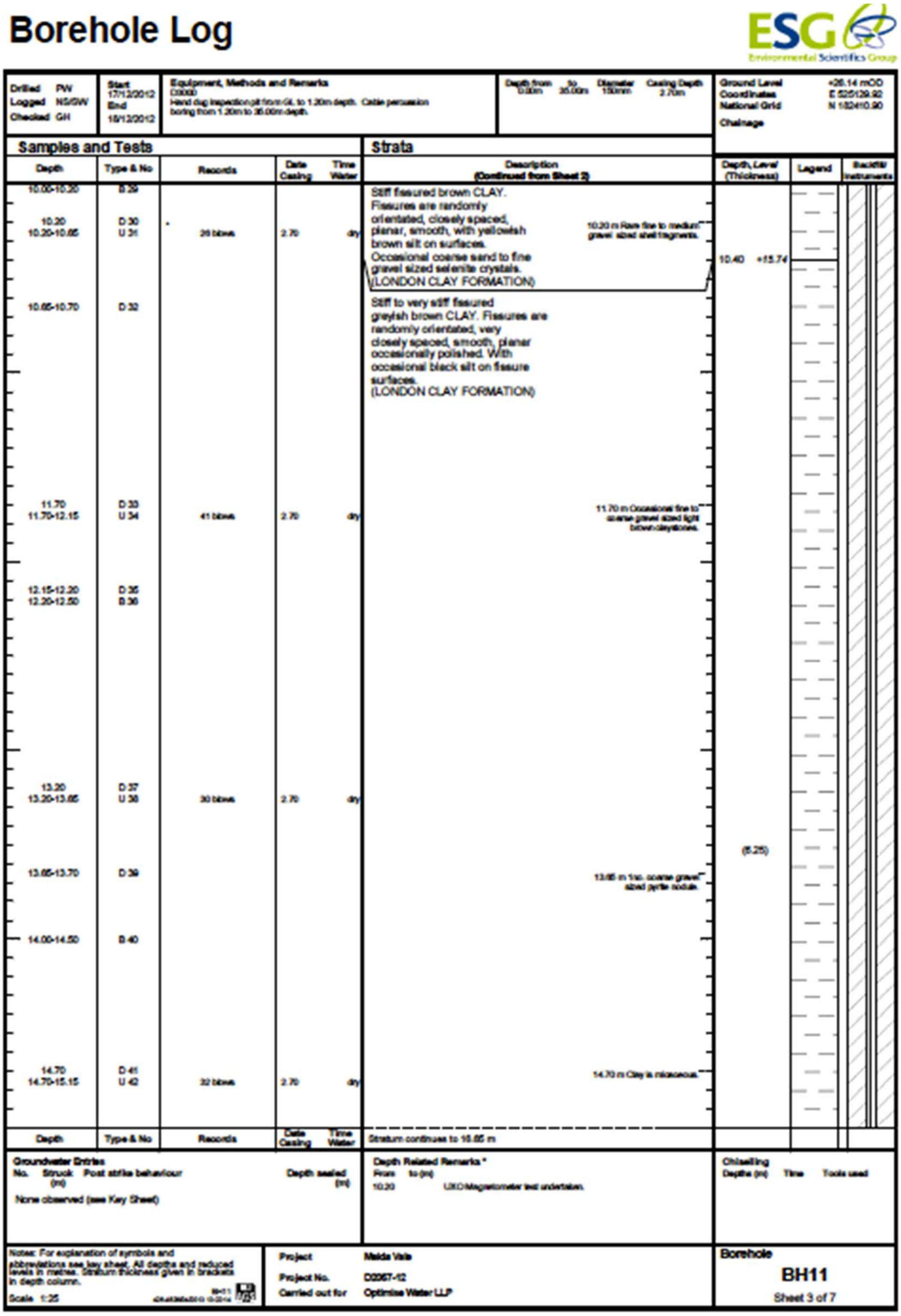
Project No. D2057-12

Carried out for Optimise Water LLP

Borehole

BH11

Sheet 2 of 7



Borehole Log

Drilled PW
Logged NS/SW
Checked GH

Start 17/12/2012
End 18/12/2012

Equipment, Methods and Remarks
D3000
Hand dug inspection pit from GL to 1.20m depth. Cable percussion boring from 1.20m to 35.00m depth.

Depth from	to	Diameter	Casing Depth
0.00m	35.00m	150mm	2.70m

Ground Level +26.14 mOD
Coordinates E 525129.92
National Grid N 182410.90
Chainage

Samples and Tests

Depth	Type & No	Records	Date Casing	Time Water
10.00-10.20	B 29			
10.20	D 30			
10.20-10.65	U 31	26 blows	2.70	dry
10.65-10.70	D 32			
11.70	D 33			
11.70-12.15	U 34	41 blows	2.70	dry
12.15-12.20	D 35			
12.20-12.50	B 36			
13.20	D 37			
13.20-13.65	U 38	30 blows	2.70	dry
13.65-13.70	D 39			
14.00-14.50	B 40			
14.70	D 41			
14.70-15.15	U 42	32 blows	2.70	dry

Strata

Description (Continued from Sheet 2)

Stiff fissured brown CLAY. Fissures are randomly orientated, closely spaced, planar, smooth, with yellowish brown silt on surfaces. Occasional coarse sand to fine gravel sized selenite crystals. (LONDON CLAY FORMATION)

10.20 m Rare fine to medium gravel sized shell fragments.

Depth, Level (Thickness): 10.40 +15.74

Stiff to very stiff fissured greyish brown CLAY. Fissures are randomly orientated, very closely spaced, smooth, planar occasionally polished. With occasional black silt on fissure surfaces. (LONDON CLAY FORMATION)

11.70 m Occasional fine to coarse gravel sized light brown claystones.

(5.25)

13.65 m 1no. coarse gravel sized pyrite nodule.

14.70 m Clay is micaceous.

Stratum continues to 15.65 m

Groundwater Entries
No. Struck (m) Post strike behaviour Depth sealed (m)
None observed (see Key Sheet)

Depth Related Remarks *
From to (m)
10.20 UXO Magnetometer test undertaken.

Chiselling
Depths (m) Time Tools used

Notes: For explanation of symbols and abbreviations see key sheet. All depths and reduced levels in metres. Stratum thickness given in brackets in depth column.
Scale 1:25

Project Maida Vale
Project No. D0367-12
Carried out for Optimise Water LLP

Borehole
BH11
Sheet 3 of 7

‘Unit B2 comprises of silty clays with weak silt and sand partings and numerous claystones. The lowest of which is the most prominent and continuous. Sedimentary cycles (up to 5 or 6) are weakly discernible within Unit B2.’
(Tan *et al*, 2003)

Figure 4.4 Description and comparison of Maida Vale London Clay

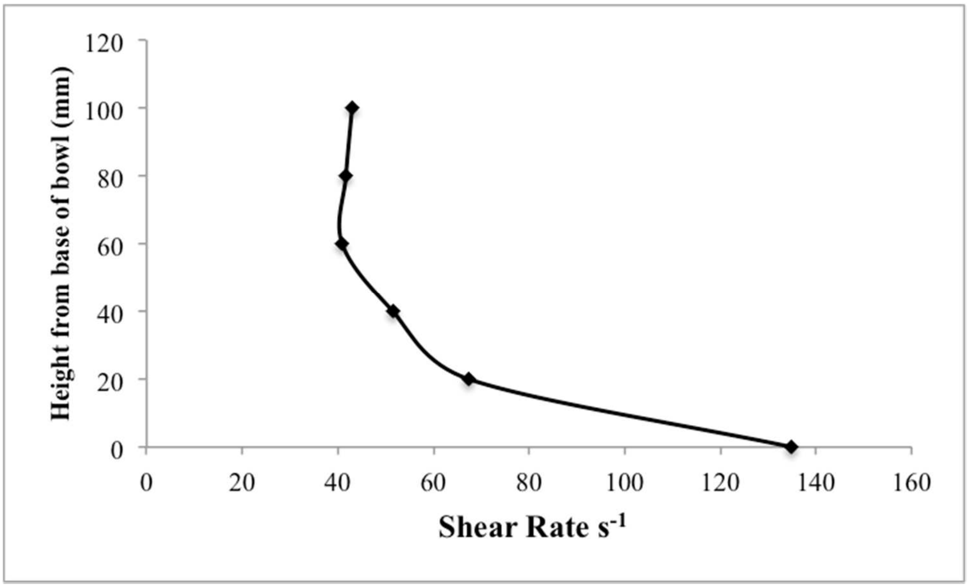


Figure 4.5 Shear rate variation with depth within a Hobart A120 mixer at speed setting 1

Figure 4.6 Hobart planetary mixer and paddle mixer

Figure 4.7 Adapted base pan for series 1 mixing test

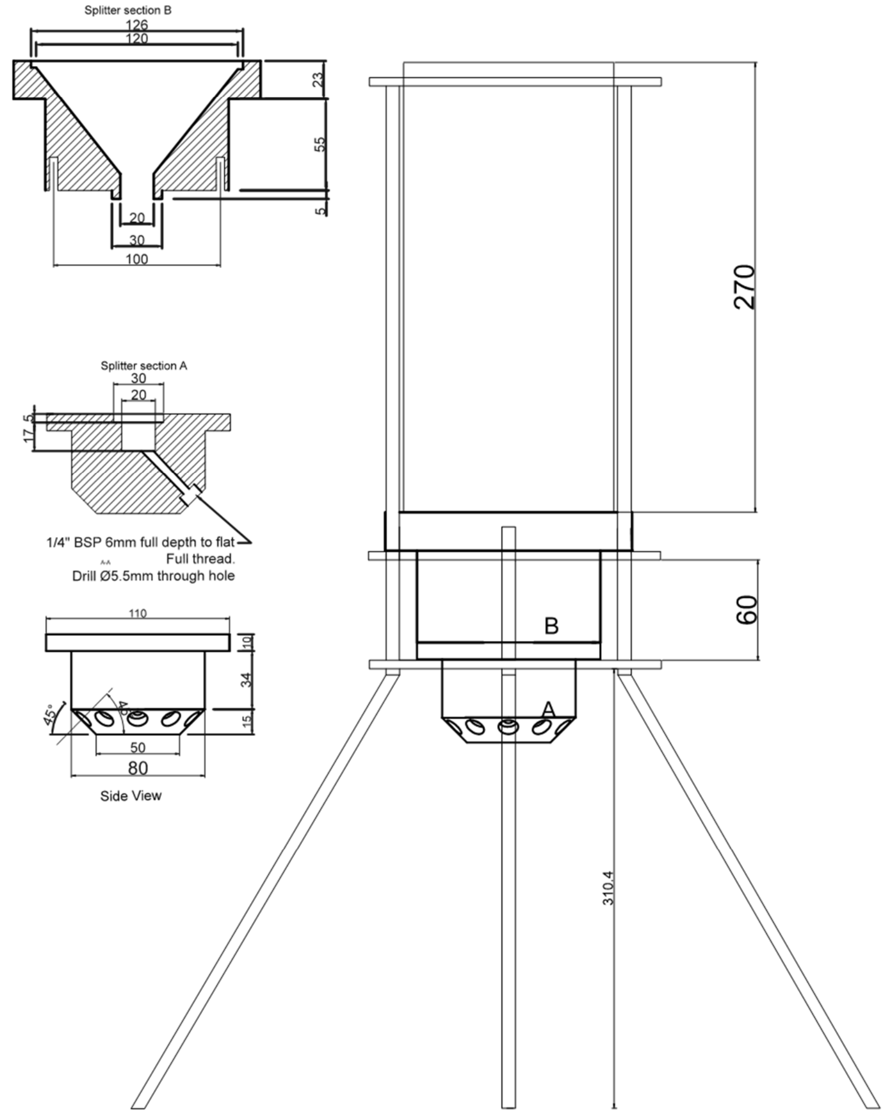


Figure 4.8 Cone splitter drawing (left) with a top view of the central splitter core (right)

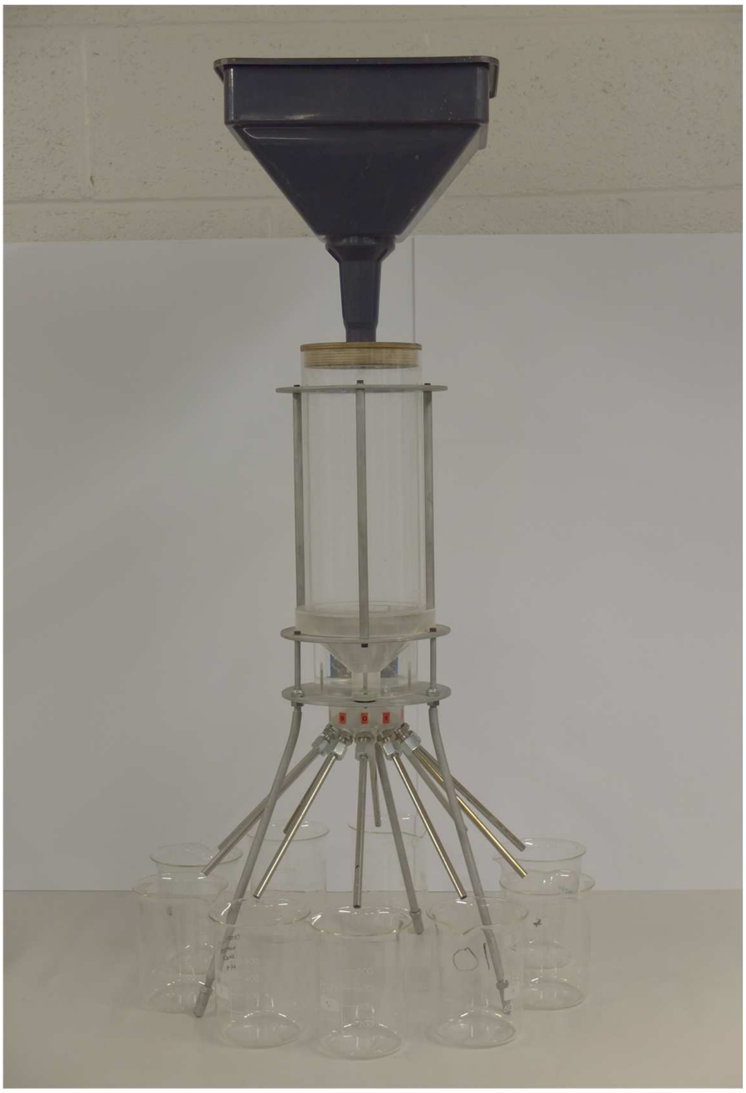


Figure 4.9 10 way cone splitter and beaker set-up

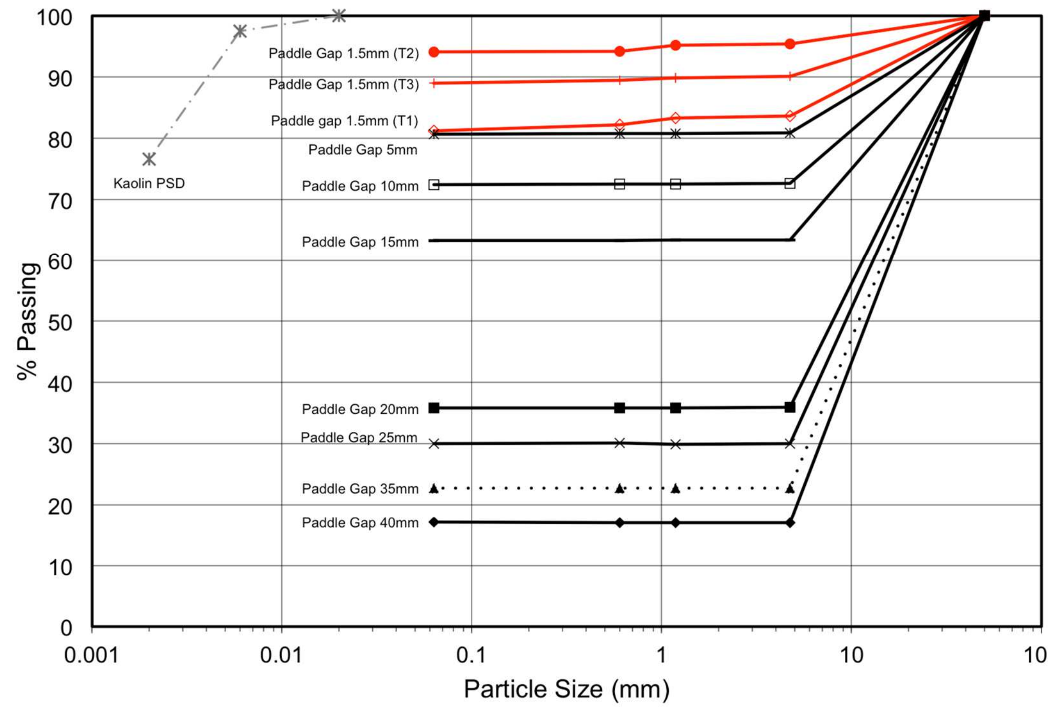


Figure 4.10 Adjusted paddle height tests, which show three 10 minute mixing tests from series 1

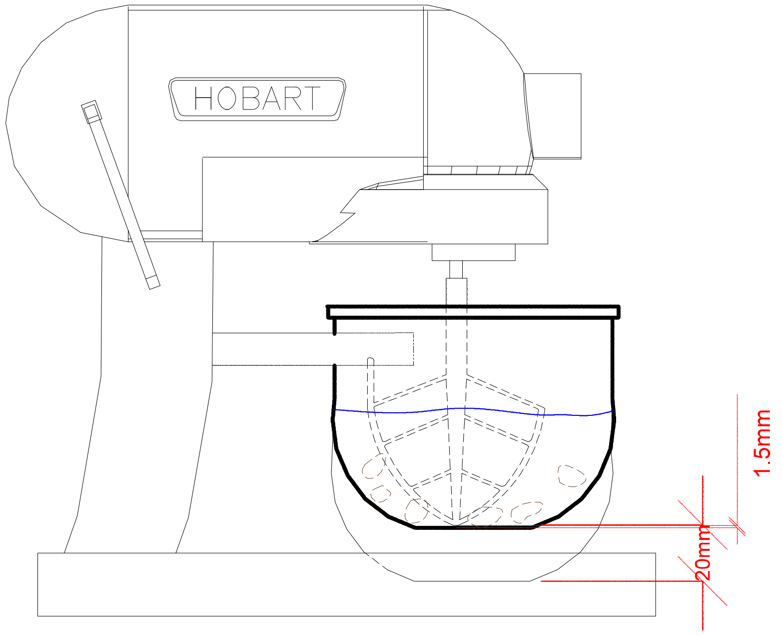


Figure 4.11 Gap between paddle and bowl on the Hobart mixer

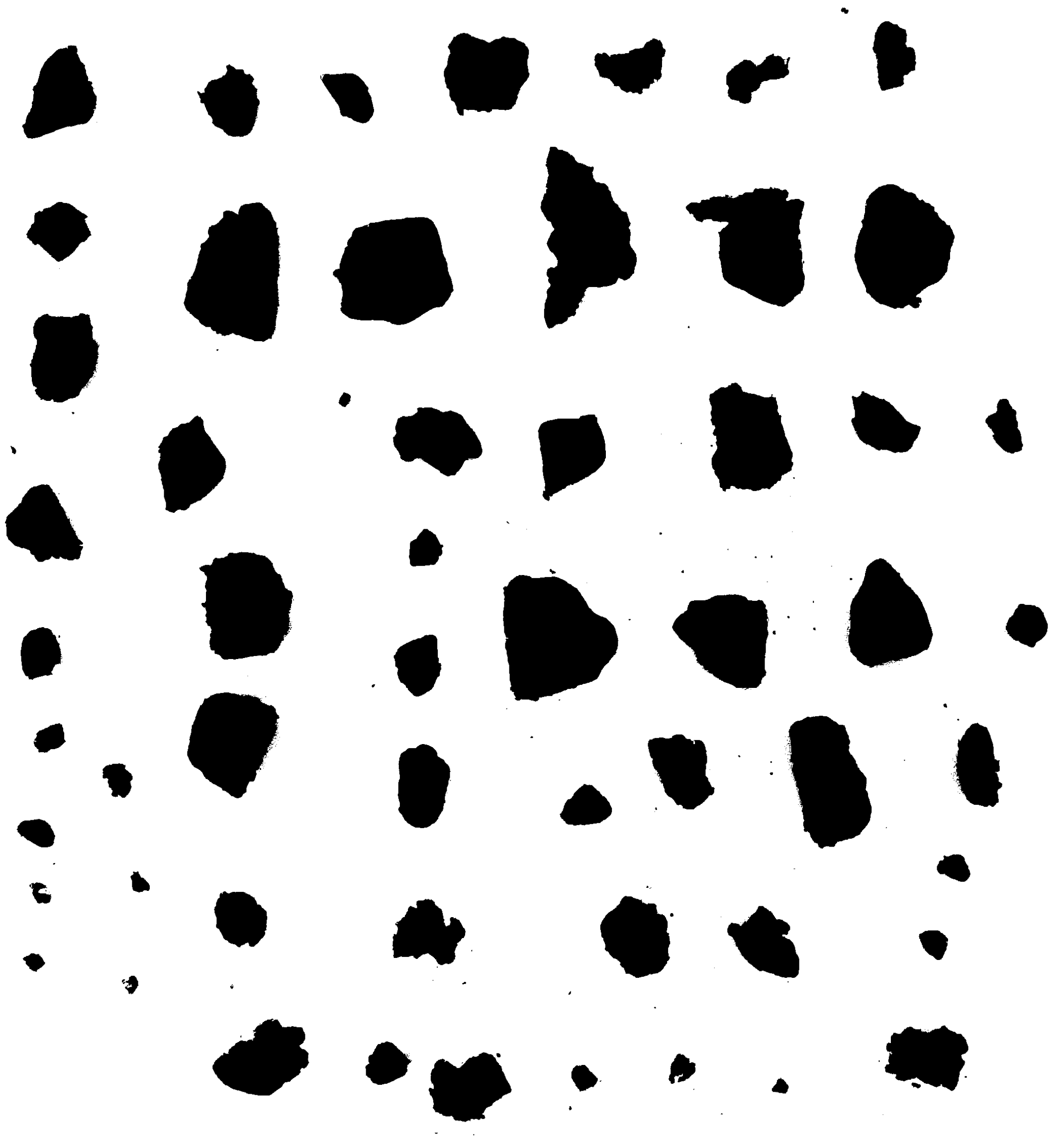


Figure 4.12 ImageJ example (London Clay Maida Vale, 30 minute mixing test)

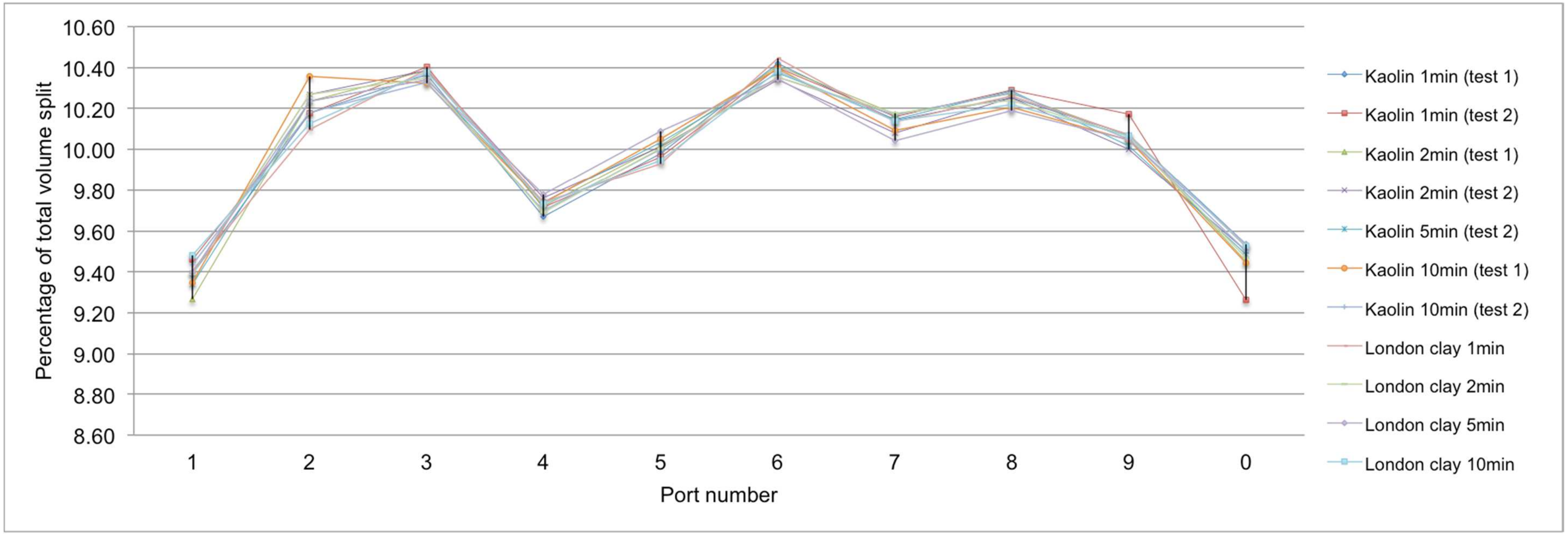
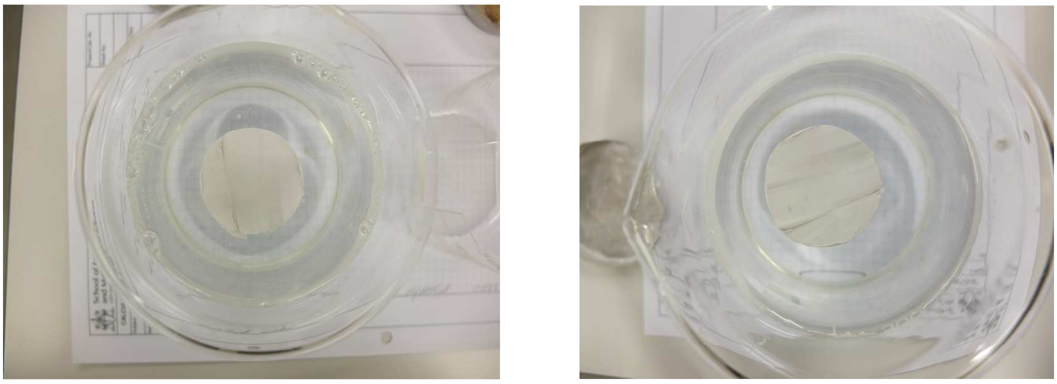
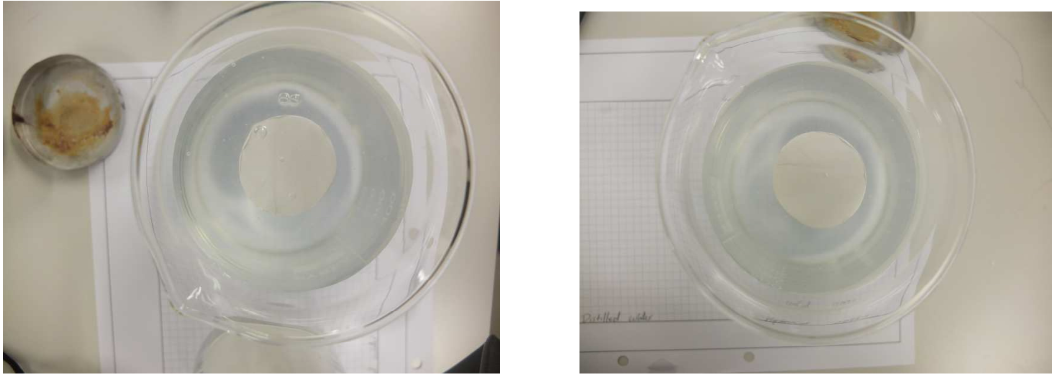


Figure 4.13 Variation in slurry mass at each port of the cone splitter



Start of test End of test

Speswhite Kaolin samples with distilled water



Start of test End of test

Speswhite Kaolin samples with HydroCut (concentration 0.075%)

Figure 4.14 Crumb test pictures

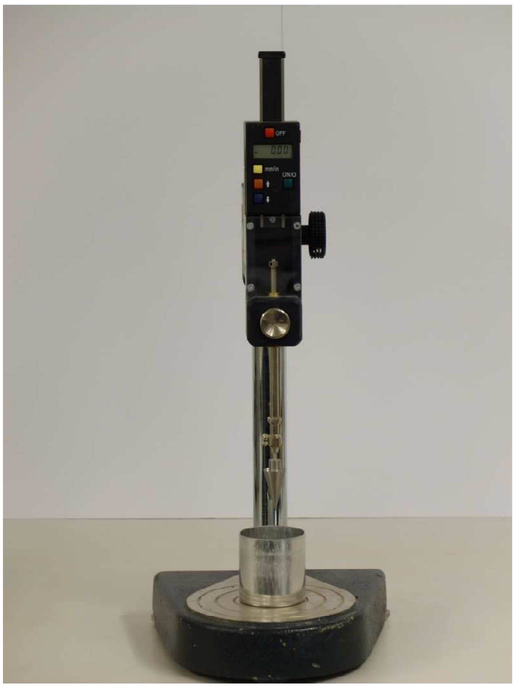


Figure 4.15 Fall cone apparatus for determination of liquid limit

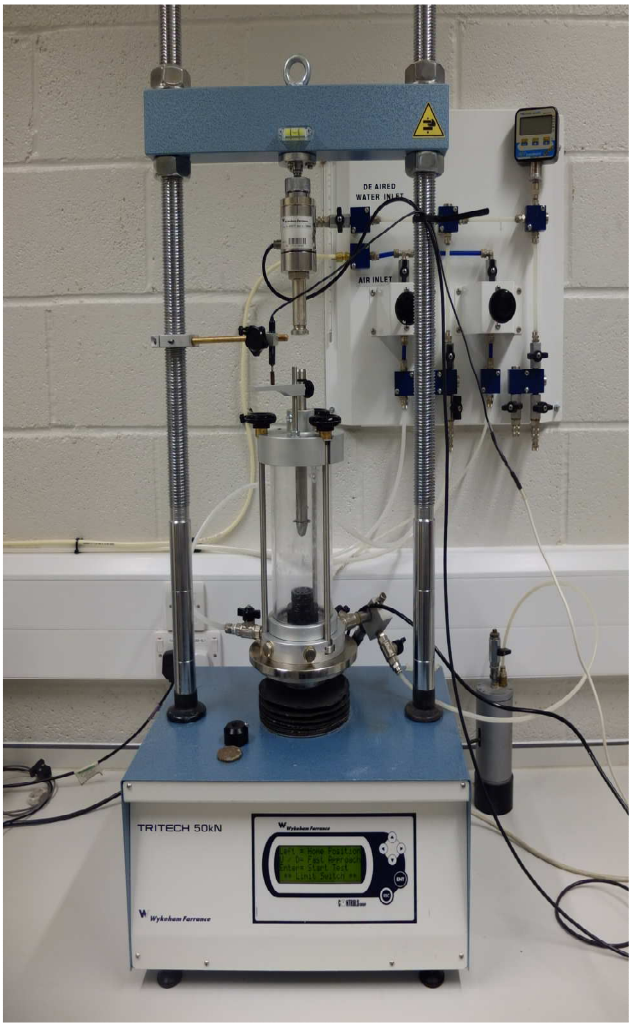


Figure 4.16 Triaxial Apparatus used for unconfined compression tests

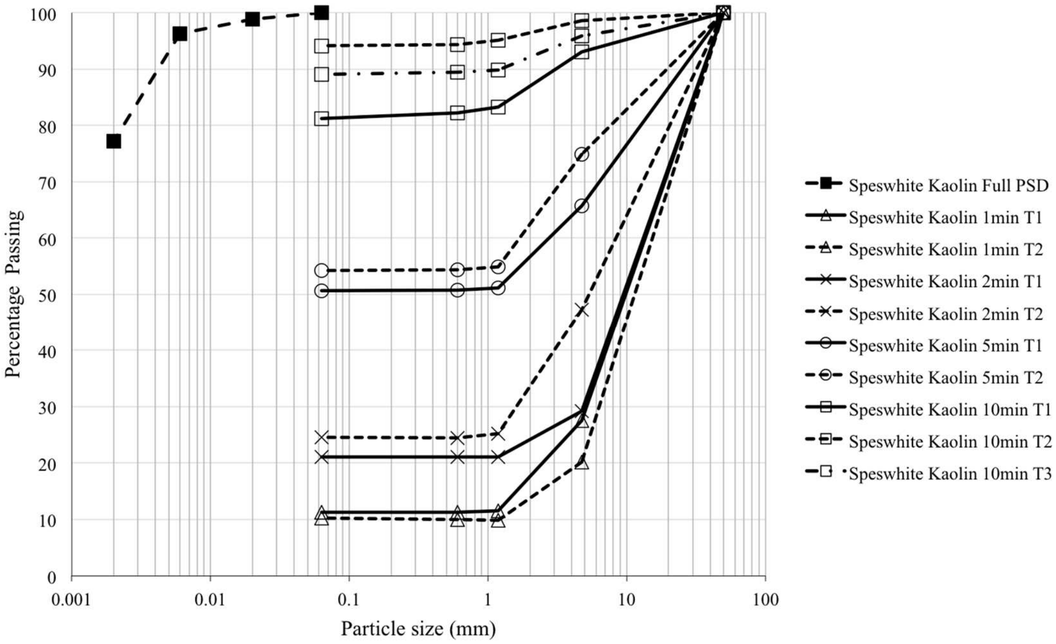


Figure 5.1 Speswhite Kaolin mixing test particle size distributions, test series 1

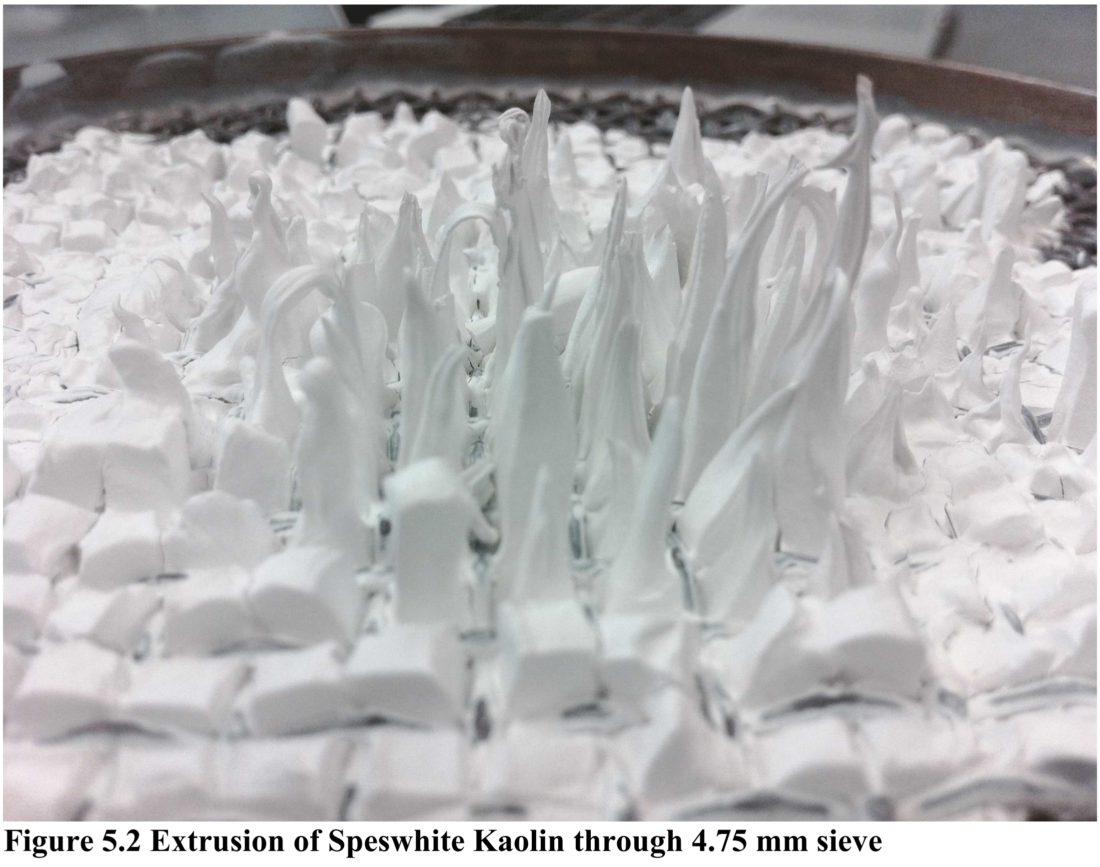


Figure 5.2 Extrusion of Speswhite Kaolin through 4.75 mm sieve

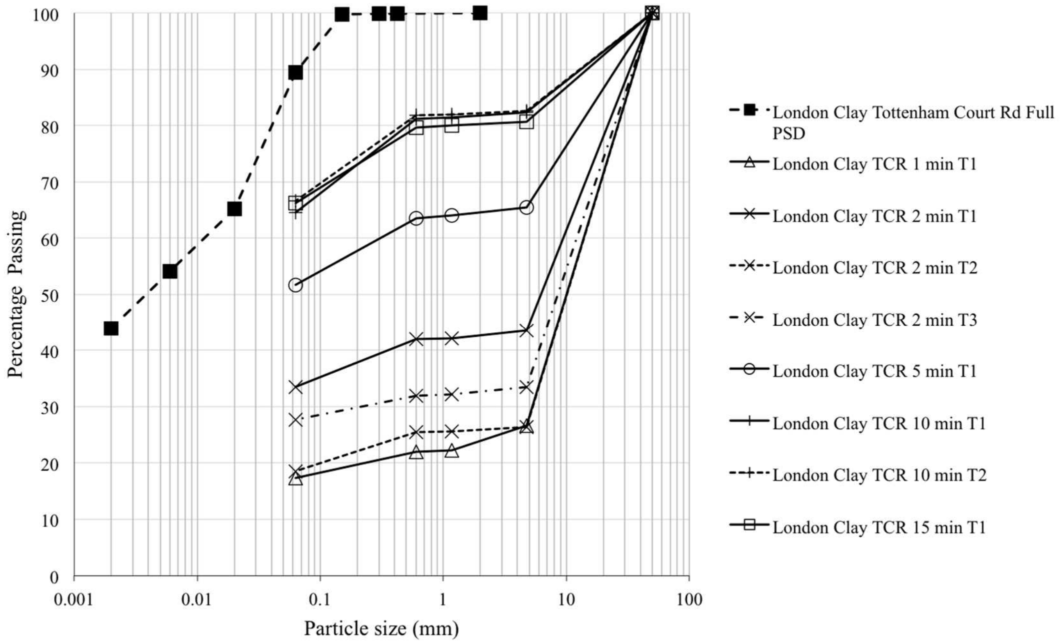


Figure 5.3 London Clay Tottenham Court Road mixing test particle size distributions, test series 1

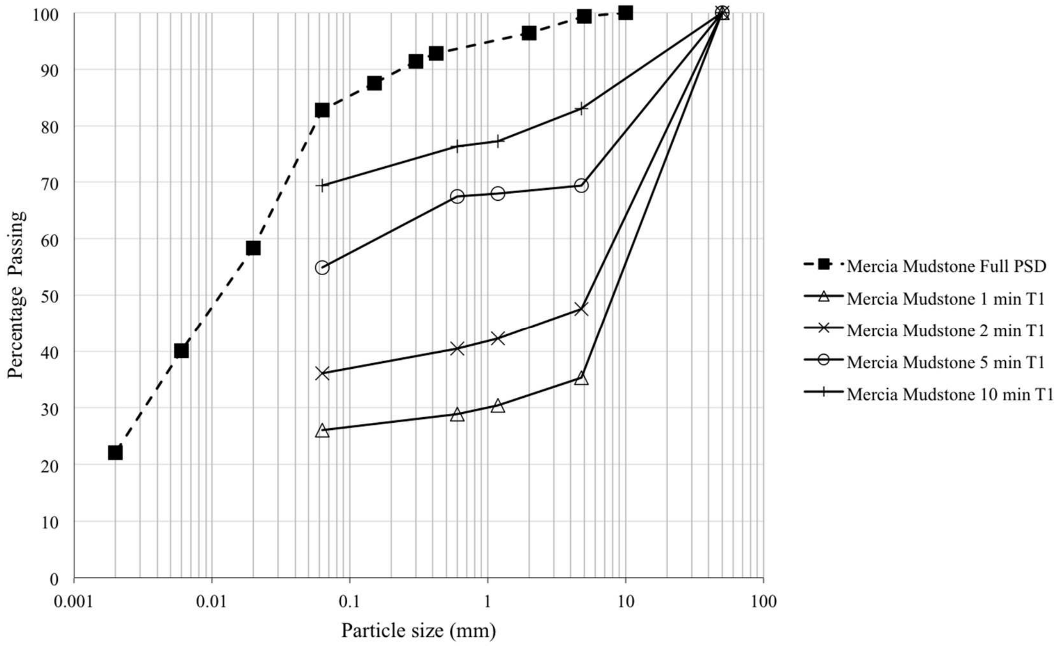


Figure 5.4 Mercia Mudstone mixing test particle size distributions, test series 1

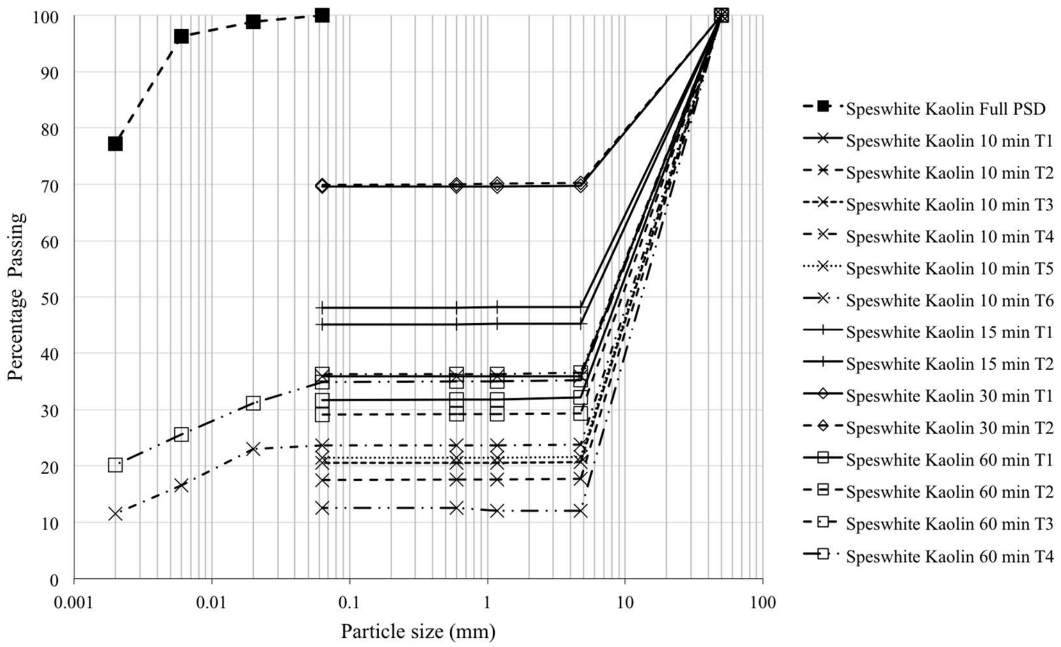


Figure 5.5 Speswhite Kaolin mixing test particle size distributions, test series 2

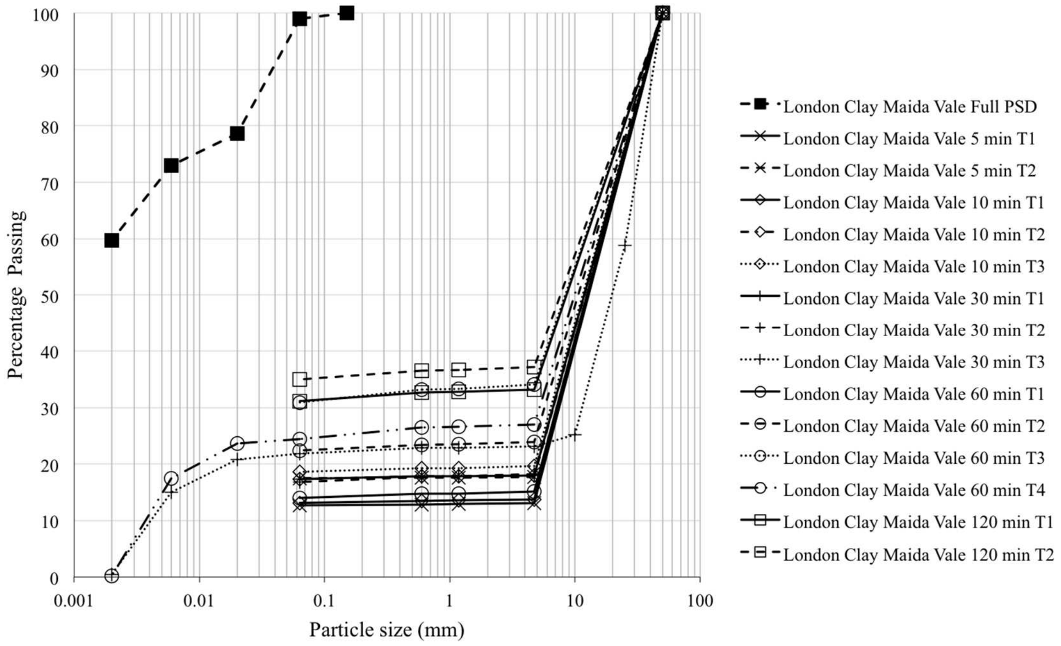


Figure 5.6 London Clay Maida Vale mixing test particle size distributions, test series 2

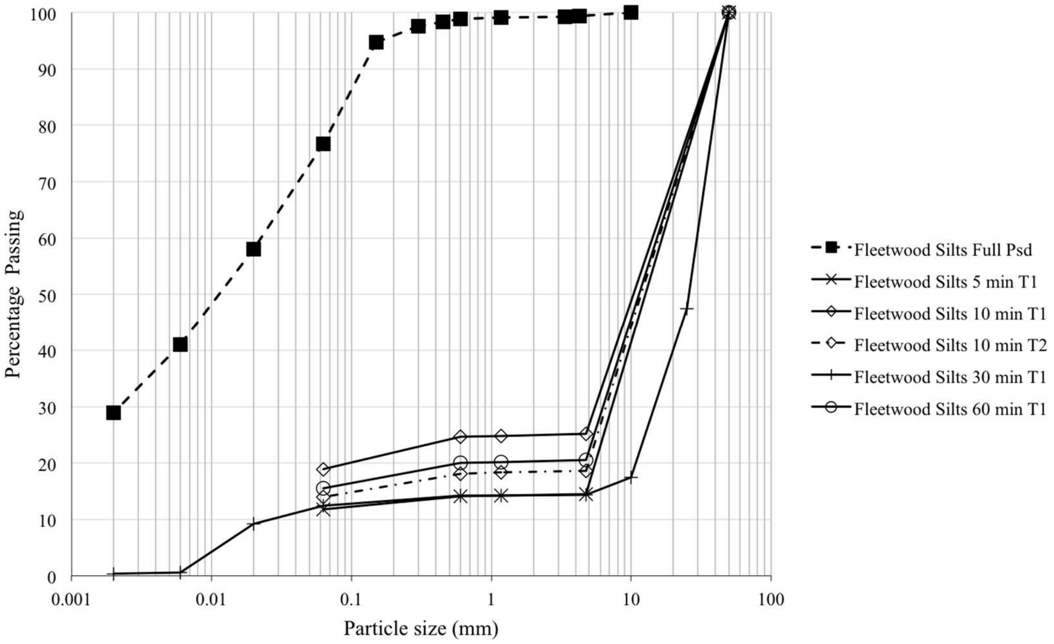


Figure 5.7 Fleetwood Silts mixing test particle size distributions, test series 2

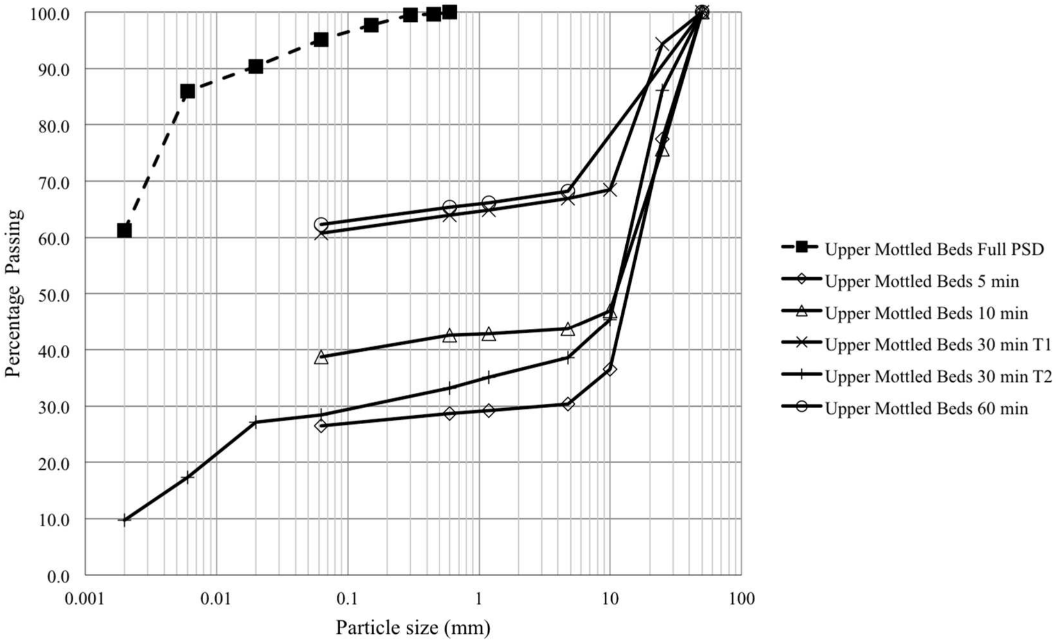


Figure 5.8 Upper Mottled Beds mixing test particle size distributions, test series 2

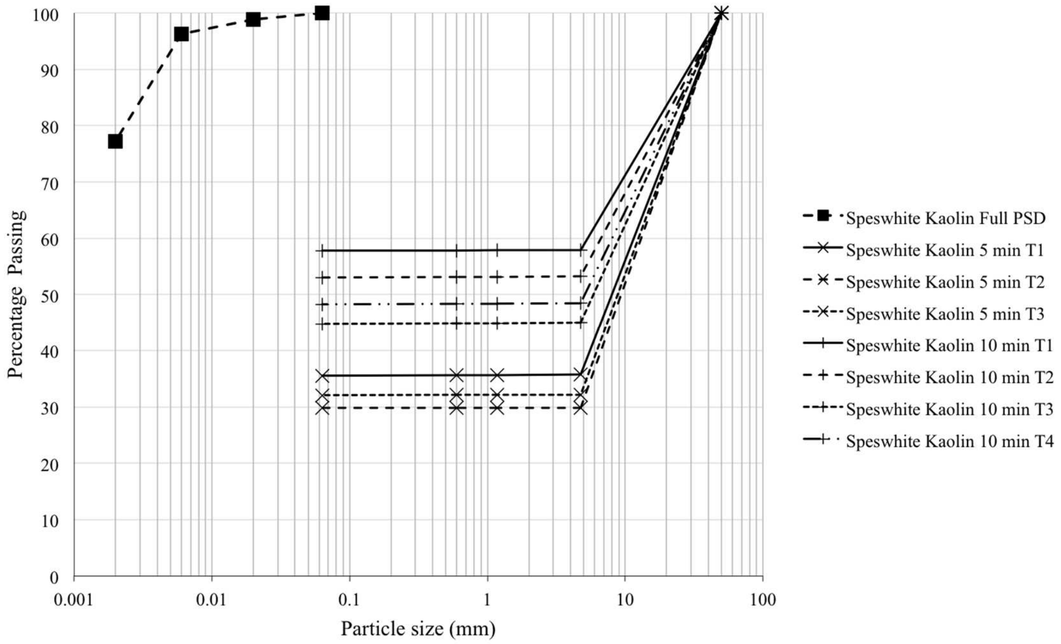


Figure 5.9 Speswhite Kaolin mixing test particle size distributions, test series 2, speed 2

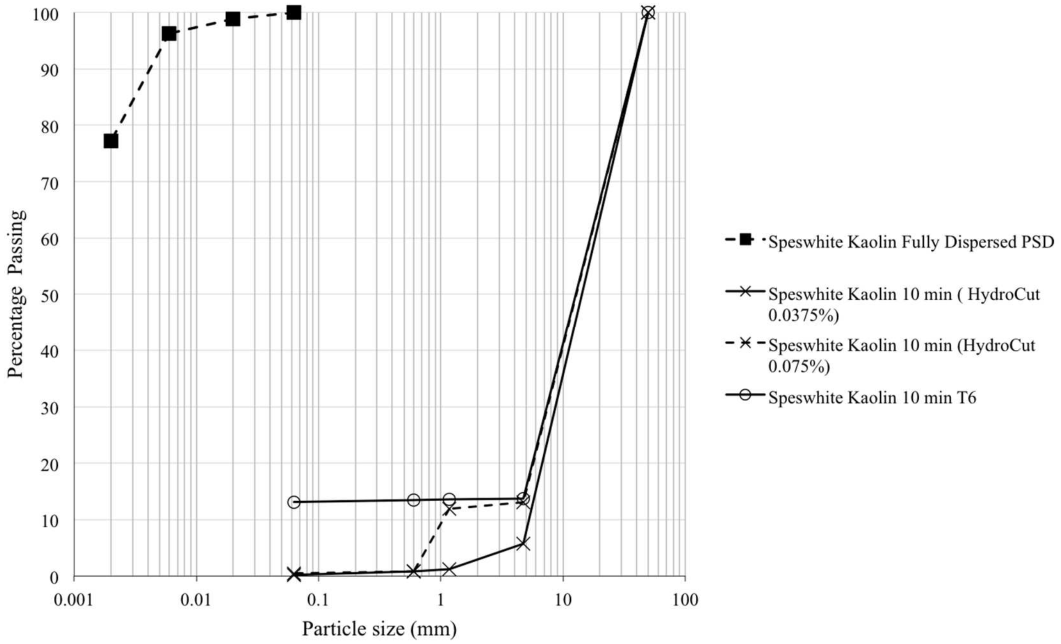


Figure 5.10 Speswhite Kaolin using HydroCut as the slurry fluid

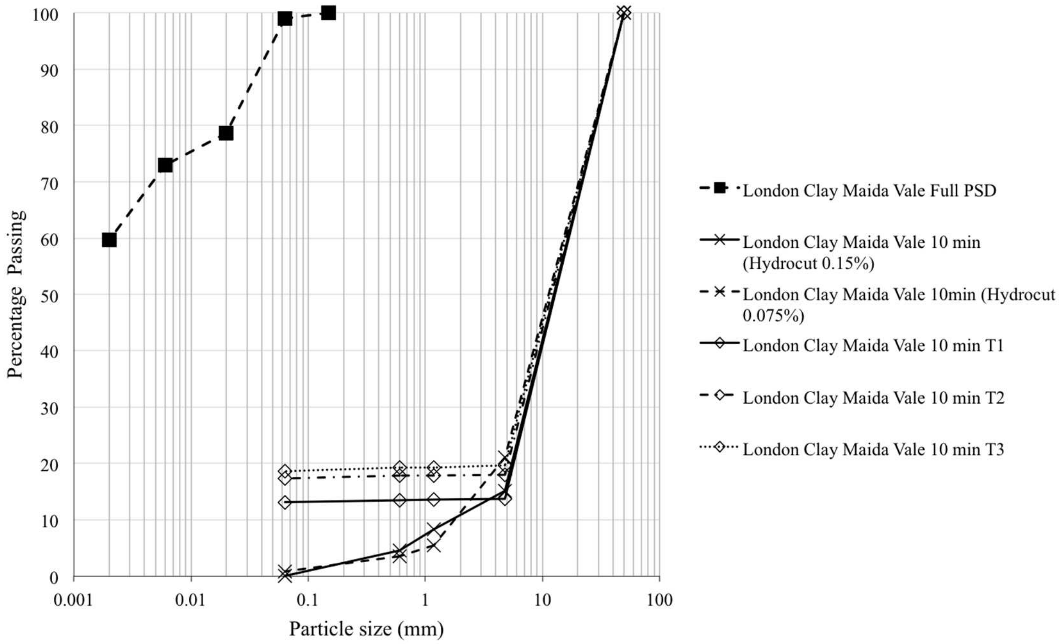


Figure 5.11 London Clay from Maida Vale using HydroCut as the slurry fluid

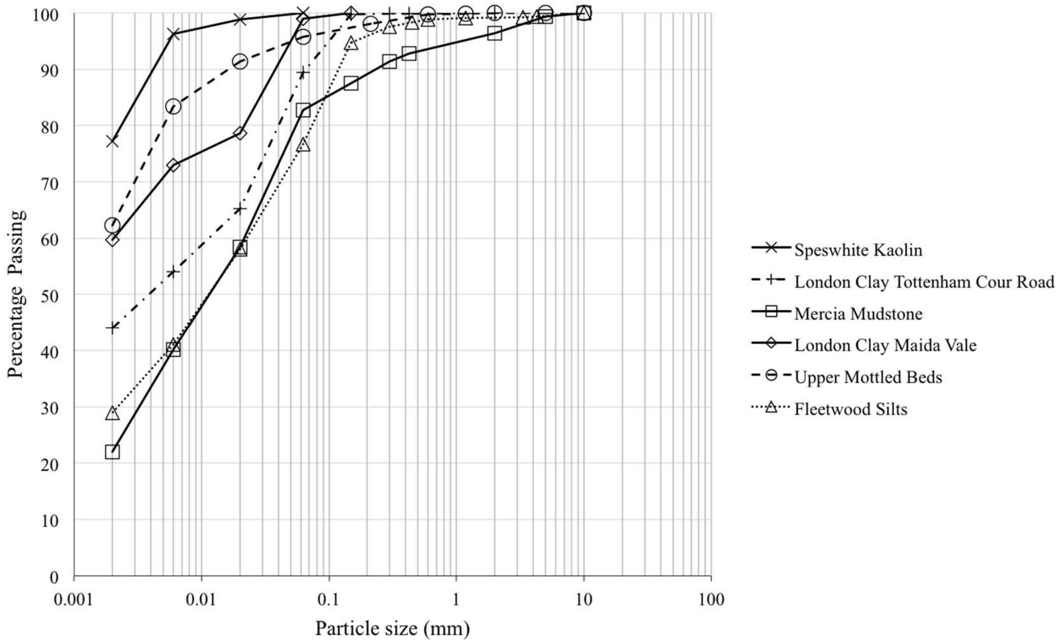


Figure 5.12 Soil sample fully dispersed particle size distributions

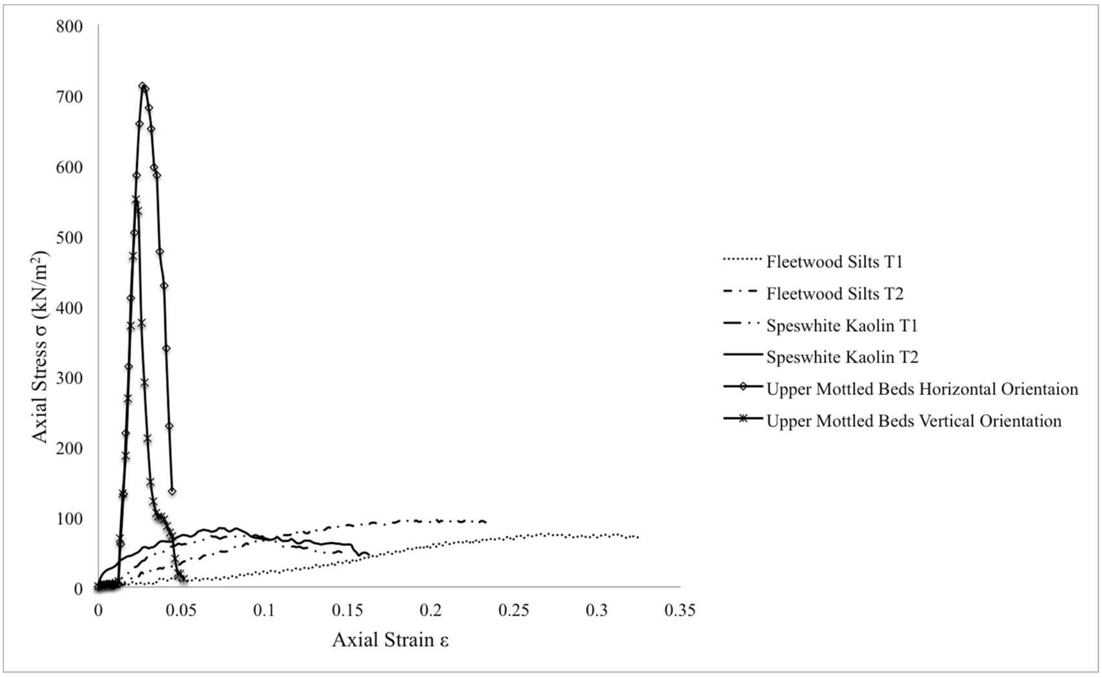


Figure 5.13 Stress vs strain graph for Fleetwood Silts, Speswhite Kaolin, and Upper Mottled Beds

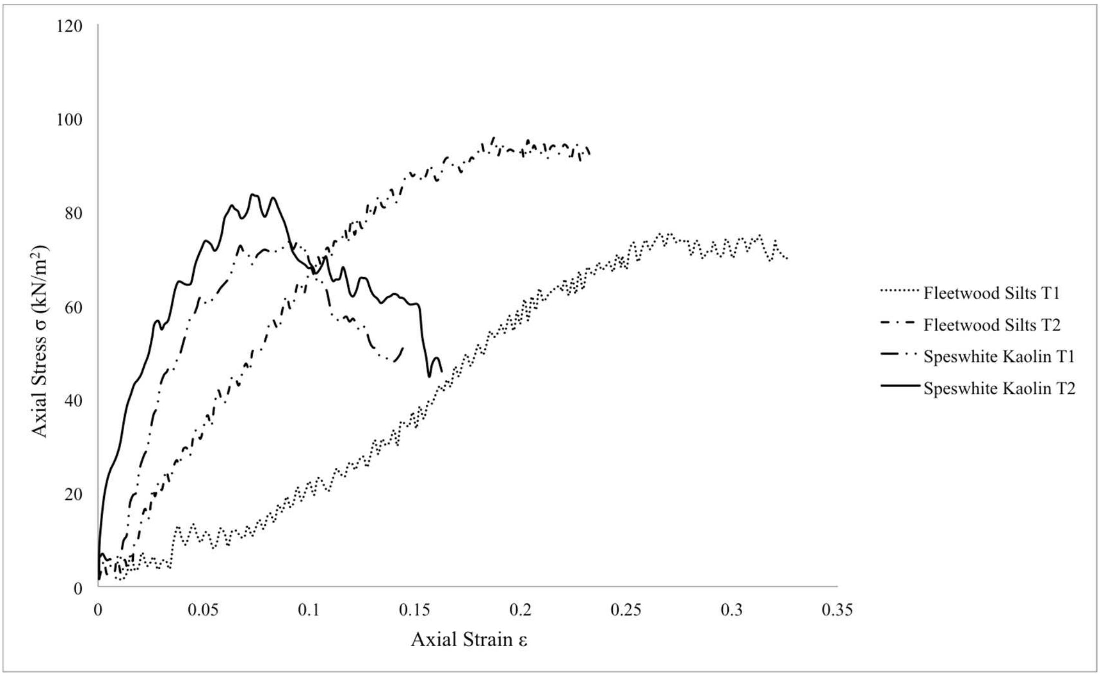


Figure 5.14 Stress vs strain graph for Fleetwood Silts and Speswhite Kaolin

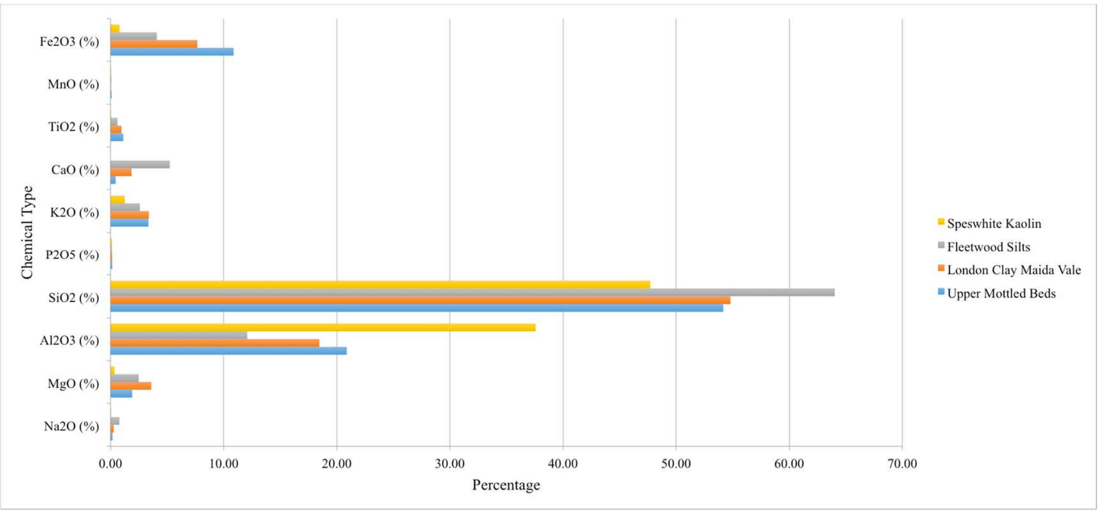


Figure 5.15 X-Ray Fluorescence chemical percentages for series 2 soil samples

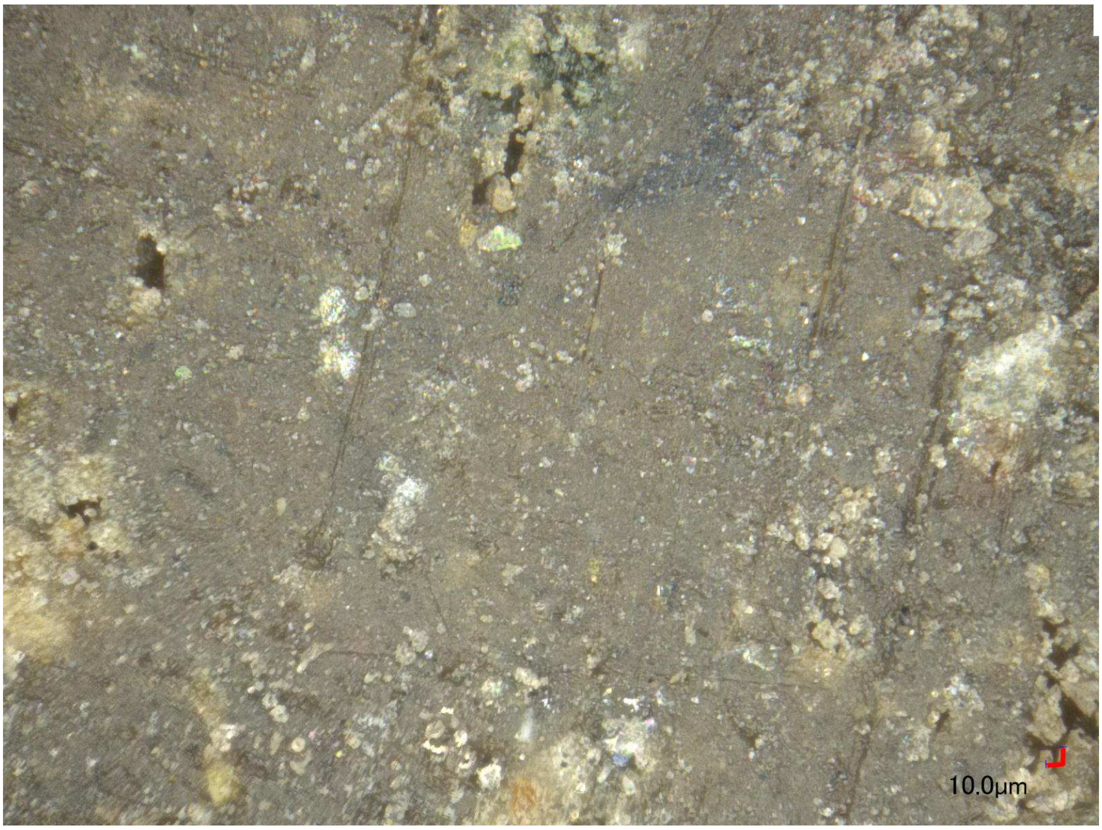


Figure 5.16 London Clay Maida Vale, 500x zoom

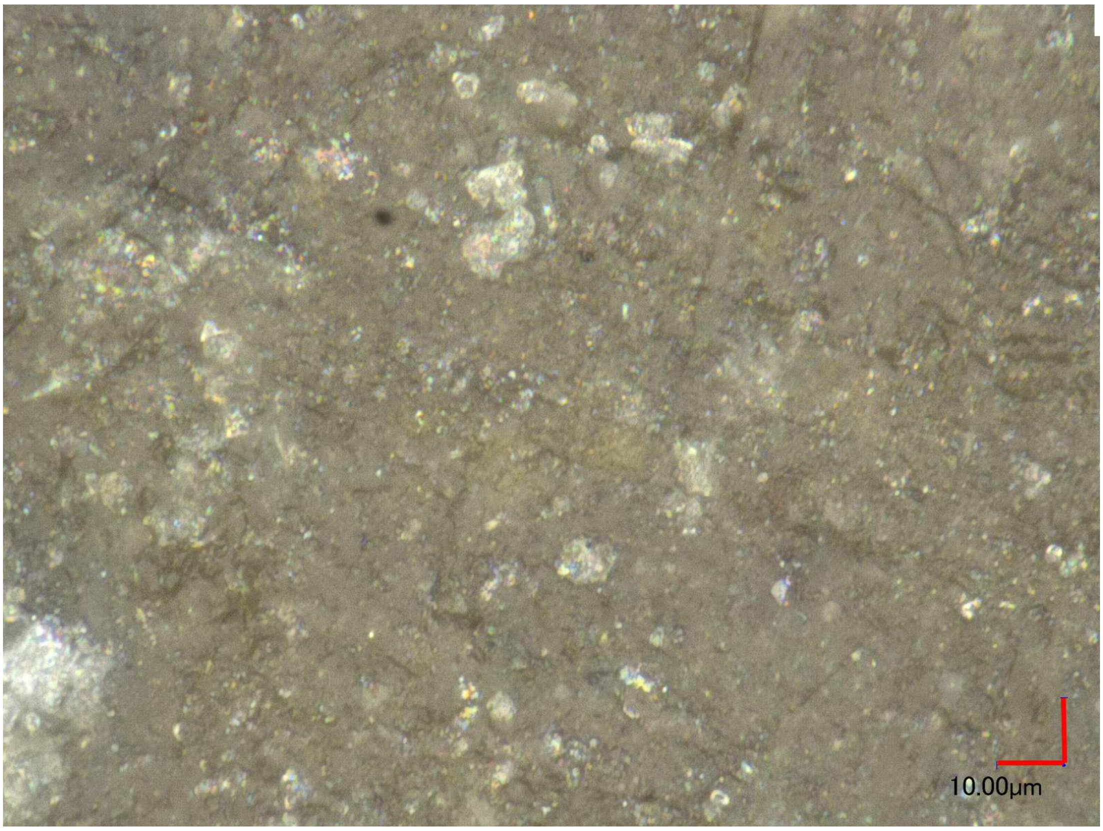


Figure 5.17 London Clay Maida Vale, 2000x zoom

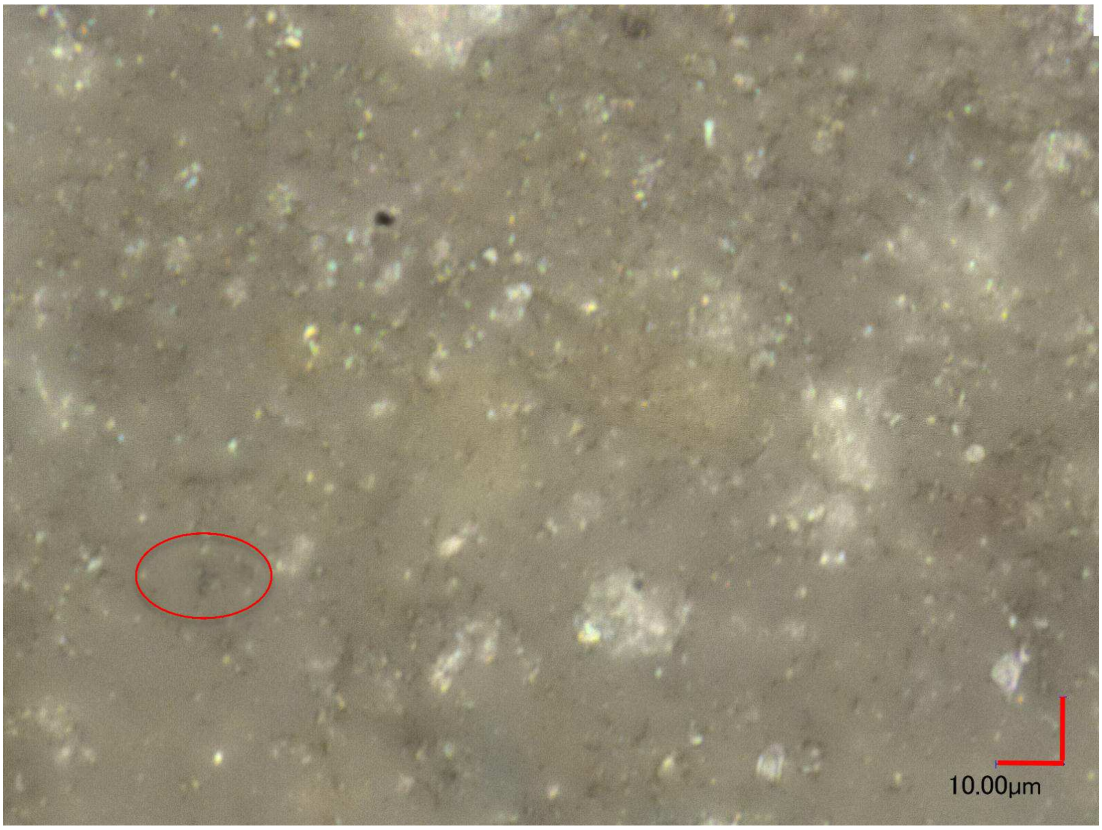


Figure 5.18 London Clay Maida Vale, 4000x zoom

(Red circled area highlights example of voids between peds, for comparison with Upper Mottled Beds images)

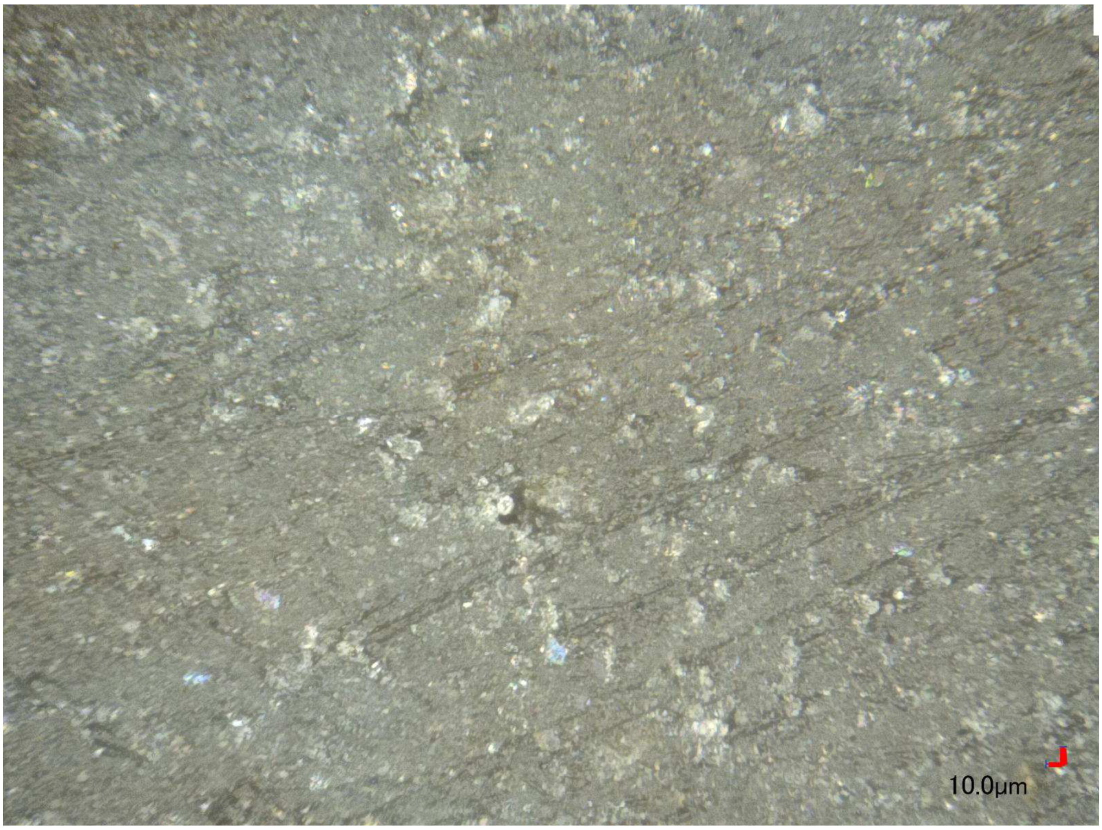


Figure 5.19 Upper Mottled Beds, 500x zoom

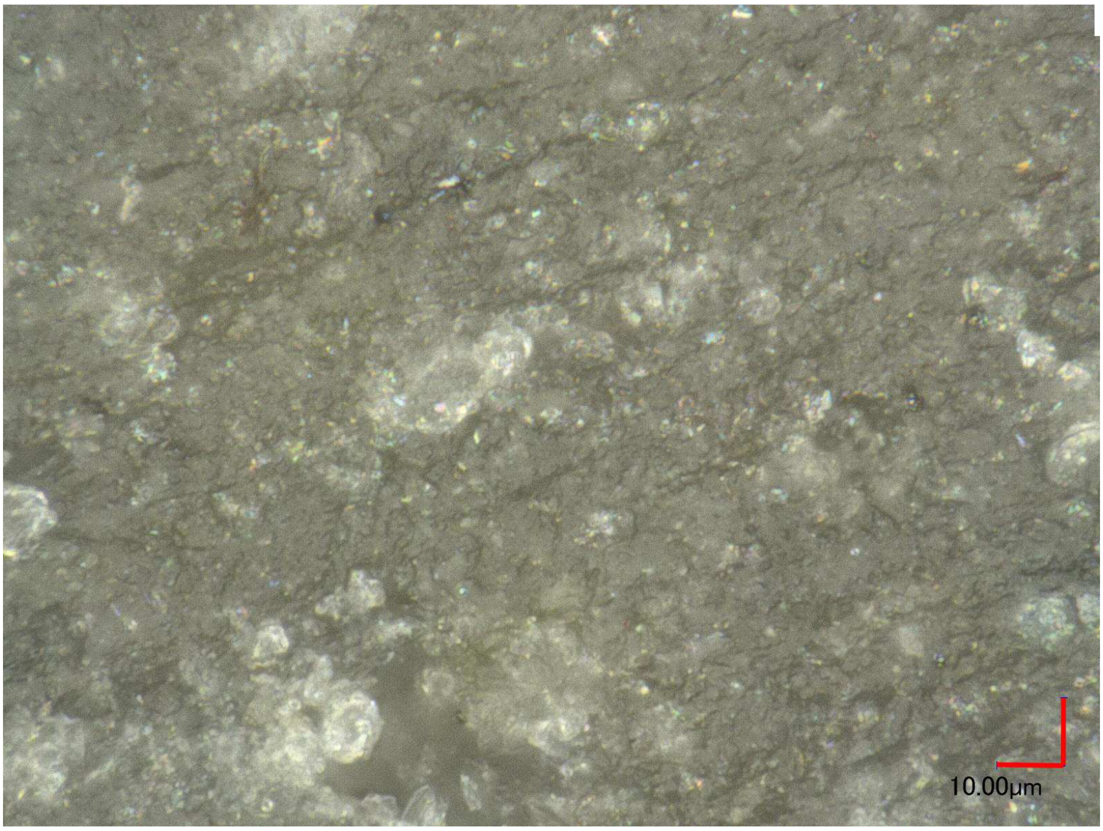


Figure 5.20 Upper Mottled Beds, 2000x zoom

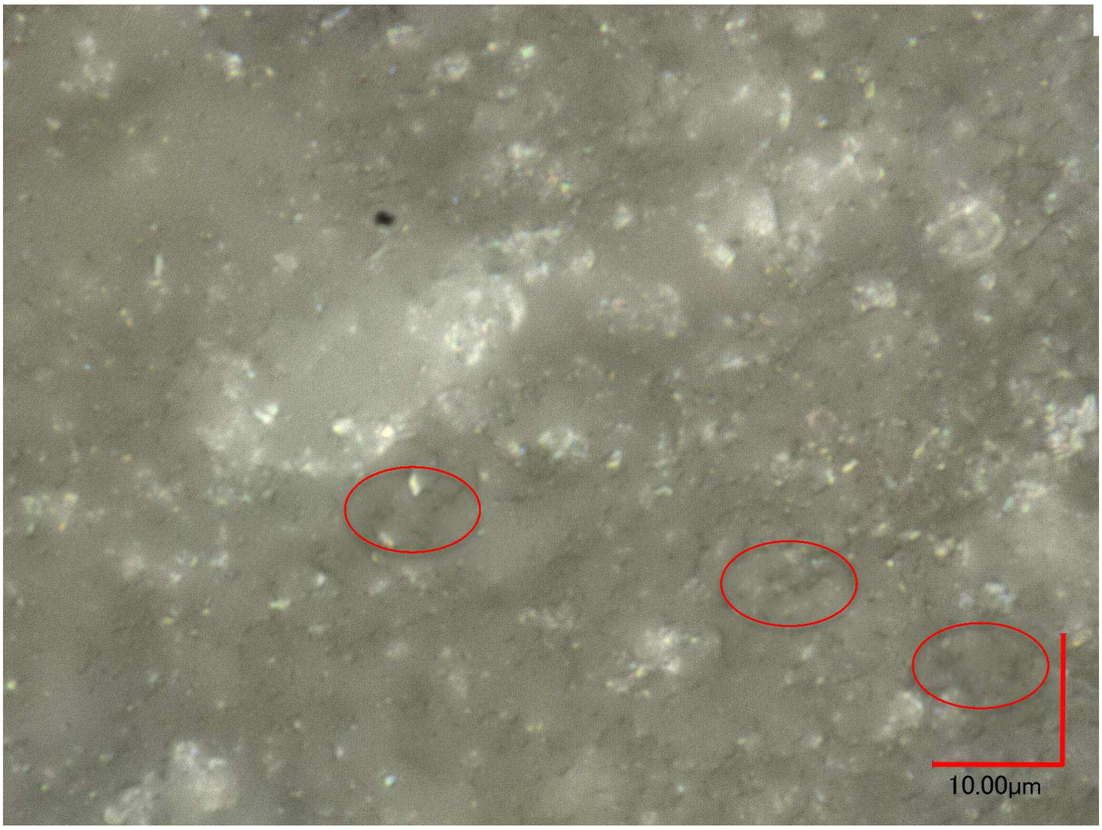


Figure 5.21 Upper Mottled Beds, 4000x zoom

(Red circled areas highlight voids between peds, for comparison with London clay images)

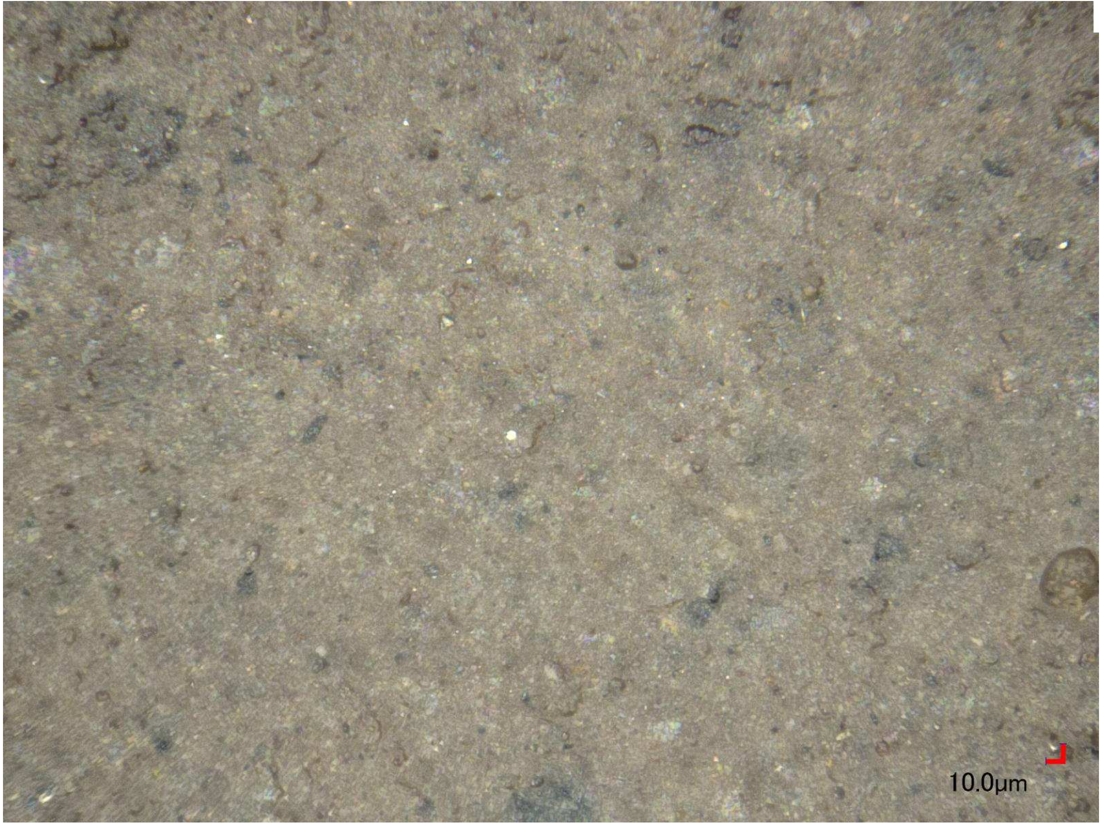


Figure 5.22 Fleetwood Silts, 500x zoom

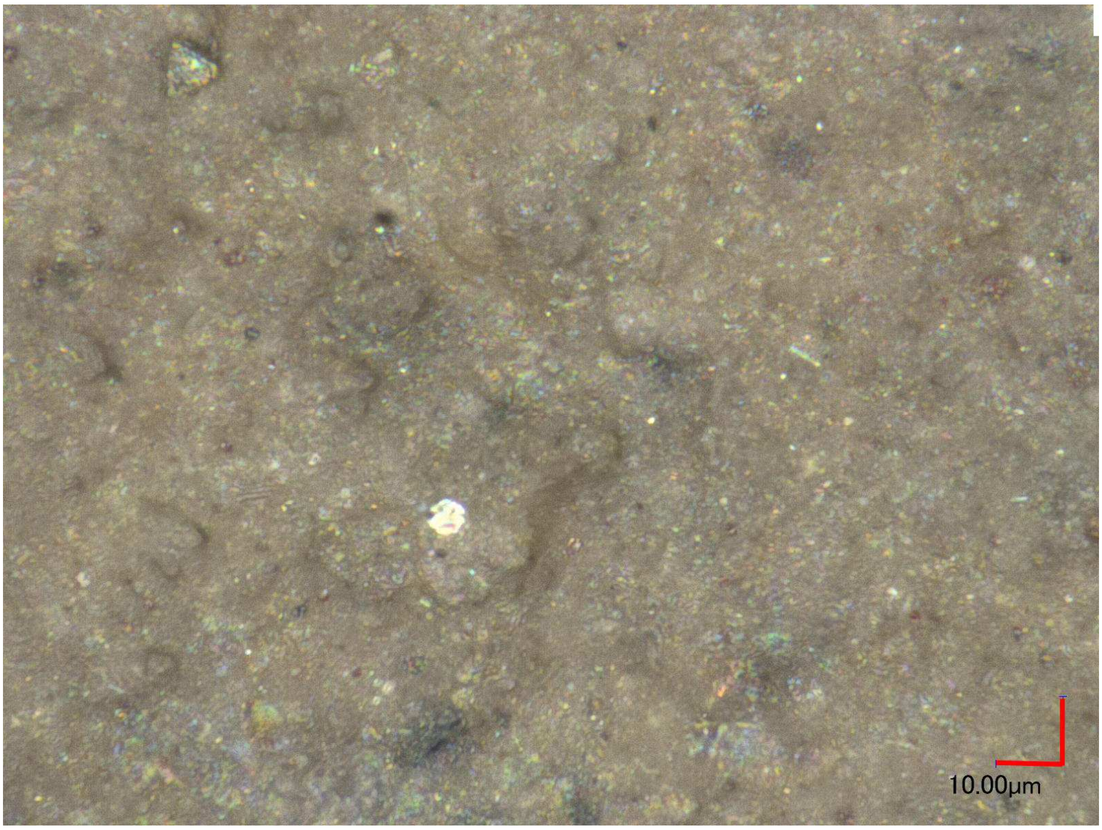


Figure 5.23 Fleetwood Silts, 2000x zoom

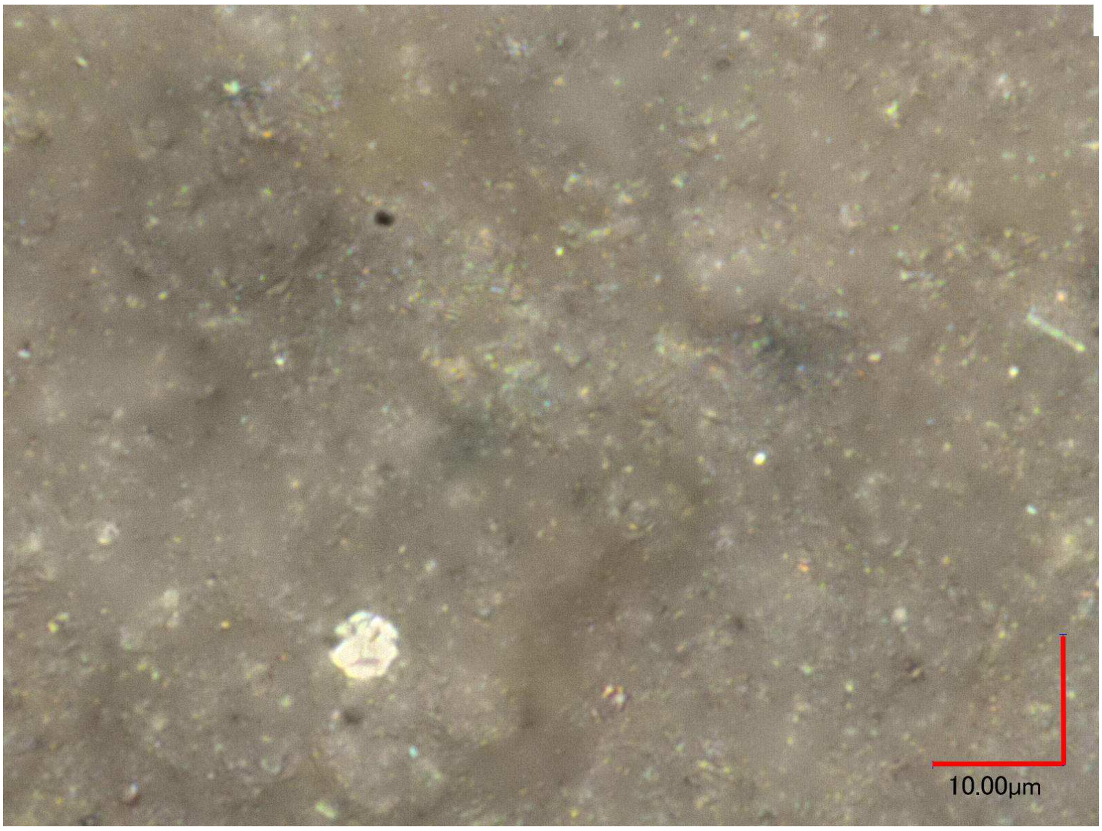


Figure 5.24 Fleetwood Silts, 4000x zoom

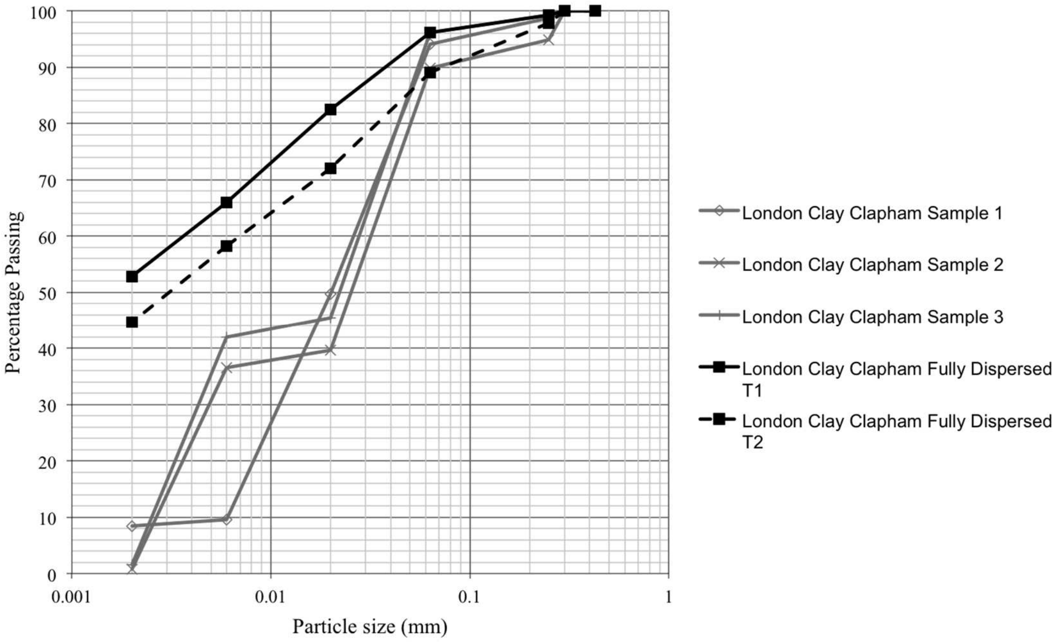


Figure 5.25 Particle size distributions for slurry samples collected from Clapham, with fully dispersed curves for clay at tunnel horizon

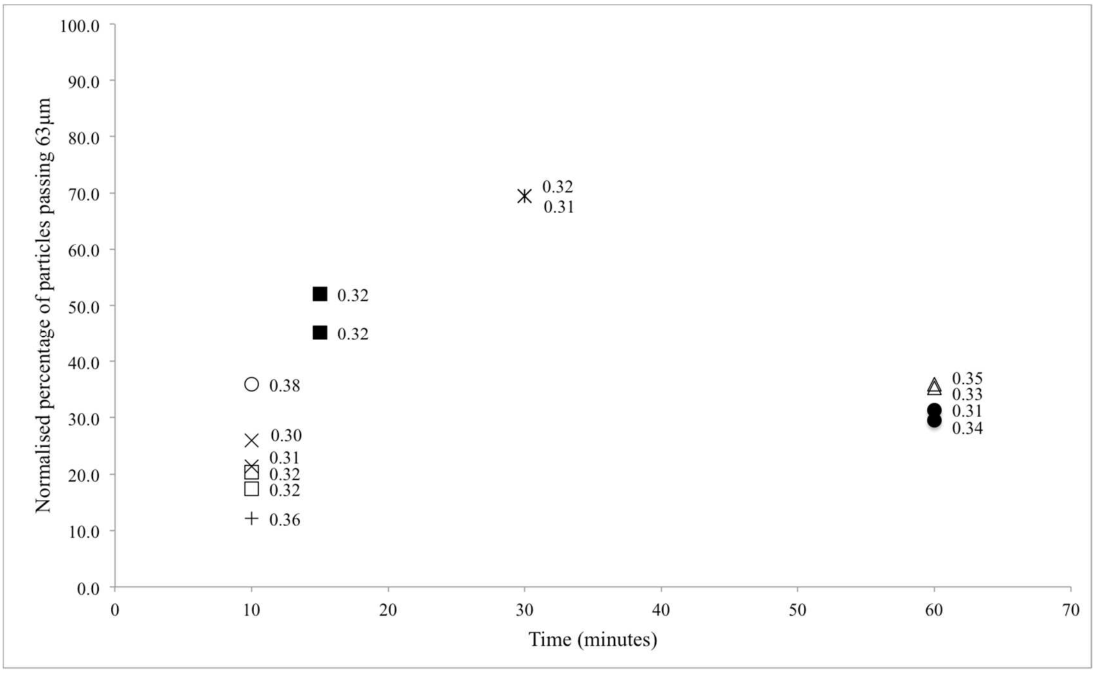


Figure 6.1 Speswhite Kaolin Series 2, mixing time against normalised percentage passing the 63 µm sieve. The data label gives liquidity index at the start of each test

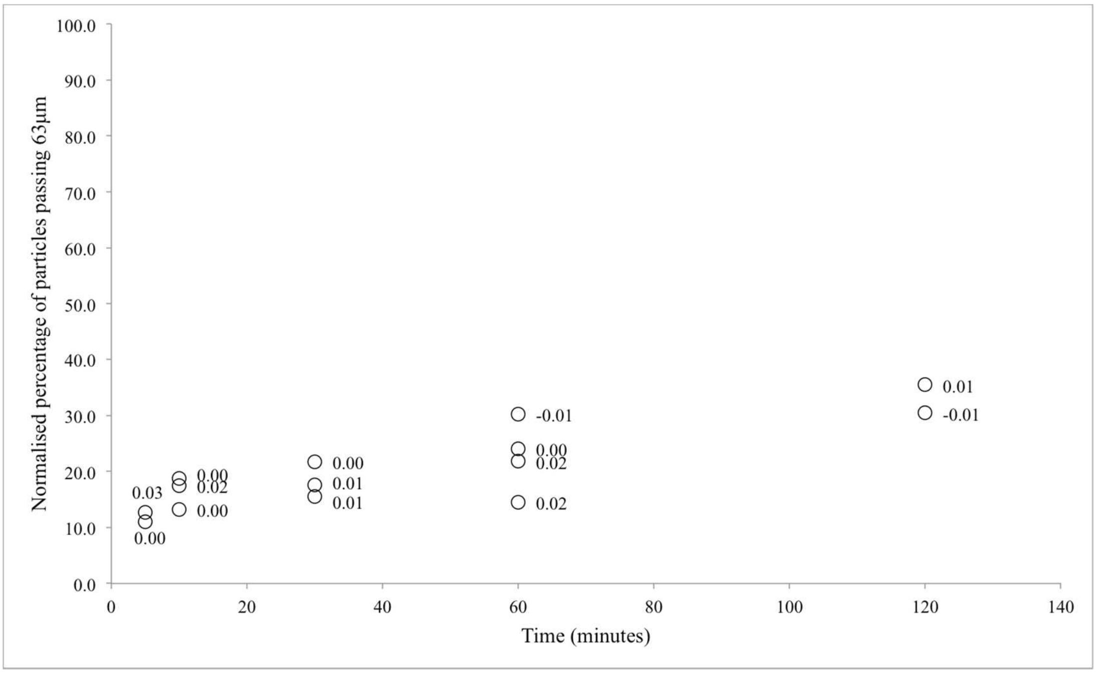


Figure 6.2 London Clay Maida Vale Series 2, mixing time against normalised percentage passing the 63 µm sieve. The data label gives liquidity index at the start of each test

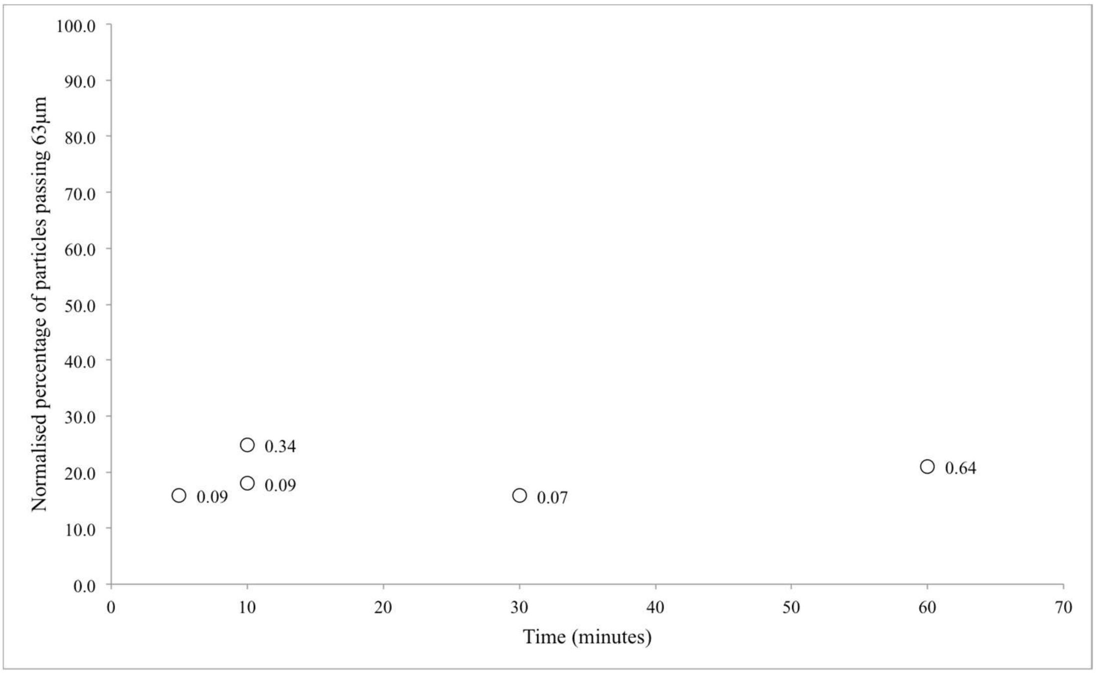


Figure 6.3 Fleetwood Silts Series 2, mixing time against normalised percentage passing the 63 µm sieve. The data label gives liquidity index at the start of each test

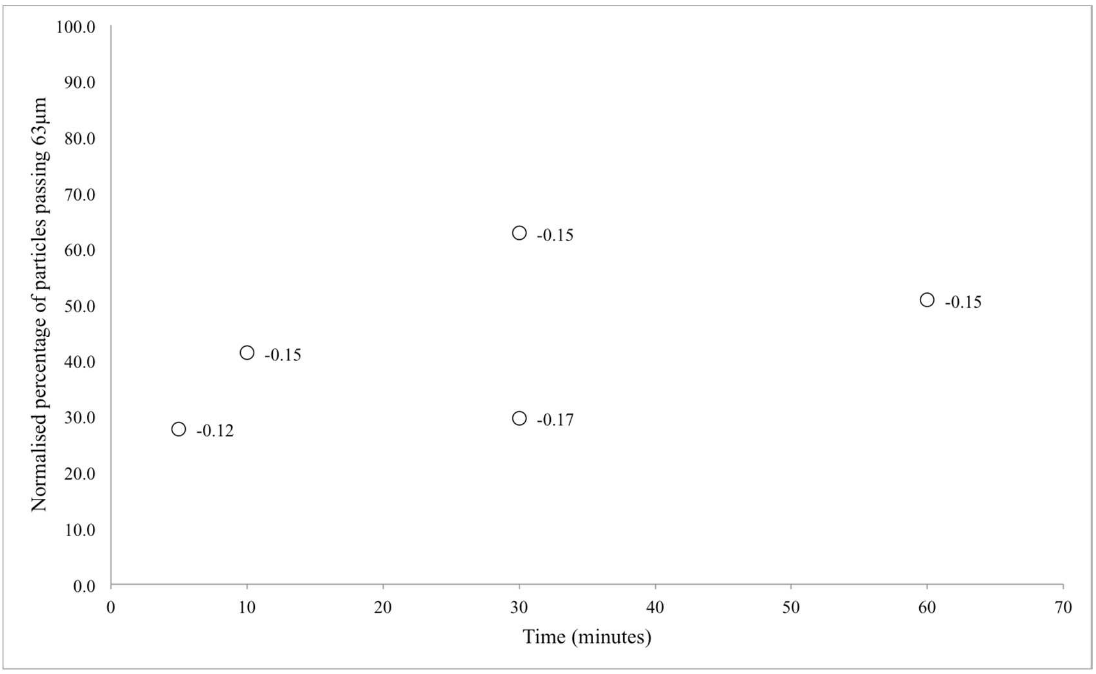


Figure 6.4 Upper Mottled Beds Series 2, mixing time against normalised percentage passing the 63 µm sieve. The data label gives liquidity index at the start of each test

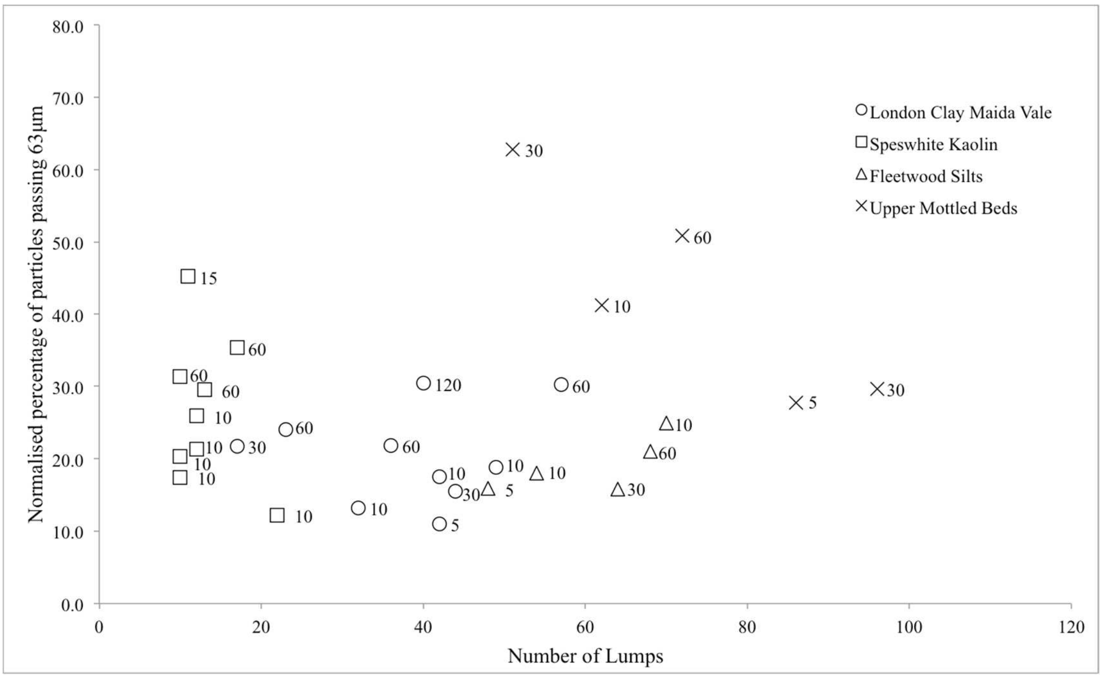


Figure 6.5 Compiled mixing test series 2, number of lumps against normalised percentage passing the 63 μm sieve. The data label gives the mixing time for each test.

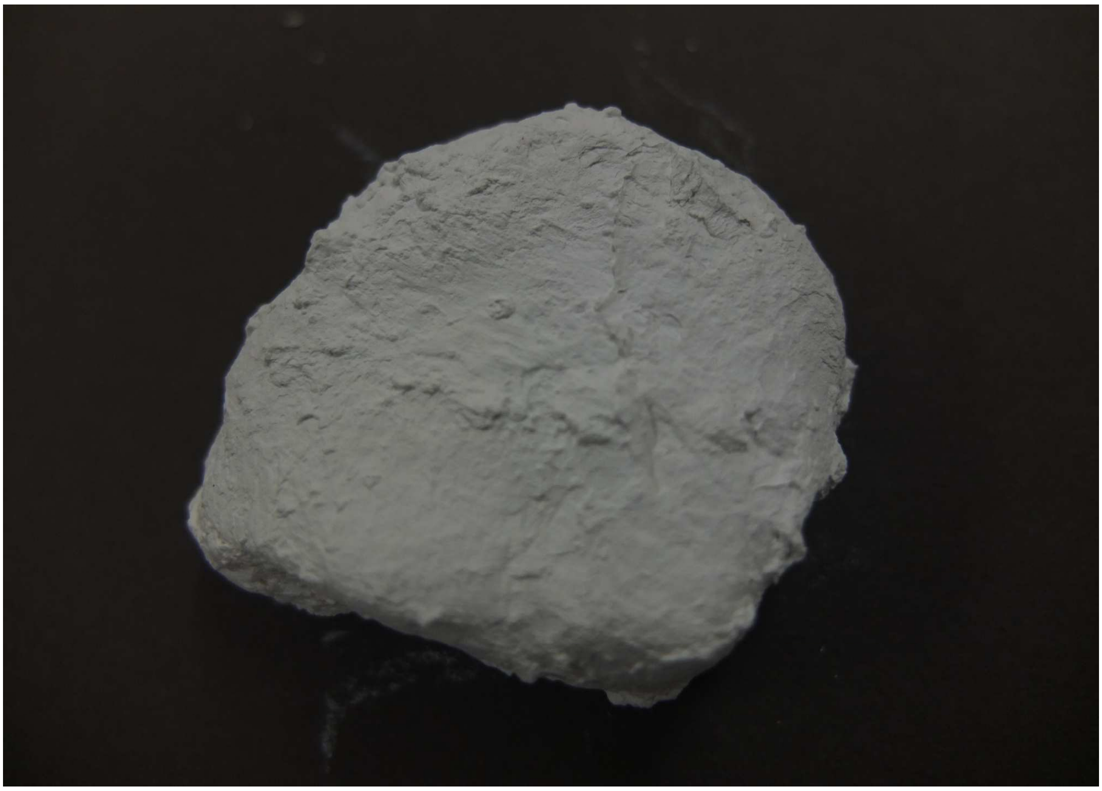


Figure 6.6 Single lump from Speswhite Kaolin 60 minute mixing test 4

Figure 6.7 Zoomed in crop of three lumps of Speswhite Kaolin from 10 minute test 4

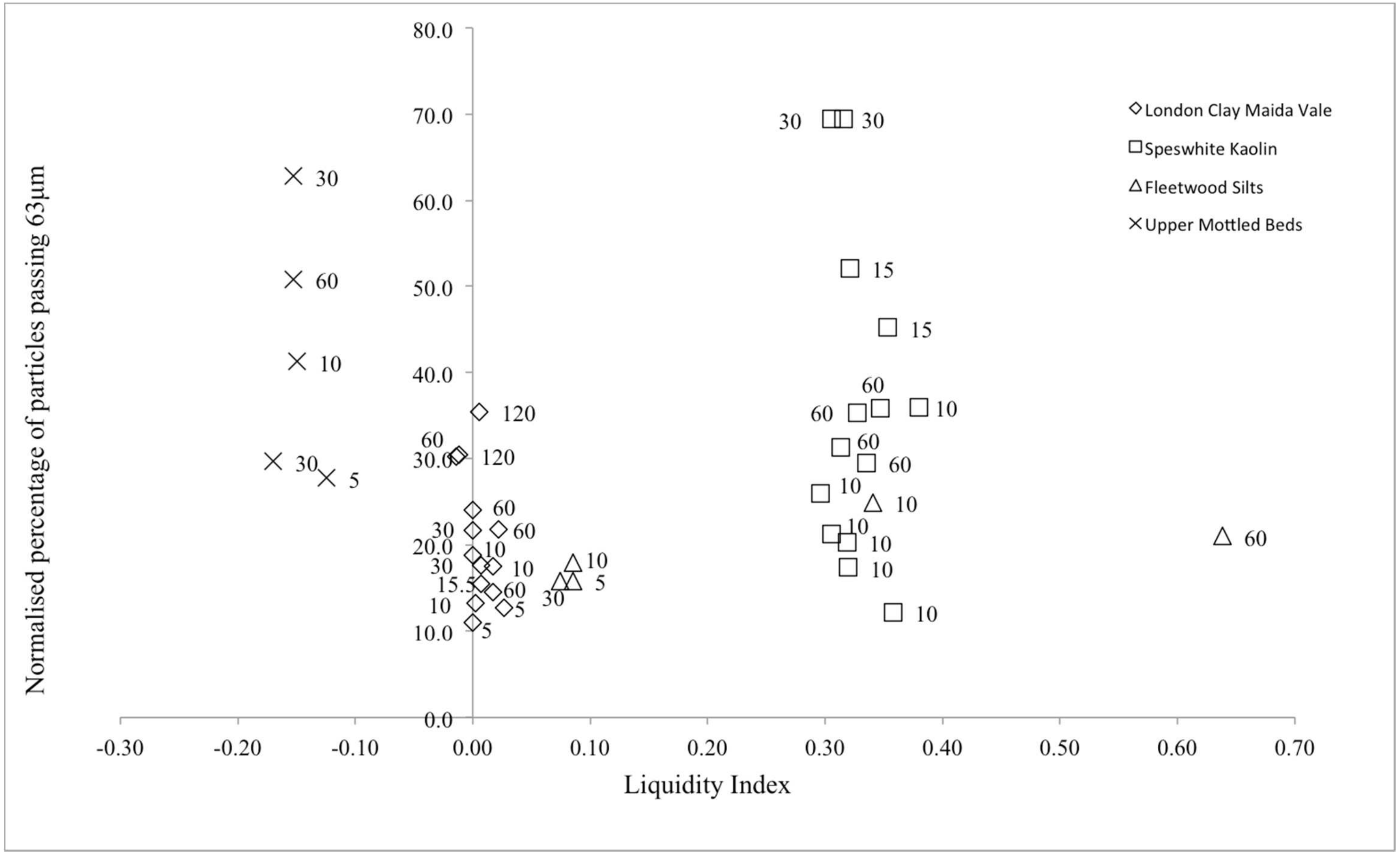


Figure 6.8 Compiled series 2 mixing test results for Liquidity Index against normalised percentage passing the 63 µm sieve. The data label gives the mixing time for each test.

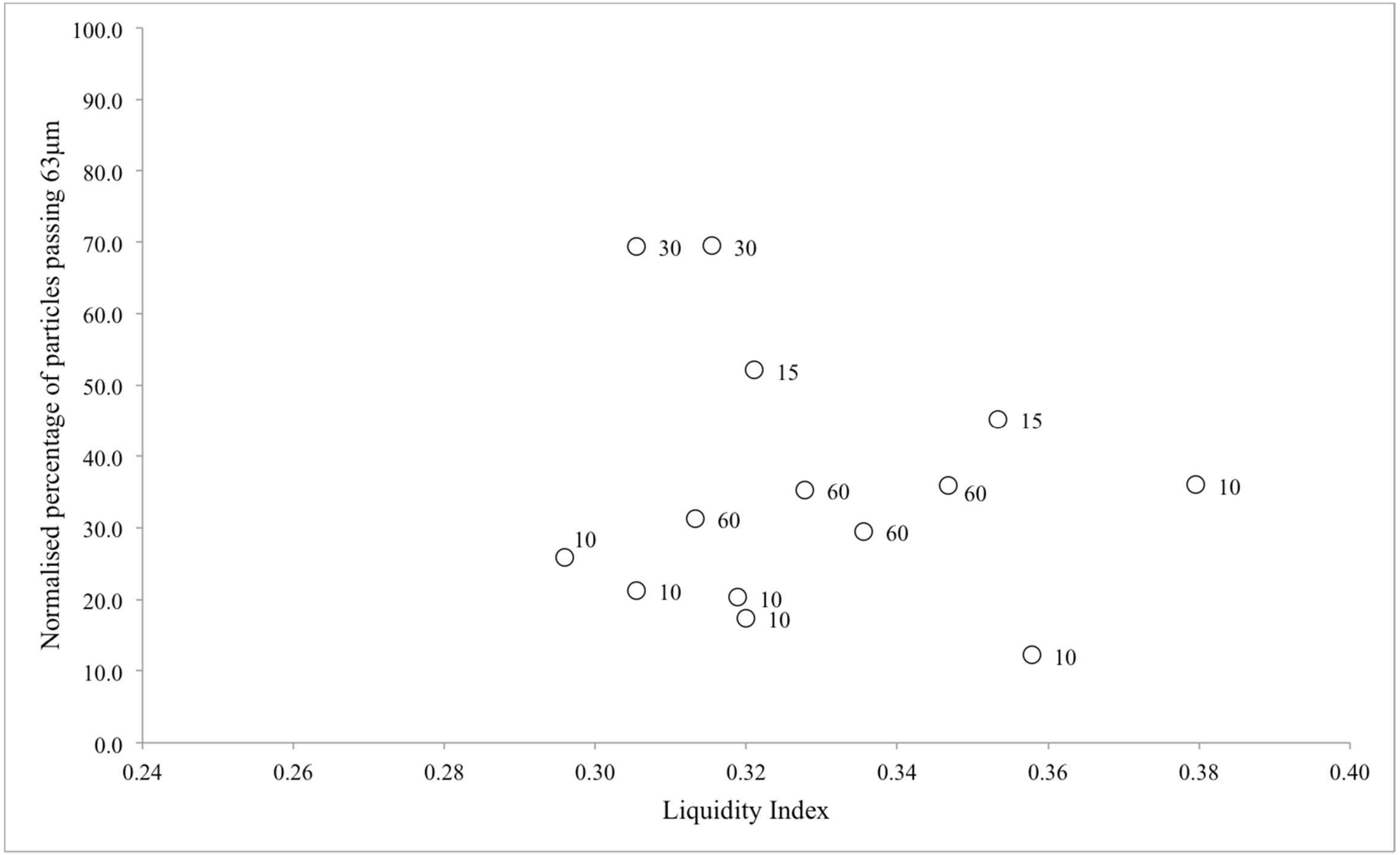


Figure 6.9 Speswhite Kaolin Series 2, Liquidity Index against normalised percentage passing the 63 µm sieve (ignoring outlying 30 minute tests and one 10 minute test). The data labels give the mixing time for each test

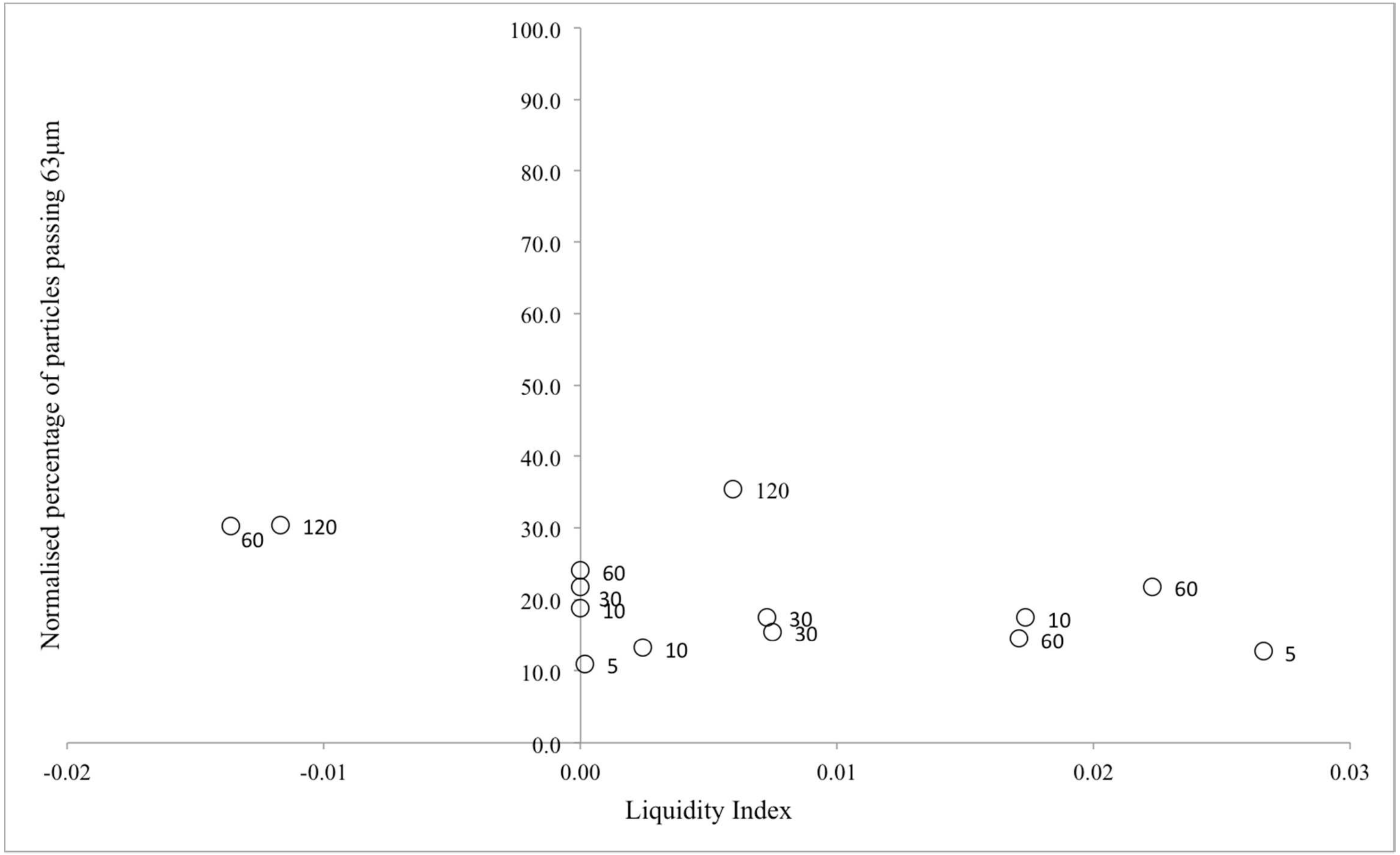


Figure 6.10 London Clay Maida Vale Series 2, Liquidity Index against normalised percentage passing the 63 µm sieve. The data labels give the mixing time for each test

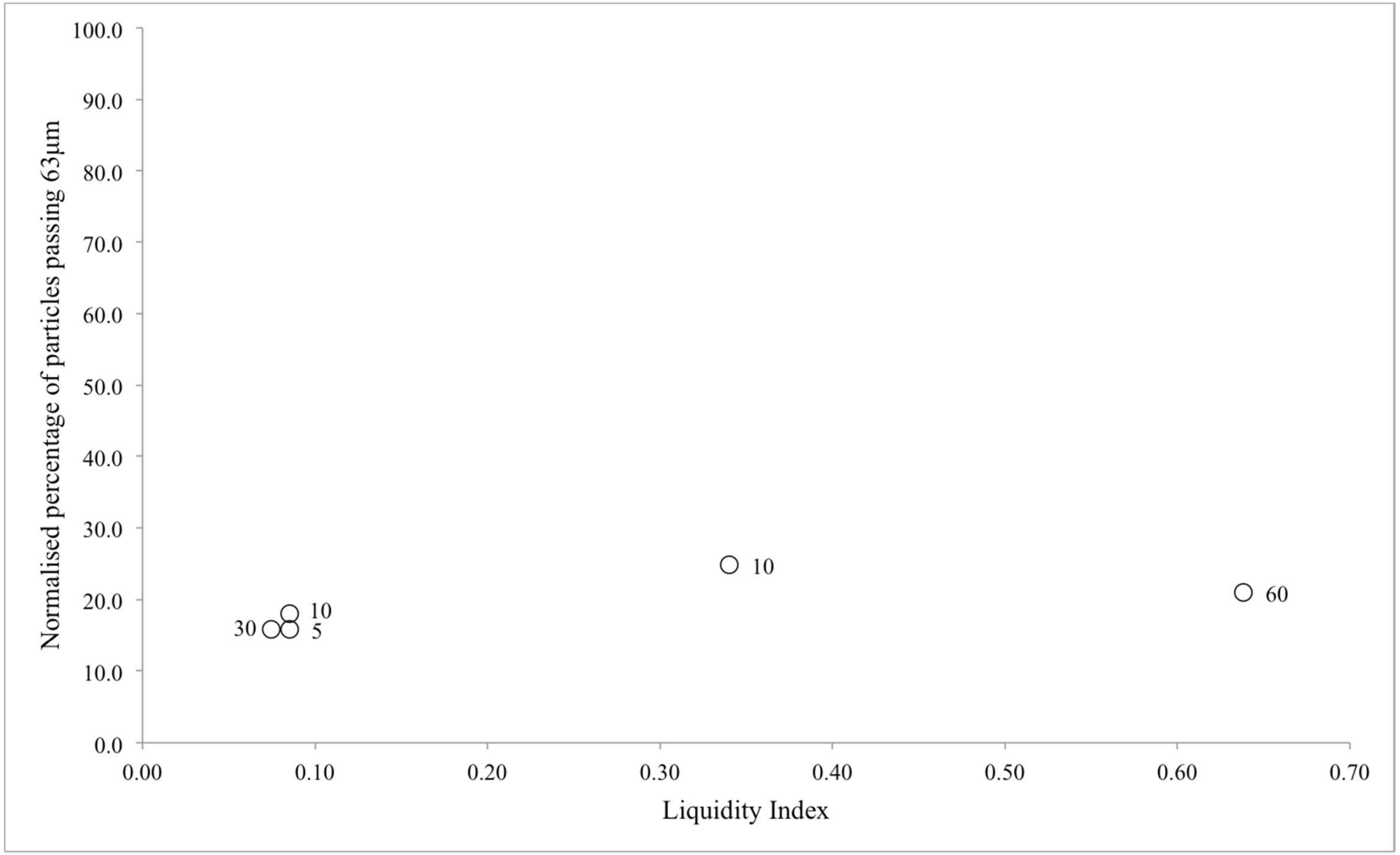


Figure 6.11 Fleetwood silts Series 2, Liquidity Index against normalised percentage passing the 63 µm sieve. The data labels give the mixing time for each test.

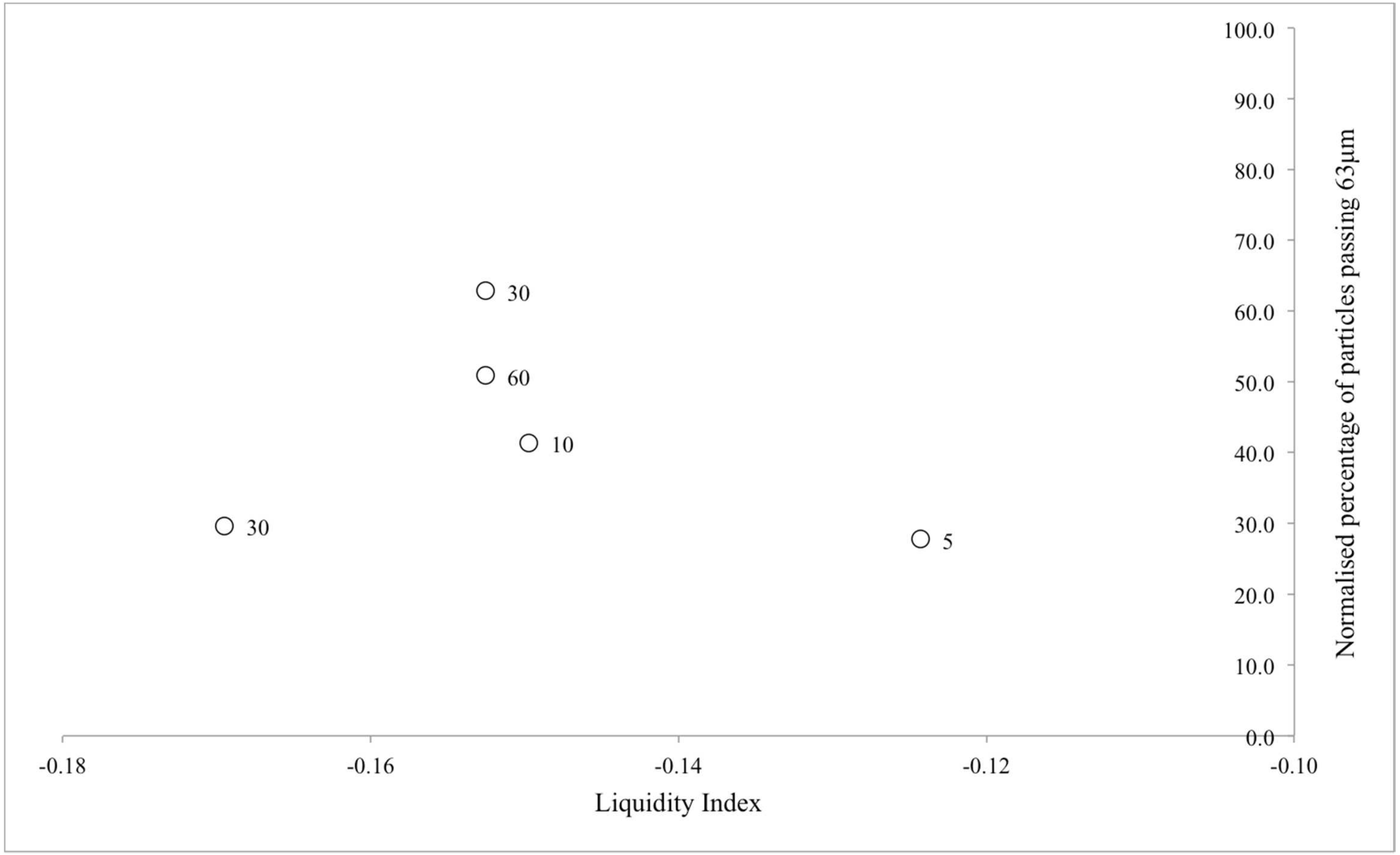


Figure 6.12 Upper Mottled Beds Series 2, Liquidity Index against normalised percentage passing the 63 µm sieve. The data labels give mixing time for each test

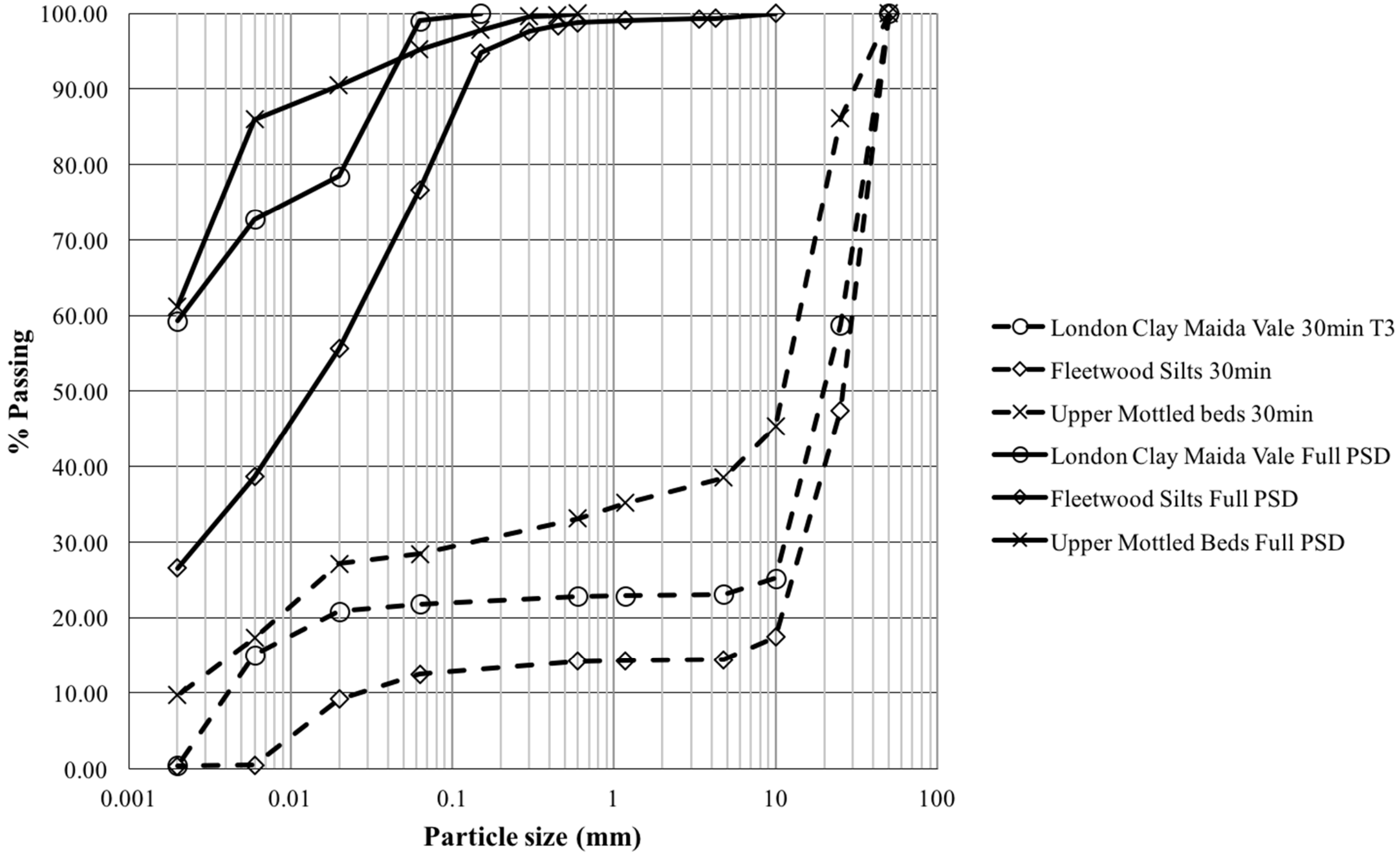


Figure 6.13 Comparison of mixing test results for 30 minute mixing time with sub 63 μm fraction

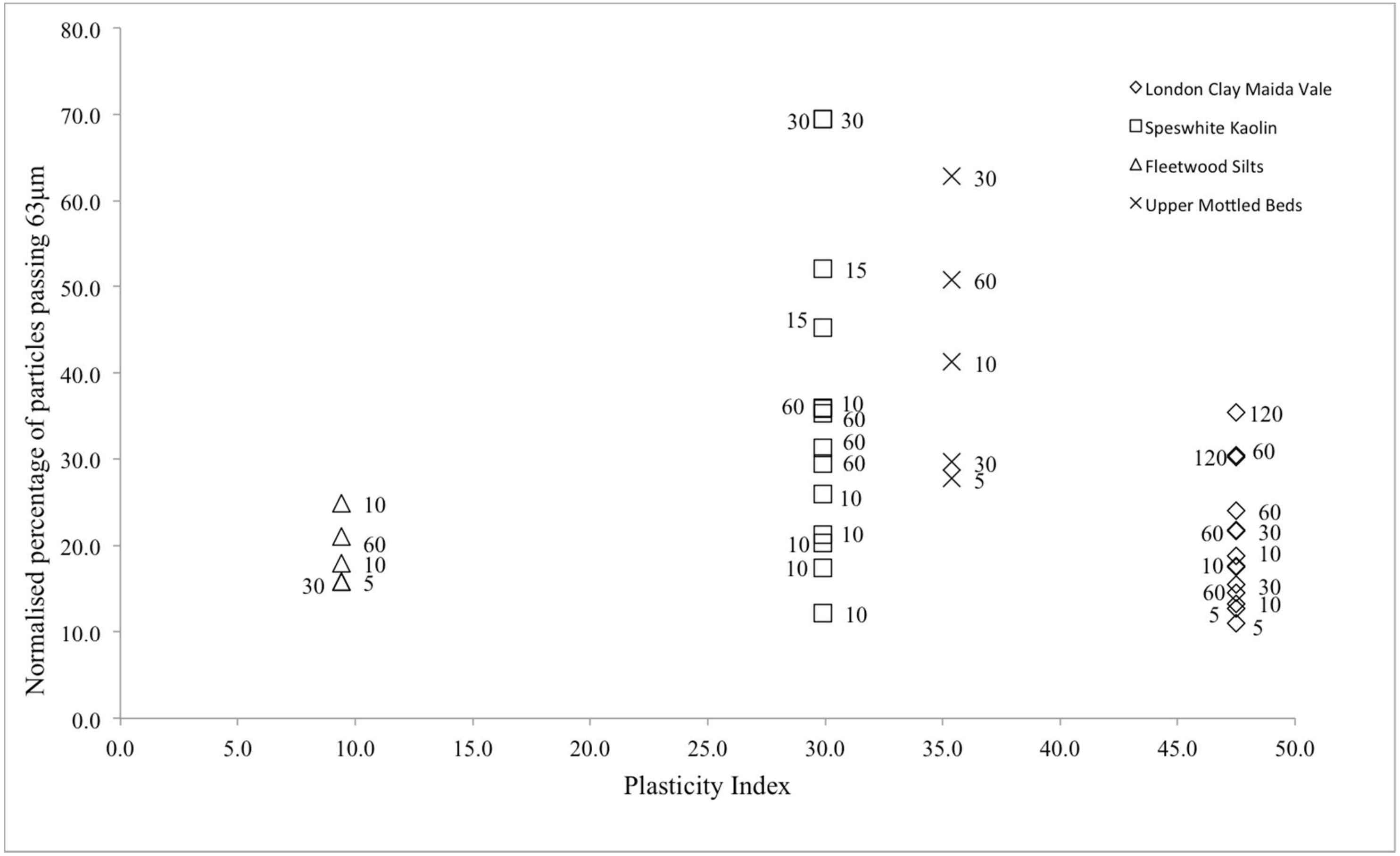


Figure 6.14 Compiled mixing test series 2, Plasticity index against normalised percentage passing the 63 μm sieve. The data labels give the mixing time for each test.

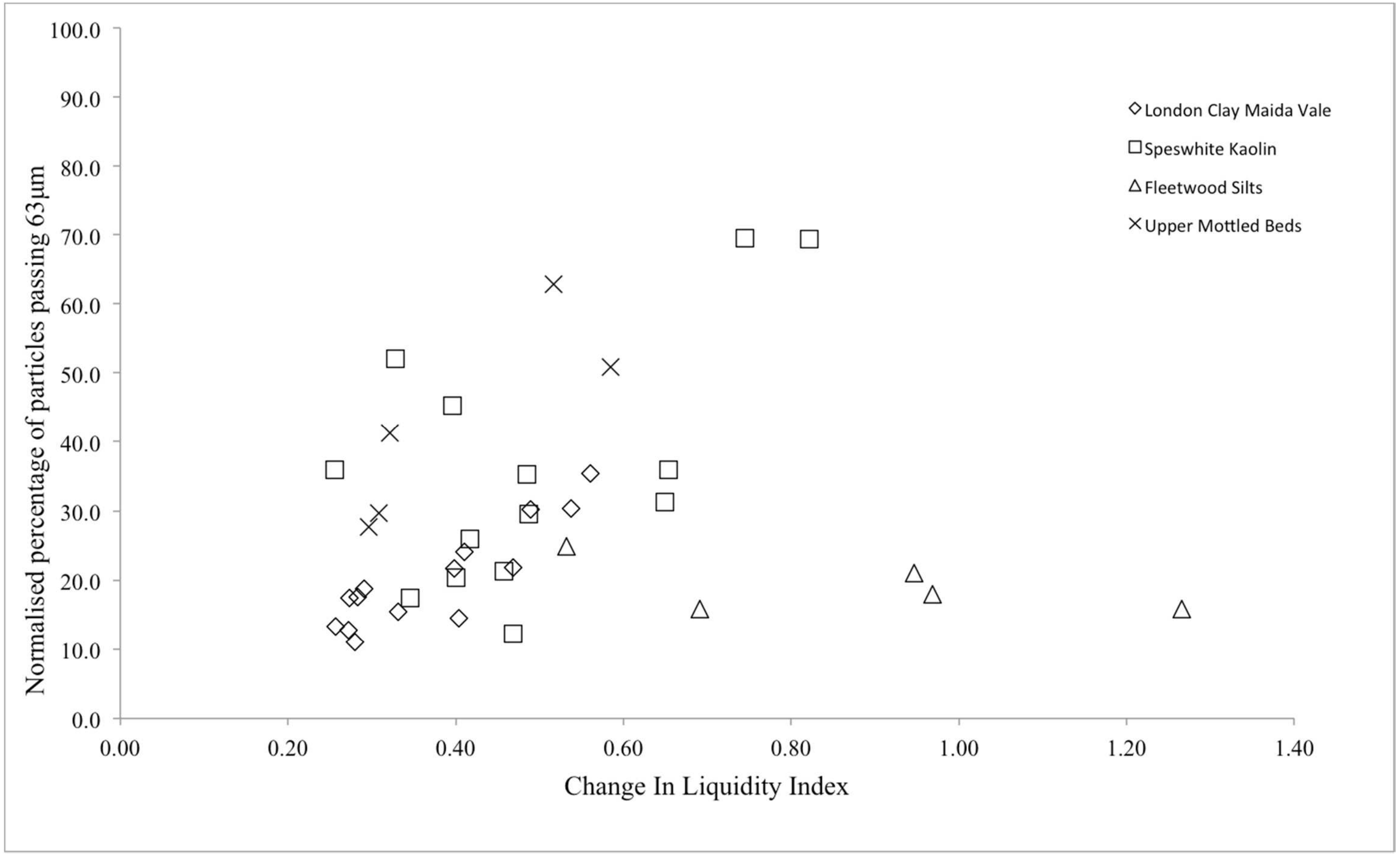


Figure 6.15 Compiled mixing test series 2, change in water content with respect to percentage passing the 63 µm sieve

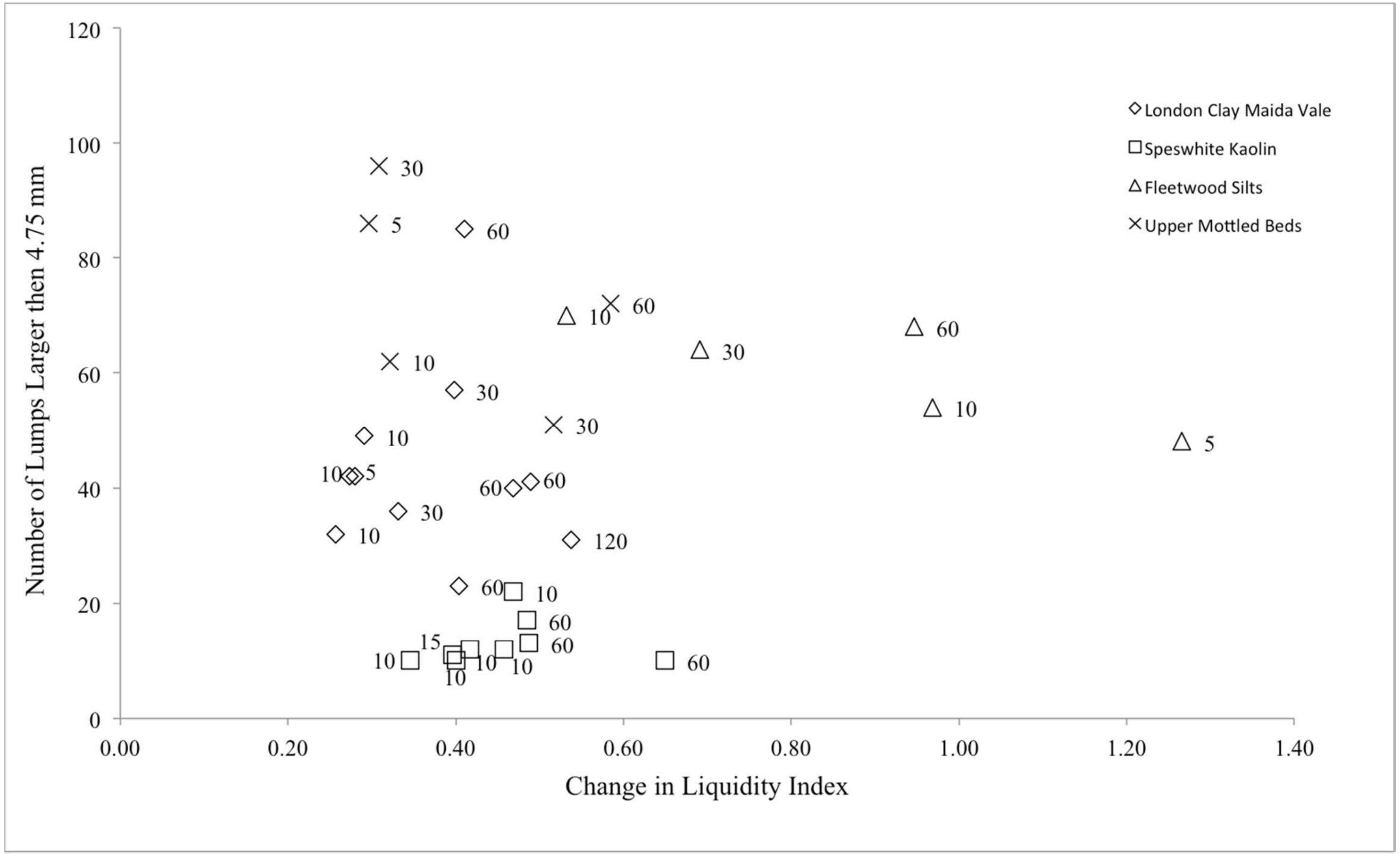


Figure 6.16 Compiled mixing test series 2, change in water content with respect to number of lumps. The data labels give the mixing time for each test.

Figure 6.17 London clay, Maida Vale, 0.15% HydroCut mixing test.) Flocculated material on the 1.18 mm sieve

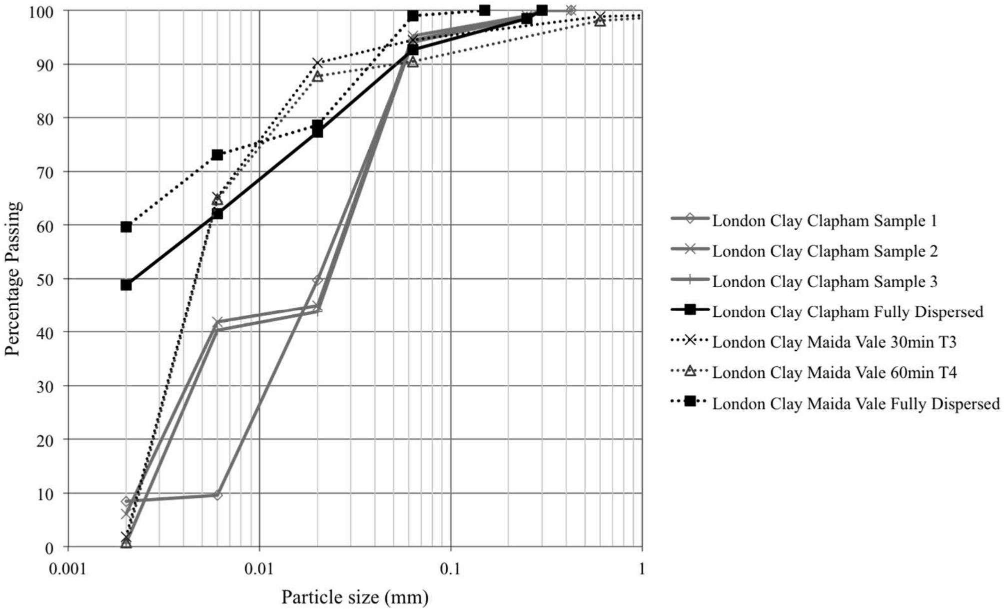


Figure 6.18 Slurry pipe jacking slurry grading (sub primary screen) and London Clay mixing tests (Sub 4.75 mm sieve)

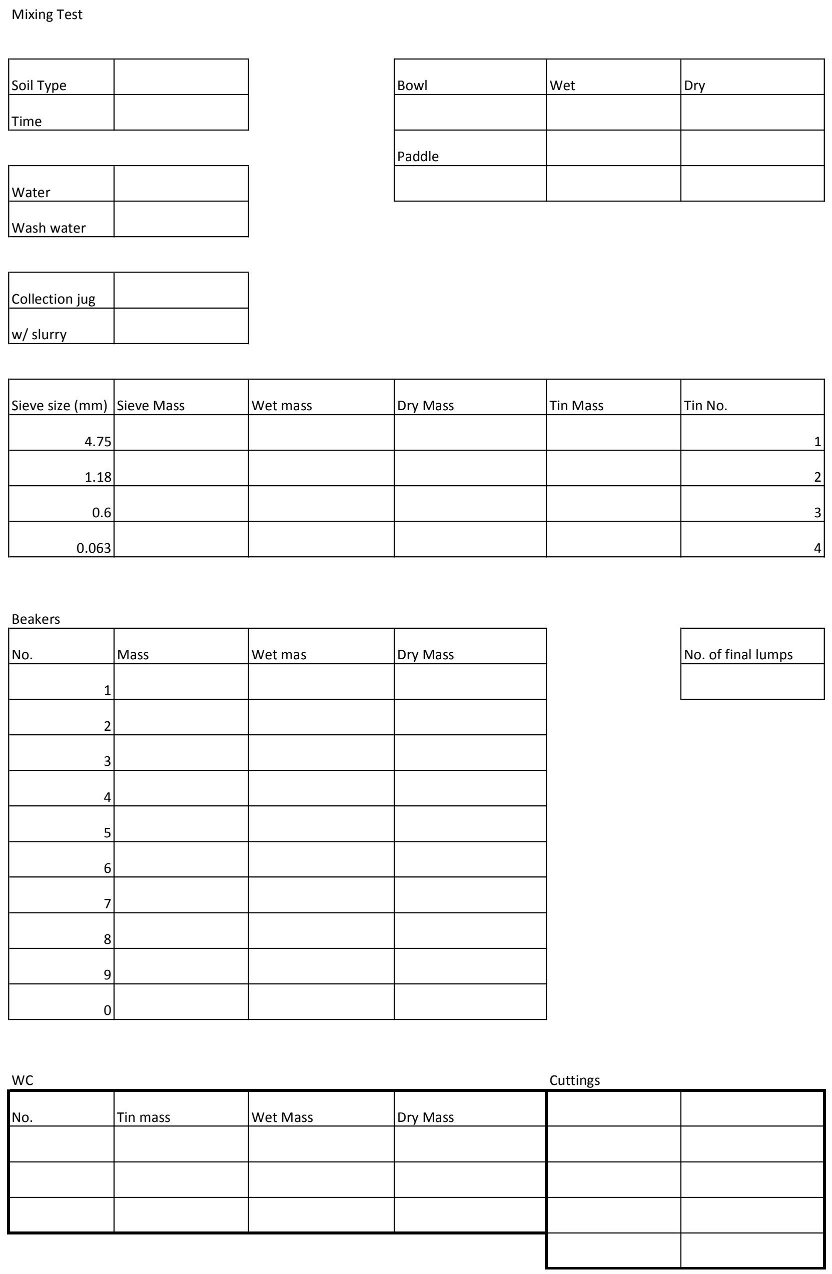
London clay cuttings on clay ball belt separator, mesh openings 3x50 mm

London Clay post 10 minute mixing test (dried and sized)

Figure 6.19 Comparison of London Clay samples from a pipe jacking site and mixing test

APPENDIX

Appendix A Mixing Log Sheet



Mixing Test

Soil Type	
Time	

Bowl	Wet	Dry
Paddle		

Water	
Wash water	

Collection jug	
w/ slurry	

Sieve size (mm)	Sieve Mass	Wet mass	Dry Mass	Tin Mass	Tin No.
4.75					1
1.18					2
0.6					3
0.063					4

Beakers

No.	Mass	Wet mas	Dry Mass
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			

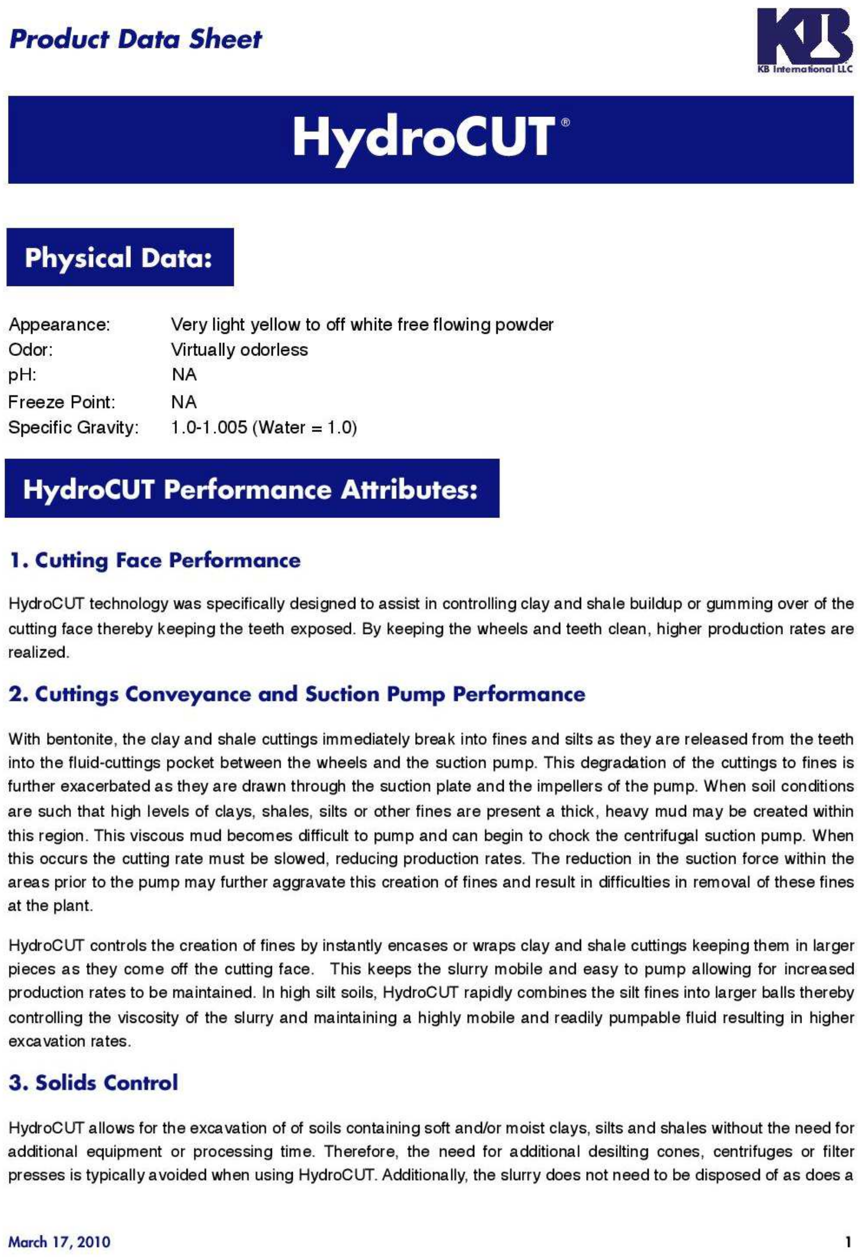
No. of final lumps

WC

No.	Tin mass	Wet Mass	Dry Mass

Cuttings

Appendix B HydroCut CF, manufactured by KB International Ltd



Product Data Sheet

KB International LLC

HydroCUT®

Physical Data:

Appearance:	Very light yellow to off white free flowing powder
Odor:	Virtually odorless
pH:	NA
Freeze Point:	NA
Specific Gravity:	1.0-1.005 (Water = 1.0)

HydroCUT Performance Attributes:

1. Cutting Face Performance

HydroCUT technology was specifically designed to assist in controlling clay and shale buildup or gumming over of the cutting face thereby keeping the teeth exposed. By keeping the wheels and teeth clean, higher production rates are realized.

2. Cuttings Conveyance and Suction Pump Performance

With bentonite, the clay and shale cuttings immediately break into fines and silts as they are released from the teeth into the fluid-cuttings pocket between the wheels and the suction pump. This degradation of the cuttings to fines is further exacerbated as they are drawn through the suction plate and the impellers of the pump. When soil conditions are such that high levels of clays, shales, silts or other fines are present a thick, heavy mud may be created within this region. This viscous mud becomes difficult to pump and can begin to chock the centrifugal suction pump. When this occurs the cutting rate must be slowed, reducing production rates. The reduction in the suction force within the areas prior to the pump may further aggravate this creation of fines and result in difficulties in removal of these fines at the plant.

HydroCUT controls the creation of fines by instantly encases or wraps clay and shale cuttings keeping them in larger pieces as they come off the cutting face. This keeps the slurry mobile and easy to pump allowing for increased production rates to be maintained. In high silt soils, HydroCUT rapidly combines the silt fines into larger balls thereby controlling the viscosity of the slurry and maintaining a highly mobile and readily pumpable fluid resulting in higher excavation rates.

3. Solids Control

HydroCUT allows for the excavation of of soils containing soft and/or moist clays, silts and shales without the need for additional equipment or processing time. Therefore, the need for additional desilting cones, centrifuges or filter presses is typically avoided when using HydroCUT. Additionally, the slurry does not need to be disposed of as does a bentonite fluid. All HydroCUT slurry is returned to the plant and augmented as required to maintain performance. This eliminates extra equipment and manpower requirements as well as the cost of bentonite disposal and the need for large quantities of makeup water.

4. Soil Stabilization and Grouting Effects

During the initial fluid loss spurt, HydroCUT penetrates into porous soils where it functions as a chemical grout, greatly increasing the strength of low cohesion porous soils. This means that a panel can be held open for prolonged periods of time without the worry of the panel becoming unstable.

When used under normal practices, HydroCUT is not effected by seawater. Slurry viscosity and performance parameters are maintained during excavation insuring that the same level of quality is achieved as in non-marine conditions without all the drawbacks of using a bentonite slurry in a saltwater environment.

5. Environmental & Slurry Disposal

Under normal excavating conditions, HydroCUT slurry is not discarded until the end of the job. It is reused throughout the length of the project. Unlike spent bentonite, which is considered a hazardous waste, there is no need to truck the remaining slurry off to a landfill or other disposal site.

KB's HydroCUT technology is environmentally friendly and readily disposed to municipal sewer systems. At the completion of a project any remaining HydroCUT fluid is typically discharged under permit to the local municipal waste system. In many cases it may even be discharged directly to the construction site under the owner's or general contractor's permit for site water disposal. There is no need to truck the remaining slurry off to a landfill or other disposal site. If the slurry's viscosity requires lowering, this can be done by dilution with locally available water (pond, run off, river, ocean, etc.) or by the addition of a small quantity of a decomposition product.

General Application Instructions:

HydroCUT should be mixed initially at a minimum rate of about 1.00 kg/m^3 to ± 1.50 kg/m^3 of fresh water. HydroCUT may be mixed in a typical bentonite mixer. More preferably, it should be added and mixed in a KB Eduction Mixing Unit due to the ease of addition and the efficiency in yield, see KB's "HydroCUT Mixing Unit" brochure for specifics of this unit. A smaller eduction unit may be setup feeding directly to the slurry line flowing to the excavation for rapid augmentation of product if required. Feed rates at this in-line unit vary from 1.0 kg/m^3 to ± 1.5 kg/m^3 of slurry. The slurry viscosity, using the Marsh Funnel Method in sec./qt., typically range between 34 seconds and 42 seconds depending on the type of soils being excavated and the formation water quality.

Small solution feed units for specialty additives are setup to feed directly into the slurry line flowing to the excavation as well as returning from the hydro mill to the solids removal plant are also recommended. These allow for addition of specialty additives to enhance the slurry's properties and performance in various soil conditions and under excavation parameters.

Pre-Project Planning & Plant Design:

Please consult with KB's Engineering department for pre-project slurry and equipment planning to insure optimization in equipment requirements, placement of equipment and feed units, and slurry design.

Packaging:

25 kilo / 55 lb. plastic bags
Super Sacks on Request were bulk addition systems are in place

Availability:

HydroCUT is currently available from KB's US warehouse in **Charleston, SC USA**

Please check with KB to see if HydroCUT is available from one of its regional warehouses in your area

KB is also open to discussing local warehousing in locations where larger projects will be conducted.

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