Mechanisms for the disaggregation of soil cuttings in slurries

Mécanismes pour la désagrégation des sédiments de sol dans les boues

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ABSTRACT A series of tests has been undertaken on a variety of different soils to understand how soil cuttings disaggregate when pumped from the tunnel face to the separation plant during slurry tunnelling for pipe jacked tunnels. It is important to understand this process to ensure that the separation plant can be optimised to remove the maximum amount of soil from the slurry prior to the reuse of the liquid. In pipe-jacking operations this liquid is normally water, which is recirculated after the soil has been removed to minimise and if possible eliminate the production of liquid waste.

The paper will present results from a series of "mixing tests", devised by the authors to investigate disaggregation, and also from standard laboratory tests undertaken to establish basic soil properties such as soil strength. The "mixing tests" simulate the softening of the cuttings due to the presence of water and the shear forces applied to the slurry by the pumps and have already allowed the effect of these factors to be quantified. This series of tests will demonstrate how the mechanism of disaggregation varies with strength resulting in different proportions of disaggregated soil particles in slurries subjected to the same mixing time and shear forces.

RÉSUMÉ Une série de tests a été réalisée sur une variété de différents types de sols de comprendre comment les sédiments de sol désagrége lorsqu'il est pompé afin de la surface du tunnel à l'usine de séparation en suspension tunnel pour les tunnels de tuyaux pillée. Il est important de comprendre le processus pour garantir que l'installation de séparation peut être optimisée pour éliminer le maximum de sol à partir de la suspension avant la réutilisation du liquide. Dans les opérations de poussée de tuyaux de ce liquide est normalement de l'eau, qui est remis en circulation après que le sol a été enlevée pour réduire et si possible éliminer la production de déchets liquides.

Le document présentera les résultats d'une série d'"essai de mélange", mis au point par les auteurs pour étudier la désagrégation, ainsi que des tests de laboratoire standards entrepris pour établir les propriétés du de base sol telles que la résistance. Les "essais de mélange" simuler le ramollissement des sédiments en raison de la présence d'eau et les forces de cisaillement appliquées à la suspension par les pompes et ont déjà permis l'effet de ces facteurs doit être quantifiée. Cette série de tests va montrer comment le mécanisme de désagrégation varie en fonction de la résistance résultant dans des proportions différentes de particules de sol désagrégés dans les boues soumises à la même période de mélange et de cisaillement.

1 INTRODUCTION

Soil slurry has been used as a support and transportation medium for tunnelling and pipe jacking since the 1970's. The slurry is normally water based and for efficiency and environmental reasons it is reused in a closed loop system, resulting in the need to remove all excavated solids from the slurry in surface treatment plant. The solids enter the slurry at the tunnel face as cuttings. The size of these cuttings and any remoulding of the soil in the cuttings are dependent on the design of the cutter head used on the tunnel boring machine (TBM).

Once the cuttings have entered the slurry they are pumped to the surface separation plant using in line centrifugal pumps through a steel pipeline laid close to the invert of the tunnel. The number of pumps and length of pipe are dependent on the tunnel length and consequently vary during the excavation of the tunnel. During this process, the excavated cuttings disaggregate due to the shear applied to the cuttings by the pumps and at the pipe walls, resulting in slurry that contains a mixture of particles and aggregates of particles of differing sizes. The separation plant has to be designed to remove these from the slurry which is achieved with a combination of shaker screens or clay belts for particles/aggregates of greater than 5 mm; hydrocyclones to remove sand and some coarse silt size particles and decanting centrifuges or filter presses to remove clay and remaining silt fraction, i.e. mainly particles smaller than 30 µm, but typically including particles up to 63 µm. The latter are the most expensive elements of the plant and consequently the initial driver for the research was to be able to predict the proportion of sub 63 µm particles in the slurry that reach the separation plant given the tunnel length/number of pumps and the soil type.

This paper investigates the dependence of the disaggregation process on some easily obtained basic soil parameters including the unconfined compressive strength of the soil being excavated – a quantity easily measured or estimated from conventional borehole logs or site investigation data and which can be an indicator of cementation or other inter-particle bonding. The disaggregation process is examined using a "mixing" test previously described in Phillips et al. (2014). Based on the correlations obtained possible mechanisms of disaggregation are discussed.

2 SOIL TESTED

A relatively wide range of soils have been tested. Results from a representative selection of these are reported in this paper and these soils are listed in Table 1 together with values for Atterberg limits and clay fraction.

Table 1. Soils tested.

Soil Type	Atterberg Limits		Clay fraction (%)
	LL (%)	PL (%)	
Speswhite kaolin	63.9	34	77.2
London clay – Maida Vale	77.0	29.5	59.3
Fleetwood – glacial silt	27.4	18	26.5
Upper Mottled clay	62.3	26.9	61.2

Speswhite kaolin was used extensively to develop the "mixing test". It was reconstituted and consolidated in a press to create a firm clay. The remaining soils used in the tests were obtained from tunnelling sites, two in London, Maida Vale (London Clay) and Farringdon (Upper Mottled Clay) and one from Fleetwood in Lancashire (Glacial silt). The Upper Mottled Clay is part of the Reading Formation of the Lambeth Group as described in Entwhisle et al., 2013 and the London clay was weathered and considered to be on the boundary between divisions B and C in King's (1981) stratigraphic sequence. The glacial silt from Fleetwood is described as soft, reddish brown, slightly sandy, clayey SILT and is from a series of deposits described by Wilson (1990).

3 EXPERMENTAL METHOD

Each set of soil samples was characterised by determining the plastic and liquid limits and the particle size distribution for the soil when dispersed "fully" i.e. in accordance with BS1377-2 (1996). Unconfined compression tests were also performed on 38mm diameter samples of the soil. For each soil a number of "mixing" tests were undertaken as described in section 3.2.

3.1 Classification and simple strength tests

To determine the particle size distribution the wet sieving and the sedimentation techniques described in BS1377-2 (1996) were followed. For all soil samples tested the organic content was negligible and hence the addition of hydrogen peroxide is omitted.

Prior to carrying out the sedimentation testing the specific gravity of the sub 63µm portion of solids is required in order to take pipette samples at correct timings. Again this procedure was carried out in accordance with BS1377-2 (1996). Two samples of each soil were tested by sedimentation to minimise errors in testing and as a check on repeatability.

The liquid limit for all the soils was obtained using the 80 g fall cone penetrometer test described in BS1377-2 (1996). The plastic limit is more difficult to define and values given are from the current thread-rolling test described in BS1377-2 (1996) backed up by the increased mass cone penetrometer test (Wood and Wroth, 1978). This does not give a value for the plastic limit, but for the plasticity index.

Unconfined compression tests were undertaken on two samples of all soils except for the London clay. This was because the bulk samples obtained from site were too small to test. The Upper Mottled clay has a clearly layered structure and the samples tested were cut so that the axis of the sample was perpendicular or parallel to these layers. The tests were carried out to BS1377-2 (1996).

3.2 "Mixing" Test

The "mixing" test has been developed to reproduce the disaggregation process that occurs in slurry tunnelling and is justified in detail in Phillips et al. (2014). It 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 and the quantity of distilled water were chosen to be representative of the composition of the slurry leaving the tunnel face. The Hobart mixer is a common piece of equipment that applies a shear rate which is similar in magnitude to that generated in a slurry pipe (at speed setting '1', the slowest of its three pre-set speeds); see Phillips et al. (2014).

The ten soil samples, each cut with a knife or saw to be approximately cubical in shape, are weighed to ensure that they are of the correct mass and to establish the total mass of dry solids in the slurry. Three soil samples are also weighed and oven dried to determine the water content of the original soil. The test requires the cut soil samples to be added simultaneously to 4.5 litres of distilled water in the planetary mixer, at speed setting '1'. The test duration is varied from 1 minute to 60 minutes, simulating the effect of a range of pumping distances. Once mixed for the required time period, the slurry is poured through the pre-weighed sieve stack (sieve sizes ranging from 50 mm to 63 μm). The mixing bowl is lightly washed using a water bottle to ensure all loose soil particles are washed into the sieve stack. If material is stuck to the bowl the bowl is weighed and dried, in order that the solids left in the bowl can be determined.

The sieves are not shaken as this could extrude soft material through the meshes. Some undersized material may not make it through a sieve but this happens on site and so it will not alter results by an unrepresentative amount. Sieves are then placed into collection pans, weighed and placed in an oven to dry. The remaining slurry in the base pan (sub 63 μm material) is poured into a collection jug, ensuring that all material is washed out, and then poured through a purpose-made 10 way cone splitter to provide manageable samples of slurry for drying. All of the resulting beakers are weighed and four are placed in a large oven to dry. The four beakers are then weighed. Data obtained are used to plot particle size distribution curves for the slurries at the end of the mixing stage.

4 RESULTS

The results of the classification tests on the soils tested are given in Table 1. Particle size distributions determined in accordance with BS1377-2 (1996) are plotted in Figure 1 below.

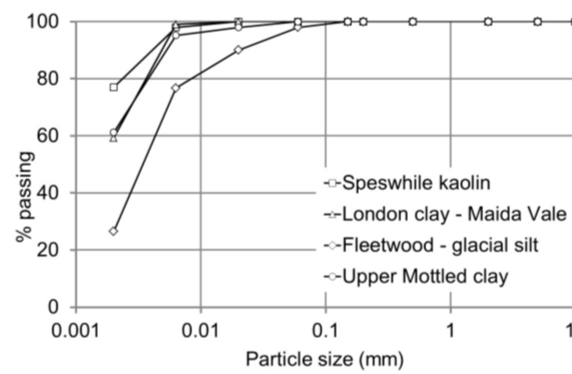

Figure 1. Particle size distribution curves for soils tested

Data for the unconfined compressive strengths of the soils are given in Table 2. The strength of the London clay is taken from tests undertaken by Gasparre (2005) for a soil of similar water content and from a similar position in the stratigraphy. The disaggregation of the soil cuttings during a mixing test can be represented on a conventional particle size distribution chart, where in this case the particles are aggregates of soil grains unlike the BS1377-2 (1996) dispersed particle size distributions shown in Figure 1. Figure 2 shows typical plots for the distribution of particles sizes in different soil slurries following a mixing test of 10 minutes duration.

Table 2. Unconfined compressive strengths.

Soil Type	Strength (kPa)	Water content (%)	Strength (kPa)	Water content (%)
Speswhite kaolin	66.8	47.50	76.45	47.54
London clay	200**	24**		
Fleetwood – glacial silt	55.3	18.95	77.8	16.46
Upper Mottled clay	513*	19.93	701+	20.37

Note: *layers vertical, +layers horizontal, ** Gasparre (2005)

All of the cuttings placed in the slurry have a major dimension less than 50mm and as can be seen from Figure 2 at the end of the mixing tests very few of these cuttings have disaggregated to particle sizes in the range 4.75 to 63 µm (0.063 mm). The particles/aggregates of particles are either smaller than 63 µm (finer than fine sand) or greater than 4.75mm. The Upper Mottled clay slurry has the highest percentage of sub 63 µm particles and the Fleetwood glacial silt the lowest. The form of the particle size distribution curves indicates that particles smaller than coarse silt are disaggregating from the surfaces of larger lumps rather than being the product of the successive splitting of lumps. However, this process will be accelerated if the larger lumps break apart to some extent, as this provides a greater surface area from which the smaller particles can separate.

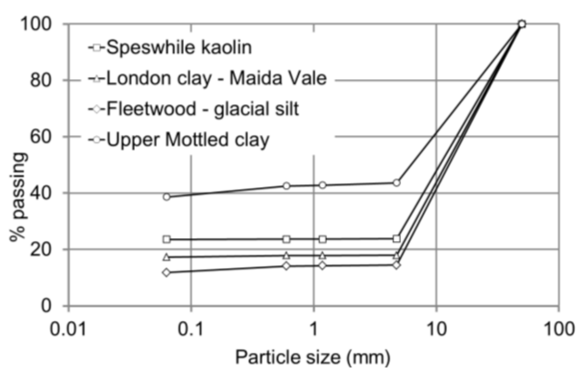

Figure 2. Particle size distribution curves for slurries following 10 minutes of mixing

Table 3 lists all the different mixing tests undertaken, including the soil tested, the initial average water content of the soil cuttings and the mass of disaggregated particles smaller than 63 µm as a percentage of the total dry mass of the cuttings.

Table 3. Soil subjected to mixing tests

Test	Soil Type	Water content (%)	Particles <63 µm (%)
K110	Speswhite kaolin	45.4	36.0
K210a	Speswhite kaolin	43.6	17.4
K210b	Speswhite kaolin	43.5	20.3
K310a	Speswhite kaolin	42.9	25.9
K310b	Speswhite kaolin	43.1	21.3
LC110	London clay	29.6	13.1
LC210	London clay	30.3	17.3
F110	Fleetwood – glacial silt	21.2	19.1
F210	Fleetwood – glacial silt	18.8	13.8
UM110	Upper Mottled clay	21.6	39.3

In order to investigate if the disaggregation process is dependent on strength, the percentage passing the 63 µm sieve has been normalised by the percentage of grains smaller than 63 µm from the fully dispersed particle size distribution and plotted against two measures of strength, Liquidity Index and unconfined compressive strength. For reconstituted soils without any structure, Liquidity Index is inversely proportional to undrained strength (see for example Atkinson, 2007). Results from the tests listed in Table 3 are plotted against Liquidity Index in Figure 3.

The Upper Mottled clay had a water content of 21.6%, which is lower than the Plastic Limit for this soil, 26.9%. Consequently, it has a Liquidity index which is negative and one would expect it to be high strength clay which would not disaggregate readily in the slurry, but the data show that the reverse has occurred with over 40% of the available particles disaggregating in the slurry. It may be that layers of coarser particles are facilitating the disaggregation process. The other soils conform to a general trend of increasing disaggregation with increasing Liquidity Index or decreasing strength. Interestingly, this trend is apparent both for soils for which there is more than one set of data, for example the glacial silt from Fleetwood or the London clay from Maida Vale, and for soils of different types.

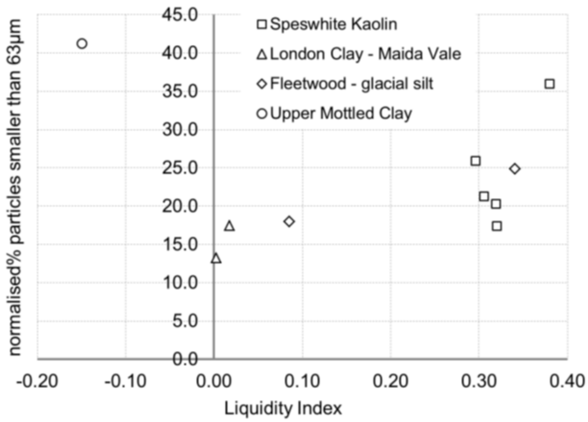

Figure 3. Proportion of grains smaller than 63 microns that have disaggregated after 10 minutes mixing plotted against Liquidity Index

The unconfined strength of the soils tested was measured in order to establish whether the natural soils were benefitting from any bonding or cementing increasing the strength beyond that which might be expected as a result of their in situ water content or voids ratio. A selection of these data and a value for the unconfined strength of London clay derived from tests presented by Gasparre (2005) are plotted against the normalised percentage of particles less than 63 µm in Figure 4.

It should be noted that as shown in Tables 2 & 3, the soil specimens subjected to these simple tests were not all at the same water content as the samples used in the mixing tests. This means that it has not been possible to fully take account of the variation in strength with water content for a particular soil. However, in all cases the strengths used are those for the soil specimens with water contents closest to the water contents of the soil used in the mixing test.

Once again the Upper Mottled clay does not conform to the general trend of an increase in the normalised percentage of particles less than 63 µm as the strength decreases. It is clear that any planes of weakness that might facilitate the disaggregation of this clay are not affecting the unconfined compressive strength. Considering the remaining data, it does not appear that much insight has been gained by considering the unconfined compressive strength. As it was difficult to obtain strengths from soil specimens at the same water content as the soil cuttings the differences between the behaviour of the same soil at different water contents has not been characterised. Consequently, it is not possible to discern any effect of bonding or cementing which might have increased the inherent strength of the soil and reduced the potential for the soil to disaggregate

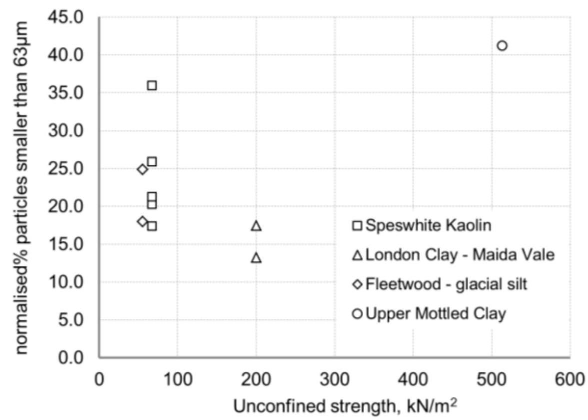

Figure 4. Proportion of grains smaller than 63 microns that have disaggregated after 10 minutes mixing plotted against unconfined compressive strength

The other feature of these soils that might affect the magnitude of disaggregation that takes place during the mixing test is the clay content, which should be linked to the permeability of the soils and affect how quickly the slurry liquid is able to seep into the soil cuttings, reducing negative pore pressures helping to hold the soil particles together. Soil cuttings will often be saturated in-situ.

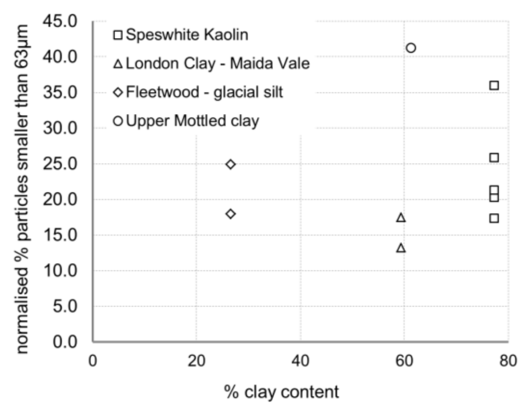

Figure 5. Proportion of grains smaller than 63 microns that have disaggregated after 10 minutes mixing plotted against clay content

Table 1 and Figure 1 show that the % clay content varies from 26.5 to 77.2% for the four soils tested, with the glacial silt from Fleetwood having the lowest clay fraction. Figure 5 shows a plot of clay fraction against the normalised percentage of particles less than 63 µm. It is difficult to discern any effect of the percentage clay fraction from these data. Similarly, there is no obvious trend in the plot of activity, defined as Plasticity Index divided by percentage clay fraction, against normalised percentage of particles smaller than 63 µm indicating that the clay mineralogy may not be a significant influence on the disaggregation of these soils.

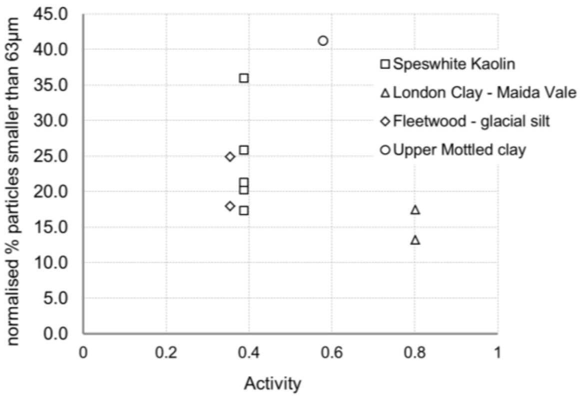

Figure 6. Proportion of grains smaller than 63 microns that have disaggregated after 10 minutes mixing plotted against activity

5 CONCLUSIONS

Results are presented from a series of mixing tests designed to investigate the disaggregation of soils during slurry tunnelling operations. Four different soils have been tested and the disaggregation of the soils has been characterised by the percentage of particles less than 63 µm present in the slurry following a mixing test of 10 minute duration. Particle size distribution data for the resulting slurries indicates that the mechanism of disaggregation is predominately silt or clay size particles separating from the outer surfaces of the soil cuttings although some splitting of the larger particles may take place so facilitating surface losses.

The proportion of clay and silt sized particles that disaggregate from the soil cuttings during the mixing tests could be linked to liquidity index, a measure of the soil strength, for three of the soils tested. However, the Upper Mottled clay was an exception and this may be because the very low water content of this soil gave it a higher swell potential, or because of more permeable layers in the clay. The link between unconfined compressive strength and the disaggregation of the clays was less clear and there appeared to be no relationship between percentage clay content or clay activity and the disaggregation of the soils, indicating that clay mineralogy may not be significant in this process.

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