Test development for the investigation of soil disaggregation during slurry tunnelling

N.S. Phillips, S.E. Stallebrass, R.J. Goodey
Geotechnical Engineering Research Group, City University, London, UK

S.A. Jefferis
Environmental Geotechnics Ltd, Oxon, UK

ABSTRACT: Slurry tunnelling uses a water based slurry to aid in tunnel face support and transportation of the excavated material. Unlike other tunnelling methods this requires expensive surface separation plant to remove the excavated ground from the slurry. Incorrect specification of this plant can lead to significant delays and added cost to a tunnel drive. Due to the tight budgets and space constraints this can cause contracts to become unprofitable, in particular where small diameter slurry tunnels are excavated by pipe jacking. For this reason accurate prediction of the size distribution of the soil particles and lumps in the disaggregating slurry is required. This research concerns the development of test procedures and methods of soil classification that will enable improved predictions of the degree to which soils/weak rocks will disaggregate during the slurry tunnelling process.

1 BACKGROUND

Soil slurry has been used as a support and transportation mechanism within tunnelling and pipe jacking since the 1970's. The slurry used 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 before the fluid is recycled back to the tunnel face. This process is most challenging with suspended solids of sizes less than 63 µm.

The majority of particles larger than 63 µm are removed from the slurry using a series of shaker screens and hydro-cyclones. The remaining particles require separation using a decanting centrifuge and flocculant treatment. In order to specify the processing capacity of the centrifuge(s) it is necessary to predict the quantity of sub 63 µm particles that will be in the slurry when it reaches the separation plant.

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

The Pipe Jacking Association has commissioned this research so that the industry can understand how varying geologies react to the processes being applied to them during tunnelling, with the aim of reliably predicting the plant required for surface separation. Errors in specifying the plant can lead to high off-site processing costs or the loss of a contract at tender stage.

2 INTRODUCTION

The research being undertaken aims to characterise samples from a range of different soils using both standard soil tests and a newly developed "mixing" test in order to develop a link between the mechanical and mineralogical properties of the intact soil and the degree to which the soil will disaggregate in slurry during tunnelling.

The first stage of the research is concerned with a systematic evaluation of how excavated soil which initially exists in centimetre sized lumps disaggregates, or breaks down to its constituent particles, in particular those particles which are smaller than 63 µm.

A repeatable test regime, a "mixing" test, has been developed to model the processes applied to the soil during excavation and whilst transported from the face in a slurry. This will examine the effect on degree of disaggregation of varying the water content of the slurry, time spent in the slurry, agitation of the slurry and soil type. The different soils tested were Speswhite kaolin, London clay and a Mercia Mudstone. Some preliminary tests have been undertaken to develop an appropriate testing method and further tests will be completed over the duration of the research programme. The reasons for initially choosing these soils are as follows.

- Speswhite kaolin; Well characterised standard clay with a narrow range of particle sizes, clay-fine silt size. The voids ratio and moisture content can easily be varied. Liquid limit 65% and plastic limit 35% (Atkinson *et al,* 1987). Typical permeability k=10^{-9} m/s (Grant, 1998).
- London clay; Well characterised natural clay, with a relatively narrow grading curve, but natural fabric and structure. Heavily over consolidated, with a low voids ratio. Liquid limit 62-76% and plastic limit ~30 (Skempton *et al*, 1969). Typical permeability k=10^{-11} m/s (Chandler, Levouil & Trenter, 1990).
- Mercia Mudstone; Very variable deposit, but the particular formation used has been comprehensively characterised (Stallebrass & Seward, 2011), larger spread of particle sizes, up to sand sizes, heavily overconsolidated and cemented in its natural state. Plastic limit ranging from 19-26% and liquid limit 27-34% (Seward, 2009). Highly variable permeability in vertical and horizontal directions, Chandler & Foster (2001) state k=10^{-7} m/s.

Additional soil samples will be tested in a subsequent phase of the project.

3 TEST DEVELOPMENT

The test to be developed needs to model the processes that the soil undergoes during the entire tunnelling process. This includes excavation, when a certain size of cuttings are created, transportation in the slurry when the soil is subjected to shear from the pipe and the centrifugal pumps driving the flow of the slurry towards the separation plant. Tests to assess the breakdown of cuttings in slurries have been developed in the past for the oil and gas drilling industry, for example the hot rolled test (O'Brien & Chenevert, 1973). In this test, shale samples are submersed in drilling fluid in a jar and rolled for 16 hours at the predicted well temperature. Time, fluid and temperature can be varied depending on the conditions to be encountered. This test was reported to give repeatable results; however, the rolling action in this test will not apply shear energy to the soil at the levels encountered by slurries used in tunnelling.

The second test used by the drilling industry is the mud triaxial test (Clark *et al,* 1976). This provides constant axial and radial stresses to a shale sample, whilst pumping slurry through a preformed central hole in the sample. The sample is prepared from well cuttings and compacted at an effective stress of 57.9 MPa. The sample is then placed in the mud triaxial cell at a predetermined stress and the slurry pumped through at a pressure of 690 kPa and a flow rate of 4 m/s. The slurry is circulated until the sample fails from the applied stress, the time taken to fail and the magnitude of erosion is used to judge whether the slurry is suitable for the drilling operation. Clark *et al* (1976) state that the test is repeatable and although it cannot be used quantitatively, the test does allow a mud engineer to compare different slurry compositions. The mud triaxial test is not suitable for looking at dispersion within the pipe jacking and tunnelling industry as the mechanism of initiating dispersion is different.

Both tests are useful in that they measure the tendency of a soil to swell in water and the influence of permeability, but they cannot assess the role that the shearing of the slurry has in determining the degree of disaggregation.

The coal industry have looked at assessing the degradation of slurries fairly extensively, with the Saskatchewan Research Council running various pipe line tests, both in the field and the laboratory. The laboratory tests are carried out in both a closed and open loop circuit. This consists of a looped pipeline with a centrifugal pump propelling the slurry around. In the closed loop there is a single pipe line which goes to and from the centrifugal pump. In the open circuit the pipe discharges into a holding tank that supplies the centrifugal pump. The pipe loops can be monitored for a range of parameters including flow rate, slurry density and pressure change. This provides an understanding of how coal tailings degrade during transportation. Gillies (1991) states that this method of testing may over predict the degradation of solids due to the extra passes through the centrifugal pump, where high shear rates are applied to the slurry, compared to that in a real pipeline. Gillies also recommends that a separate test regime is required for each type of material to be pumped. The disadvantage of this method is that to avoid passing the slurry through a centrifugal pump too frequently in proportion to the pipe length, a long pipe is required, making the test impractical for regular industry use.

The new "mixing" test described here is a simpler, more cost efficient method designed to assess the soil breakdown in slurry. The experimental method is as follows:

The soil or weak rock is divided into 50-60 g "cuttings". These cuttings are then mixed with distilled water, at a water content of 800% to create the initial slurry. The appropriate water content was determined from typical slurry flow rate to excavation rate ratios obtained from the pipe jacking industry. The choice of "cutting" size was taken from typical cutting sizes measured in a 1.2 m ID pipe jack tunnel. This size of cutting is also used in the slake durability test (ASTM, 2008).

The slurry is placed in a Hobart planetary mixer with a paddle mixer attachment and mixed for a set time that will be varied over the course of the research. The mixer is set at speed setting one, which is the slowest of three speeds available, see table 1. This mixing action shears the soil in the slurry in a way that is representative of the shear applied during transportation of the slurry to the separation plant. Initial mixing times were 1, 2, 5 and 10 minutes. The slurry mixture is then removed and sieved for one minute through 4.75, 1.18, 0.6, 0.063 mm sieves, which represent typical cut sizes within the separation plant. The sieving time is not to BS1377-2 (1996) as the material being sieved is often clay that sticks and extrudes through the sieve if longer shaking times are used. Minimal disturbance to the samples is required to give a representative picture of the effects of mixing. For consistency a 6 minute pause is allowed between the end of mixing and the start of sieving.

Speed Setting	Ω_R	Ω_r
	rad/sec	rad/sec
1	20.9	6.4
2	42.9	13.2
3	88.9	27.1

Table 1 Hobart Planetary mixer speeds. Ω_R= rotational speed of the paddle about its centre, Ω_r= Orbital speed of the mixer

The sub 63μm particle slurry is collected in an adapted tray that allows the slurry to flow into a jug. All sieves and the material in the jug are then oven dried and the proportions of different sized dry solids are determined. The accuracy of the method is checked by ensuring that the dry mass collected is equal to the dry mass of the original "cuttings". Initial trials demonstrated the difficulty of performing this check when the moisture content of the natural soil varied by as little as 2%. This was a particular issue because the sub 63 μm samples were split to deal with the high volume of liquid that accompanied this fraction, often in excess of 4.5 litres. If the split is not equal and the original mass of solids is also unknown it is not possible to determine the proportion of particles in this range.

The solution was to manufacture a cone splitter (Siu, Pitt & Clark, 2008). The 10-way splitter (Figure 1) provides manageable samples of slurry that can be oven dried. The slurry collected from the sieves is then poured through the splitter dividing it into ten Pyrex beakers. To wash out the small quantity of solids in the jug and cone splitter, 500 ml of distilled water is subsequently poured through the system.

During the initial tests on Speswhite kaolin and London clay all ten sub samples of slurry were dried to establish whether there were any small variations in the division of the slurry due to small dimensional variations arising during the manufacture of the splitter. The repeatability of the splitting was evaluated for both the mass of the split slurry and the dried solids. The compound errors for the ports ranged from 1.0-2.7%, some ports performing more reliably than others. Where all the slurry was not dried sub specimens from the most reliable ports were selected for drying. With an error of 2.7% the predicted variation in dried solids content in a beaker with a slurry density of 1.02 g/cm^3 would be 0.4g. Further work is required to check whether these errors are independent of the slurry viscosity.

Figure 1. Cone splitter

The Hobart planetary mixer applies shear to the slurry in a measurable and repeatable way, which is similar to the way shear rates are applied to the slurry during transportation, both by the pipe used for transportation and by the centrifugal pumps driving the flow. The wall shear rate (γ_w) applied during the transportation of soil cuttings in a pipe can be estimated using the Rabinowitsch equation (1) (Son, 2007), by assuming that the slurry is a non-Newtonian fluid under laminar flow:

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

Where n is a constant and is derived from equation 2, using the shear stress at the wall (τ) and apparent shear rate (γ_a)

$$n = \frac{d(\ln \tau)}{d(\ln \gamma_a)} \tag{2}$$

The apparent shear rate is calculated using the velocity (*V*) and the pipe diameter (*D*), equation 3 (Darby, 2001).

$$\gamma_a = \frac{8V}{D} \tag{3}$$

For a typical 1200 mm internal diameter pipe jack, with a pipe flow velocity of 2.83 m/s this method gives a shear rate at the wall of 272 s^{-1}. Although this is a simplification as the flow is not laminar, it does give an estimate of the magnitude of shear rate that is being applied.

The shear rate applied in a Hobart planetary mixer has been modelled by Chesterton *et al* (2011). The action of a planetary mixer produces varying shear rate, depending on the gap between the paddle and the bowl wall (δ) and the distance from the centre of the paddle (*R*). The tangential velocity of the paddle (V_D) is calculated using equation 4.

$$V_D = \sqrt{((\Omega_R - \Omega_r)^2 R^2 + \Omega^2{}_r r^2 - 2\Omega_r(\Omega_R - \Omega_r) rR\cos(2\pi\Omega_R t))} \tag{4}$$

Where Ω_R is the rotational speed of the paddle around its centre, in this case speed setting one is 20.9 rads/sec. Ω_r, the mixers orbital speed is 6.4 rads/sec, *r*, the radius of the orbital motion, is 30 mm and *t* is time. The shear rate (γ_w) can then calculated by using equation 5.

$$\gamma_w = \frac{V_D}{\delta} \tag{5}$$

As mentioned the shear rate varies depending on the particle position. The maximum shear applied on speed setting one is 128 s^{-1} and the lowest is 70 s^{-1}. Although these figures are below that of the maximum estimated shear rate in a pipe, the shear rate profile in a pipe goes from a maximum at the wall to zero at the centre and consequently the shear rates are of the same order of magnitude. Shear rates through centrifugal pumps will be higher and may be better modelled by speed setting 2 on the mixer (Table 1). Further work will be undertaken to relate the shear rates applied by the mixer to those experienced by the slurry during transportation.

4 RESULTS

Mixing tests have been carried out on the three soils identified above. In each case slurries have been mixed in the planetary mixer for four time intervals, 1, 2, 5 and 10 minutes. Along with the mixing tests, fully dispersed particle size distribution tests have been carried out for each soil in accordance to BS1377-2 (1996) labelled as (PSD) in the figures. The effective particle size distribution for each mixing time along with the corresponding dispersed particle size distribution has been plotted for each soil.

Figure 2 shows the results for over consolidated Speswhite kaolin, where two tests (T1, T2) were performed for each mixing time. The Speswhite kaolin samples were all prepared in the same way from powdered clay, so that repeating the tests should enable the test method to be evaluated. Figure 2 shows that in these initial tests there is a difference between the value obtained for percentage passing 63 µm of approximately 12% for each pair of tests with the same mixing time. Further work is required to minimise this variation. The shape of the curves obtained indicates that for Speswhite kaolin the soil cuttings disaggregated by losing individual particles from the outside of the cuttings which then entered into suspension within the slurry. If the cuttings had broken apart into larger lumps, solids would be retained between the 63 µm and 4.75 mm sieves, but the curves show that there is minimal material retained. The material found on the 1.18 mm sieve was predominately clay extruded during shaking for one minute.

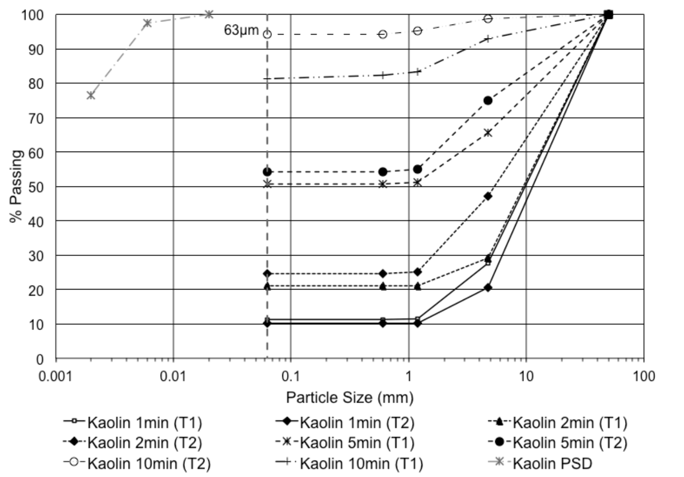

Figure 2. Particle size distributions of Speswhite Kaolin at varying times

Figure 3 shows the same results for London clay. Although London clay is not a strata that a slurry tunnel boring machine would be chosen to tunnel through, it may be encountered during a drive where slurry tunnelling is being used to cope with less favourable conditions. It is also a well researched stratum, with a fully dispersed particle size distribution in the silty clay range that lies between Speswhite Kaolin and the Mercia mudstone tested, which is predominantly clayey silt.

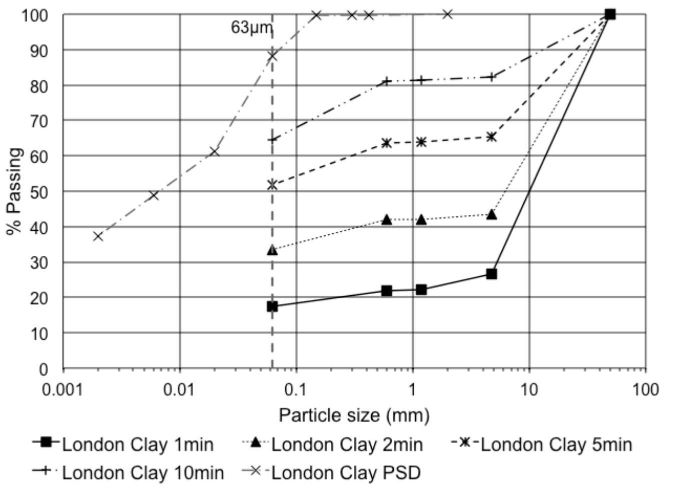

Figure 3. Particle size distributions of London clay at varying mixing times

Unlike the Speswhite kaolin, some material was retained on the 0.6 mm sieve for London Clay, indicating that some larger aggregations of particles detached from the cuttings and remained intact. The link between soil properties and disaggregation has not yet been fully examined. However, it is possibly due to weak cementing within the natural sample, which is lost when the soil is subjected to a BS1377-2 (1996) particle size distribution test. There are no particles of this size present in the fully dispersed particle size distribution suggesting this link. London clay is less permeable than Speswhite kaolin and probably explains why the particle size distribution for a mixing duration of 10 minutes is further from the fully dispersed distribution.

Figure 4 shows the equivalent plots for the Mercia mudstone, which is taken from the Gunthorpe member. The fully dispersed particle size distribution has a much wider range of particle sizes compared with the other soils. The Mercia mudstone tested is more permeable than the other soils which should lead to more disaggregation for a given mixing duration, although this will be counteracted by the presence of natural cement bonding particles together. This explains why at low mixing durations there is more disaggregation than for the other soils, but for the 10 minute mixing duration the Speswhite kaolin, where there is no bonding has disaggregated more.

These results are plotted for the ratio of the percentage passing 63 μm in the mixing test to the fully dispersed particle size distributions, against mixing duration as shown in Figure 5. This shows that the initial rate of breakdown for the natural soils is faster than that of the Speswhite kaolin. Gillies (1991) notes that for the coal tested the initial rates of breakdown can be faster due to cutting breakage along existing crack planes and also the rounding off of the cuttings. In the natural soils, fissures and lenses of higher permeability soil may explain the increase in initial breakdown rates, as the Speswhite kaolin samples will not have layering or local fissuring.

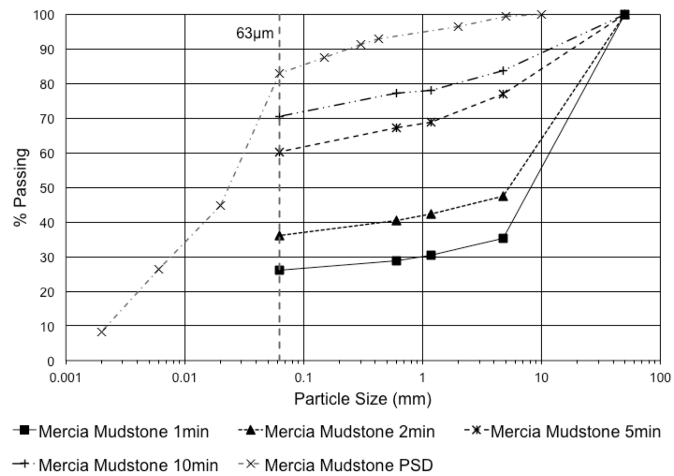

Figure 4. Particle size distribution of Mercia mudstone at varying mixing times

Figure 5 also shows that for the mixing times used the rate of disaggregation is non-linear for the natural soils with the proportion of the available sub 63 μm tending to a value which appears to be less than 1, although it may ultimately reach 1.0 after considerably more mixing. However, it is likely that most soils will never reach full disaggregation within the time spent in a slurry circuit.

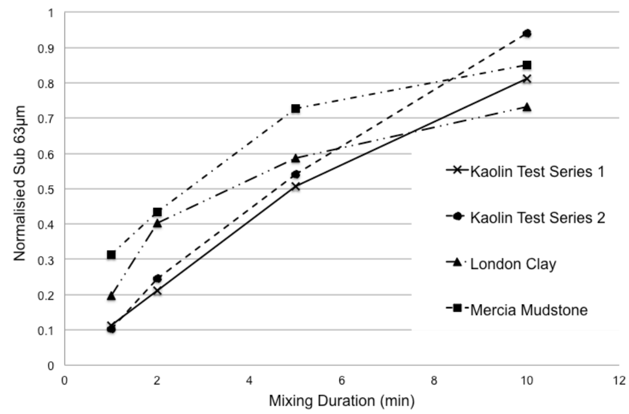

Figure 5 Percentage of sub 63 μm particles pass at increasing mixing times normalised against fully dispersed data.

5 CONCLUSION

From the work carried out to date, it can be seen that the mixing test proposed can produce results which are reasonably repeatable to within 12% for Speswhite kaolin and allow trends to be indentified for the two natural soils tested. In the current tests the mixer speed, and hence the shear rate, was kept constant. These tests effectively model the effect of increasing the length of the pipeline transporting the soil as the tunnel is excavated. At the shear rate applied and for the durations tested it was observed that the rate of disaggregation slowed significantly indicating that it may be possible to determine a limiting level of disaggregation which is less than the fully dispersed state. Further tests will be undertaken at an increased shear rate to model the effect of passing the slurry through centrifugal pumps. Test results will also be compared with samples obtained from site at the tunnel head and during transport of the slurry to the separation plant to verify that the mixing test is correctly representing the site process.

6 ACKNOWLEDGEMENTS

The Pipe Jacking Association along with the Pipe Jacking and Tunnelling Research group are gratefully acknowledged for both their funding and valuable input in to this project.

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