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The effects of synthetic flocculants on some geotechnical properties of kaolin clay

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Abstract

Synthetic flocculants have been used for decades in the mining industry, particularly in solid liquid separation related to thickening. Recently, the use of these chemicals to achieve improved depositional behaviour of tailings has been trialled, and implemented at a small number of mine sites. In these early attempts, flocculant addition just prior to deposition has improved the dewatering of deposited tailings and resulted in a steeper beaching angle. This has the potential to reduce capital and operating costs for tailings management if implemented correctly. While this is a promising new technology, very little research is available on the impact of flocculants on a number of important geotechnical parameters. An experimental programme has commenced to quantify these impacts.

The increased settling rate of flocculated material provides implicit evidence of the increased apparent particle size resulting from this process. However, this increase in apparent particle size is known to be sensitive to shearing and other effects. Therefore, it is possible that sufficient confining pressures or shear would quickly break down the flocculated particles, making the geotechnical behaviour of a material indistinguishable whether flocculated or not. However, little evidence exists to support or disprove this hypothesis.

Preliminary results from a laboratory testing programme to determine consolidation properties and particle size distribution for kaolin with, and without, flocculant addition are presented. Unique sample preparation methods have been utilised in an attempt to isolate the effects of flocculant addition. Initial results indicate that the effects of flocculant addition are not noticeable upon application of relatively small effective stresses to the samples. Further laboratory testing is required to assess if this conclusion can be extended to a variety of other tailings, flocculants, and resulting geotechnical properties.

1 Introduction

The use of synthetic flocculants addition to mine tailings slurries to produce steepened beach profiles, enhance water recovery and improve decant water clarity is increasing in popularity (Brumby et al., 2008; Daubermann and Földvári, 2009; Wells et al., 2011; da Silva, 2010). The addition of these flocculants 'in-line', to produce steepened beaching angles is one of the most promising avenues for this technology. Steepened beaches, through allowing the possibility of small (or non-existent) perimeter embankments, can have excellent economic benefits. However, the importance of managing liquefaction risks becomes even greater with such geometries where tailings are not fully contained by a perimeter embankment.

Particle size distribution (PSD) and consolidation behaviour are two important inputs to any tailings facility design. Their importance increases further when liquefaction is a concern. The PSD of a soil can provide significant insight into the likely behaviour of that material. This includes insight into the potential for liquefaction (USNRC, 1985; Ishihara, 1985).

Consolidation behaviour allows estimation of the dry density and void ratio that can be achieved in storage and estimates of the time required for these densities to be achieved. It is also an important consideration in some methods of liquefaction assessment of steepened beach facilities (Li et al., 2009).

To gain insight into the impacts of flocculants on these properties, a testing programme was carried out on kaolin with, and without, flocculant addition. PSD determination and Rowe Cell consolidation testing were utilised. This is outlined below.

2 Background and previous related work

A limited number of published studies on the effects of flocculants on geotechnical properties are available. A greater amount of work seems to have been directed towards understanding the chemical interactions and rheological behaviour of flocculated slurries.

The increased settling rate resulting from flocculant addition provides evidence that an increase in apparent particle size is occurring. The PSD of a soil is one of the most basic and important index properties. If the PSD is changed owing to flocculant addition, then a number of other properties such as permeability and compressibility would likely also change. To further complicate the situation, it is currently unknown how long the apparent increase in particle size induced by flocculants would last, for example under the vertical loading of additional material.

Alam et al. (2010) utilised the laser diffraction method to assess the impacts of flocculants on particle sizes. Their results are as expected, with flocculants resulting in larger particle sizes. The laser diffraction method has obvious appeal for testing of flocculants owing to its ability to test samples without subjecting them to oven drying or dispersants. In addition, a comprehensive analytical and experimental programme by Lu et al. (2000) provided evidence that the hydrometer underestimates particle sizes of non-circular clay-sized particles such as kaolin. This further points to laser diffraction as the preferred method.

Some limitations exist for this method, however, Alam et al. (2010) indicate that they utilised different speeds for the overhead impeller of the system during their testing (without providing a rationale). The speed of the overhead impeller in the particle size analyser is known to affect the particle size results (Avadiar, 2011, pers. comm.).

It is well established that changes to the preparation water chemistry can result in significant changes in the density and mechanical behaviour of kaolin. As shown by Sachan and Penumada (2007), quite different compression lines for kaolin resulted when the depositional water chemistry was changed. These conclusions are compatible with the established understanding that there is not a unique normal compression line (NCL) for soil. Mitchell and Soga (2005) provide extensive evidence of this in regards to clay. Jefferies and Been (2000) have provided evidence of similar behaviour in sands.

The apparent infinity of NCL for soils raises the question of whether flocculant addition could induce similar changes. This has not been investigated sufficiently. Attempts are made to address this in the work presented here.

3 Experimental programme

3.1 Material tested

The material used for the experimental programme conducted thus far is a kaolin clay, manufactured by Unimin Australia. This material has been used frequently in experimental work at the University of Western Australia (UWA). A comprehensive summary of this material is provided by Lehane et al. (2009). The material has a Liquid Limit of 61% and a Plasticity Index of 34%. Direct PSD measurements for the material studied are provided below. All test work was conducted on kaolin from the same source bag of material.

While this laboratory standard material cannot be considered representative of a full thickened tailings gradation, it should adequately simulate the clay fraction of some tailings streams. As the effect of synthetic flocculants is most pronounced on the finer portion of a material’s gradation, the results here have relevance to thickened tailings.

3.2 Flocculant preparation selection

A selection of 12 flocculants of the MAGNAFLOC® and RHEOMAX® range were supplied to the authors by BASF. A series of settling tests was then performed to determine which flocculant resulted in the highest initial settling rate at a 100 g/t dosage rate. This is, admittedly, a first-order selection criteria in comparison to more comprehensive methods utilised for flocculant selection on mining projects (Stocks and Parker, 2006). However, it was sufficient to indicate a flocculant that induces significant changes to the apparent particle size of the slurry.

Flocculant was prepared in the typically recommended manner, whereby a primary solution is first prepared to a concentration of 0.25%. This is then diluted to 0.025% for addition to the slurry.

Settling tests were performed as follows:

1. Dry kaolin and Perth tap water were mixed thoroughly at a slurry moisture content of 500% in a 500 mL graduated cylinder.
2. Half of the flocculant was added and the graduated cylinder fully inverted twice.
3. The remainder of the flocculant was added and the graduated cylinder fully inverted three times.
4. Timing was started, with depth of interface recorded until settling had ceased.
5. Upon recording the final interface depth, the settled material was emptied from the cylinder and oven dried to allow determination of the final settled dry density.

Another series of settling tests was then performed with similar procedure to identify the effects of dosage on settling rates.

3.3 Rowe Cell consolidation testing

A series of Rowe Cell consolidation tests were conducted to assess the potential for flocculants addition to impact on the density, one-dimensional stiffness and permeability of kaolin. The tests were conducted on a 76 mm diameter Rowe Cell in the UWA Civil and Resource Soil Laboratory. A settling column attachment to the Rowe Cell was utilised to allow the deposition of slurry samples into the device. The Rowe Cell with attached column is shown in Figure 1. This column had been constructed under the direction of an undergraduate student at UWA, who developed it as part of an Honours Thesis (Das Neves, 2011, pers. comm.).

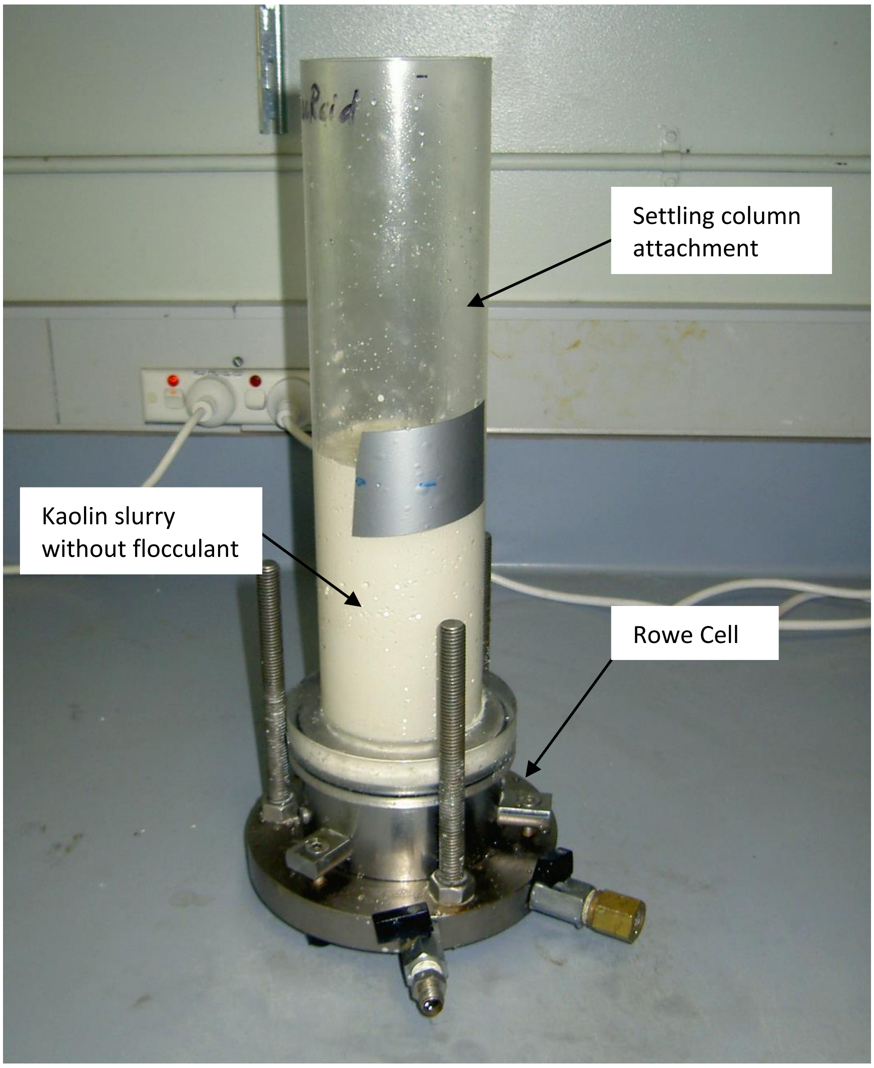

Figure 1 Rowe Cell slurry column

Samples were initially prepared similarly to the method utilised in the settling tests. They were then poured into the Rowe Cell and settling column. Flocculant can only be added to a soil sample if that soil is in a slurry state. This limits the available options for laboratory sample preparation. The method adopted here allowed this difficulty to be overcome. All Rowe Cell samples were prepared in this way.

Upon completion of settling, two small weights were gently lowered onto the surface of the material. Filter paper was bonded to the base of the weights, which had been specially manufactured to include an integrated filter medium and drained pathway. The combined mass of the two weights when both added induced a pressure of 5 kPa onto the settled samples.

Initial consolidation with the weights was allowed to proceed for a minimum of 12 hours. The weight system was then removed and water decanted from the settling column with a syringe and small hose. The settling column was then removed. From this point, the Rowe Cell testing was performed consistent with the guidelines published by Head (1992).

A grease or silicone spray is typically spread onto the sides of the Rowe Cell to reduce loading system friction. This was not done in the testing performed here. In an early attempt to utilise this system, it was observed that the presence of silicon spray adjacent to the slurry could increase settling rates by a factor of as much as three. This indicates that the silicon spray was dissolving into the slurry water to some degree and influencing the water chemistry. The impacts of water chemistry on the performance of flocculants (Stocks and Parker, 2006) and on the depositional fabric of kaolin (Sachan and Penumada, 2007), are well established. It was therefore judged prudent to eliminate this potential source of influence on the results.

This omission will result in increased friction on the loading system, meaning that slightly less effective stress is applied than would be indicated by the difference between diaphragm and pore pressure. However, this increase in friction will apply to all tests conducted to a similar degree. Therefore comparison of the tests is still valid.

3.4 Particle size distribution

Estimates of PSD were obtained using the laser-diffraction method. A Malvern 2000 Particle Size Analyser with overhead impeller speed set to 2,400 RPM was utilised on all tests. This type of device was utilised with success by Alam et al. (2010) to provide direct evidence on the increase in apparent particle size that can result from flocculant addition.

An initial series of tests was conducted on kaolin without flocculant, and with flocculant dosages of 100, 500 and 1000 g/t. While 1000 g/t is a very high dosage, it is within the range being utilised or considered in some recent publications on in-line flocculation (Wells et al., 2011). The flocculant preparation and dosing methods are outlined above. The samples for testing were obtained from the surface of settled material at the end of additional settling tests performed to provide material for this testing.

Following the results of the initial PSD and Rowe Cell testing, additional samples were obtained from the Rowe Cell as follows: at the end of selected load increments, the cap of the Rowe Cell was removed and the upper surface of the kaolin gently scraped away to a depth of approximately 0.5 mm. Samples were then obtained from the new surface of the sample. At the end of sampling, the surface was smoothed as far as was practical, the Cell reassembled and loading continued. Samples were also obtained from oven dried material at the end of the Rowe Cell test.

A minimum of two PSD tests was performed on each sample. Little divergence between test results was observed. The average results of all the tests conducted on each sample are presented below.

4 Results

4.1 Settling tests

Based on a comparison of the flocculants provided, RHEOMAX 9070 flocculant was found to result in the highest initial settling rate and was utilised on all further testing outlined in this paper. Following selection of the flocculant, a series of settling tests were performed to determine a dosage range for the work (Table 1). The results indicated that dosages above 100 g/t resulted in relatively minimal increases in settling rates. Initial testing was therefore conducted at 100 g/t. Based on some initial results, it was decided to extend the testing program to include 500 and 1,000 g/t. It should be noted that for the 1,000 g/t samples, the flocculant was added at a higher concentration of 0.1%. This was conducted to assess the impacts of flocculant solution concentration.

Table 1 Settling test summary

Dosage	Initial Settling Rate (cm/min)	Final Settled Dry Density (t/m^3)
Without flocculant	0.05	0.49
100 g/t	8	0.34
500 g/t	10	0.32
1000 g/t	2.5	0.34

It is worth noting the reduced settled dry density resulting from flocculant addition. The question of how long this looser state persists under increasing vertical effective stress is addressed with the Rowe Cell work.

4.2 Rowe Cell consolidation testing

The compression line determined from the series of Rowe Cell tests are shown in Figure 2. Significant variance in the void ratio of the tests is evident at 10 kPa, which diminishes at 20 kPa. From 40 kPa and above, the compression lines are quite similar. The results are compared to a range of tests conducted on the kaolin used at UWA, as reported by Lehane et al. (2004) and Stewart (1990). The unloading results are not shown.

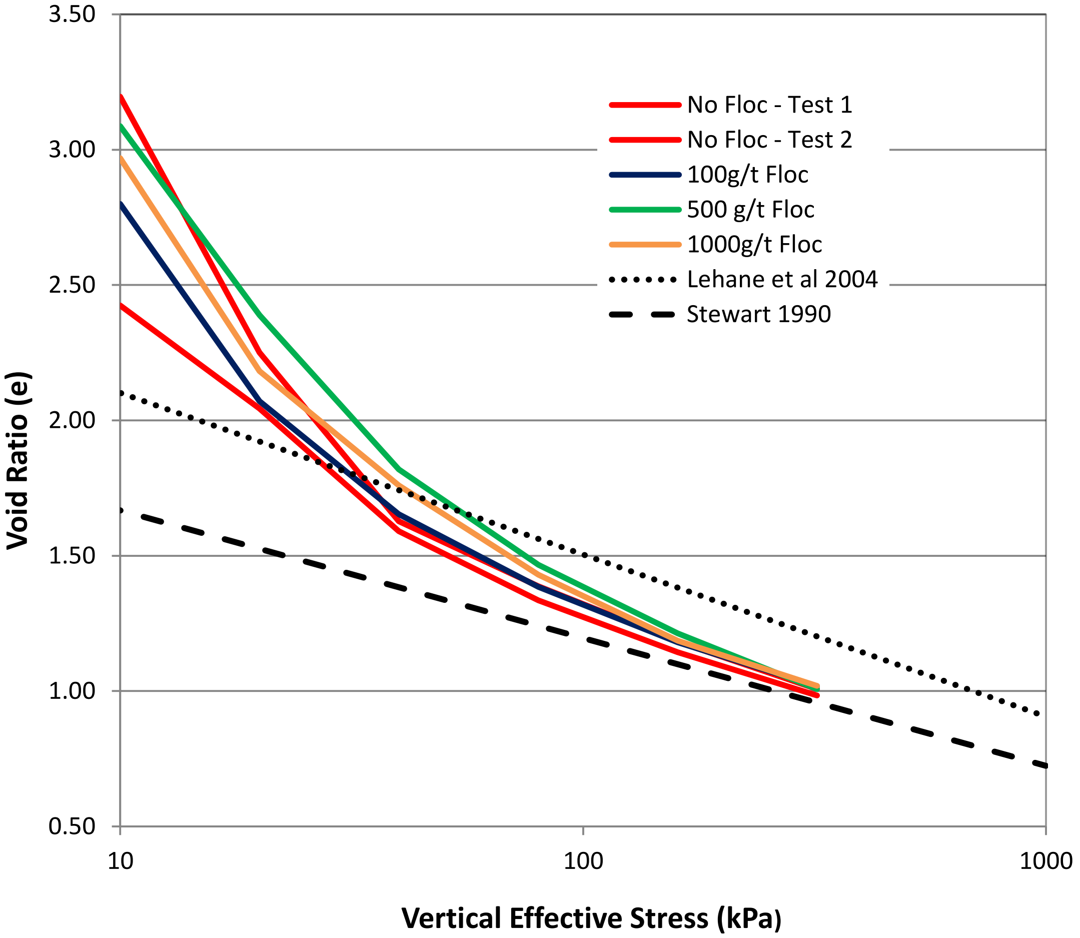

Figure 2 Compression results

The data at vertical effective stresses less than 20 kPa should be considered as indicative only. The samples, as prepared above, were extremely soft and sensitive. In early tests, the weights were added without the loading plate. As the weights had a diameter of about 3–4 mm less than the cell, this allowed material to ‘squeeze’ up around the plate. More importantly, in early tests it was attempted to settle out a quantity of material that would result in the maximum possible sample depth at the start of the test. This was problematic, however, as it meant that when the Rowe Cell cap was placed, pressure was applied immediately from the diaphragm. Some investigation of the Cell during testing indicated that small amounts of material squeezed up around the loading plates under the first load application of 10 kPa. The loss of small amounts of material under the initial few loads would explain why the results exhibit excessive compressibility and why the tests are quite variable in this range. As the results are back calculated from the final void ratio and displacements, the observed void ratios in the 40–320 kPa range are considered reliable. The unloading results were indistinguishable across all effective stresses.

Time dependent results are shown in Figures 3 and 4. Coefficient of consolidation and permeability were calculated based on the decay of pore water pressure observed at the bottom of the Rowe Cell. The c_v and

k_v data points were taken to be relevant to the average effective stress experienced by the soil between the starting and ending effective stress during a given loading increment.

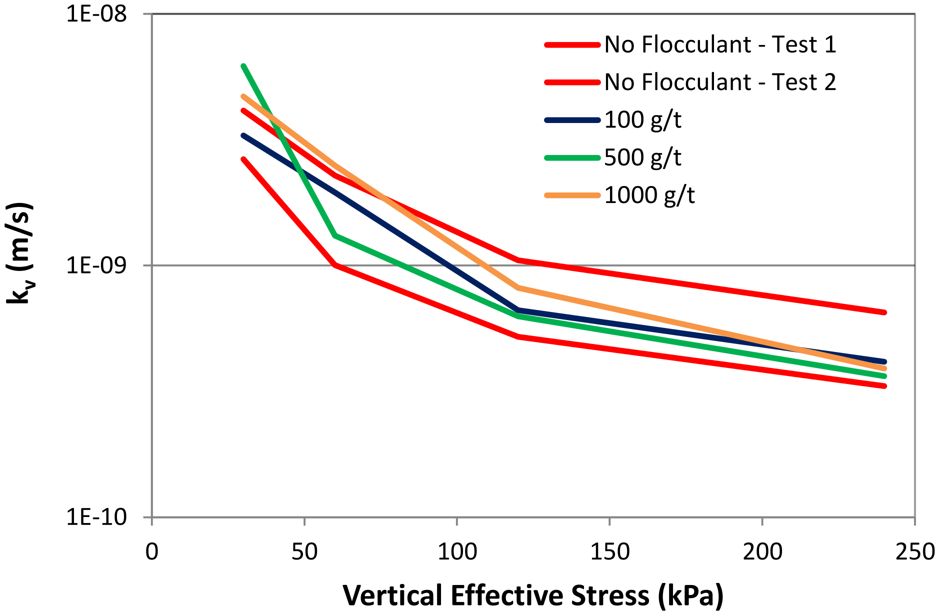

Figure 3 Permeability results

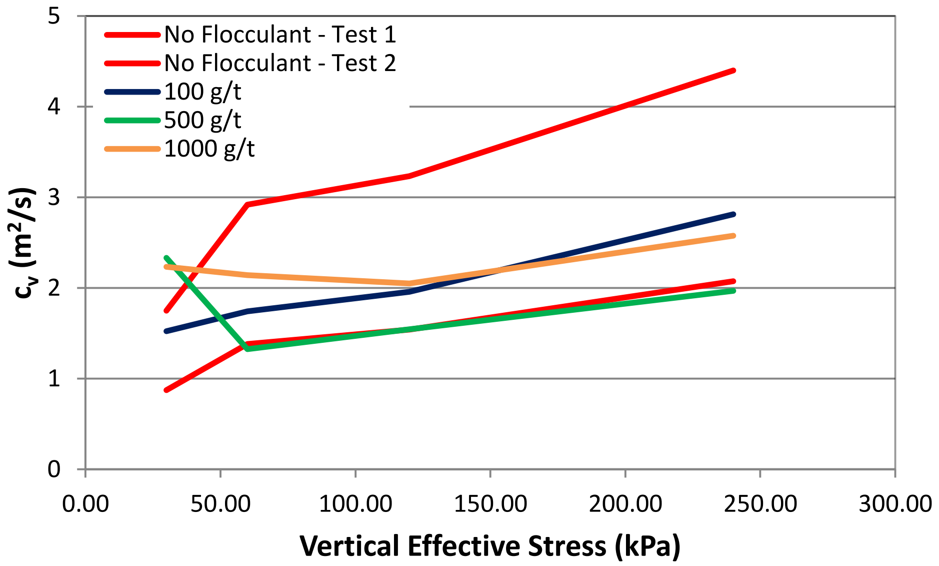

Figure 4 Coefficient of consolidation results

As indicated, the permeability and coefficient of consolidation results are quite similar. Given the typical accuracy range expected for permeability testing, the results indicate that flocculants are having no effect on permeability. This is further reinforced by the observation that the largest divergence is seen on the two tests that were not flocculated. The results obtained, above an effective stress of 40 kPa, are within the expected range for kaolin.

4.3 Particle size distribution

The results of testing on settled samples are shown in Figure 5. Some of the relevant gradation parameters are shown in Table 2.

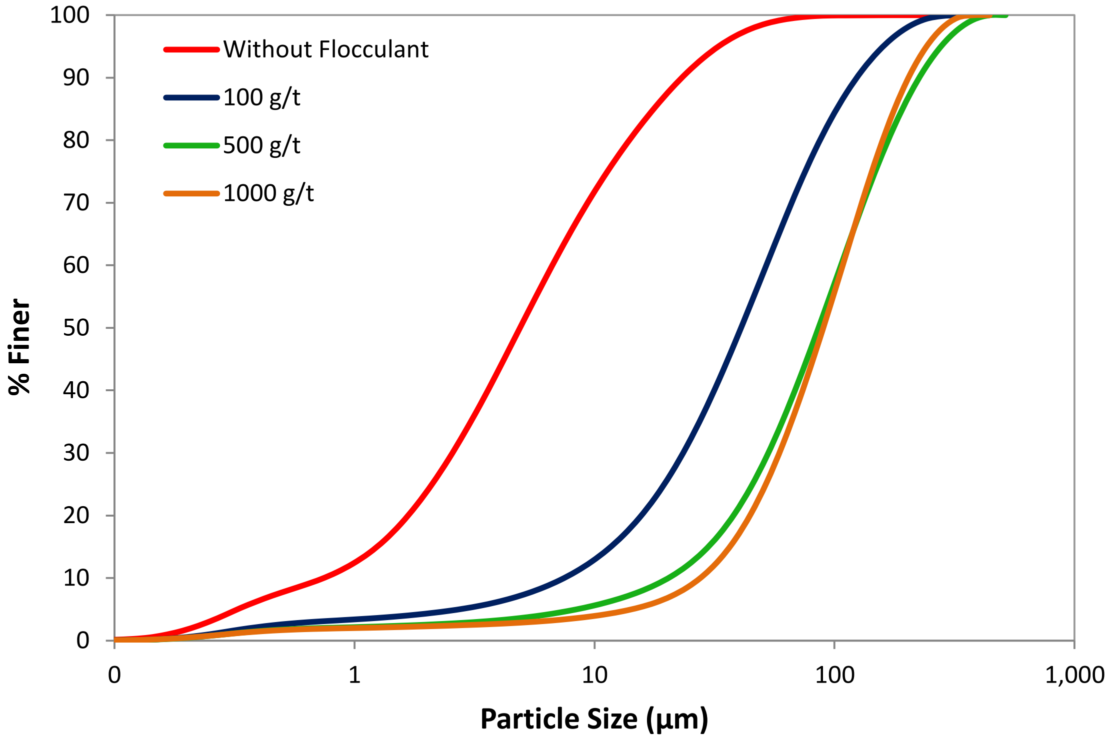

Figure 5 PSD results on settled samples

Table 2 PSD parameters

Dosage	% Clay Size	% Finer than 75 µm	d_{50} (µm)	Cu (Uniformity Coefficient)
Without flocculant	24	100	5	8.5
100 g/t	4	75	41	7.3
500 g/t	3	38	99	5.0
1,000 g/t	2	41	96	4.0

The above results clearly show that flocculant addition results in an increased apparent particle size. This increase is substantial, with the 500 and 1,000 g/t samples classifying as sand in the USCS system based on the proportion of the sample larger than 75 µm. It also appears that the samples are becoming more uniformly graded with flocculant addition, although this effect is less pronounced.

As outlined above, the similarity of the Rowe Cell tests, contrasted to this change in PSD when settled, led the authors to address the question of how the PSD changes would persist under loading. The tests collected from the surface of the Rowe Cell were performed to address this, with the results shown in Figure 6.

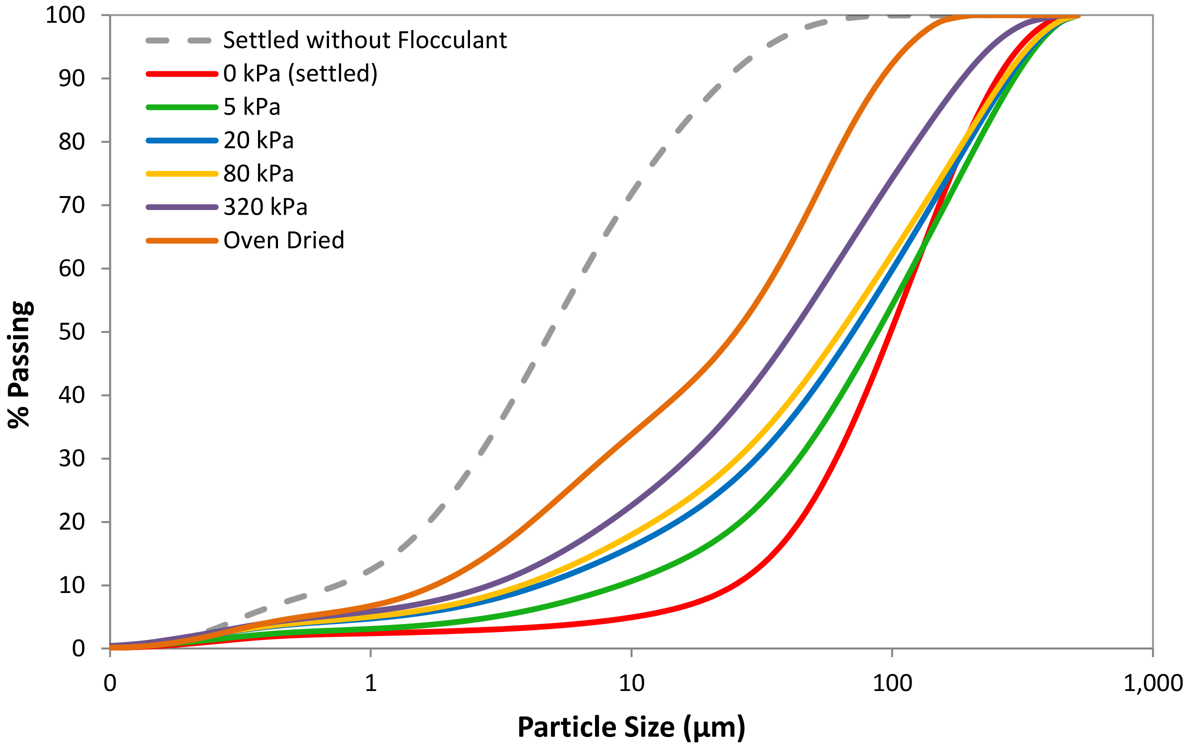

Figure 6 PSD results from Rowe Cell

The results of these tests indicate that the application of load to the samples is breaking up the flocculated particles to some degree. However, the extent of this is relatively small in comparison to the increase in particle size resulting from flocculation. As an additional check on the durability of the flocculated particles, the final oven dried sample was tested. This indicated that oven drying further damaged the flocculated particles, but did not completely remove their effect.

5 Discussion

The results of the two types of testing presented are curious. The PSD changes induced by the flocculants are substantial. This is supported by the increased settling rate achieved. This change to PSD appears to persist under application of significant loads. On the basis of the PSD changes alone, quite different consolidation behaviour would be expected. However, the consolidation behaviour was quite similar regardless of apparent particle size.

McFarlane et al. (2006) used Scanning Electron Microscopy (SEM) to examine kaolin after flocculation. The flocculants appeared to produce a more porous structure, with flocculated clumps forming a ‘honeycomb’ pattern with large voids. This structure could be expected to result in higher permeability. However, this was not detected in the tests conducted. McFarlane et al. (2006) also showed that under shearing, this structure was damaged. Despite this damage, the flocculated particles seem to remain intact to some degree.

It is clear that greater understanding of the particle interactions is required. The authors propose to employ SEM to further investigate this. A number of other comparative test work is underway and planned at the time of writing. This includes triaxial testing to determine the critical state line, cyclic direct simple shear, and possibly ring shear testing as well, to investigate residual strength.

It should be noted that the above results may actually be considered positive in relation to the use of flocculants ‘in-line’. Many in the industry (the authors included) have assumed that the higher settled densities created by flocculants would persist under loading to some extent. At least in the case of kaolin with the selected flocculant, this does not appear to be the case. In addition, if flocculants do not affect the geotechnical behaviour of soil under typical engineering effective stresses, this will simplify the testing regime required during design studies.

The work will also be extended to an investigation of a range of tailings streams and other soils. In particular, predominately silt-size material with some clay will be manufactured from standard laboratory material. The produced grading will aim to target that of mine tailings.

The improvement in sample preparation method developed from this initial series of tests will be used on all future tests. A series of duplicate tests will be conducted on all the types of samples tested here to produce more reliable results in the 5–40 kPa effective stress range.

The most important point to emphasise is that the results presented here are relevant for one soil type and one flocculant. Owing to the time consuming nature of the testing and the publication deadline, only one combination could be tested in anything approaching a comprehensive manner. The combinations of flocculants, mineralogy and gradations are nearly infinite. A significant quantity of additional test work will be required before any general conclusions about the impacts of flocculants on geotechnical parameters under typical engineering effective stresses can be made.

6 Conclusion

A series of Rowe Cell consolidation tests and PSD determinations for kaolin flocculated with dosages of RHEOMAX 9070 were presented. These indicated that the flocculant appears to have negligible impact on the stiffness and permeability of the material across a wide range of effective stresses relevant to geotechnical engineering. Conversely, the flocculants appear to be creating a much larger effective particle size. This increased particle size appears to survive significant perturbation, including application of vertical effective stresses. Reconciling these two contradictory conclusions will be the focus of future work by the authors. It is emphasised that these conclusions apply only to the material tested; tailings streams that include a wider range of particle sizes may not necessarily follow the behaviour described.

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