The Effect of Polymer Solutions on the Settling Behaviour of Sand Particles

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Contents

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Abstract

The formation of sediment at the base of bore holes that are supported by polymer fluids during construction can lead to serious problems. The load bearing capacity of foundations placed upon a soft layer of sediment is significantly reduced, which can lead to them sinking and damaging the structure. Understanding the formation of this sediment layer is essential so that it can either be avoided or effectively removed.

The rate of sediment build-up in suspensions of sand in a shear thinning polymer solution was investigated using a light backscattering technique in a machine called a Turbiscan. The two factors that were investigated to see how they influenced sedimentation were the concentrations of both the sand particles and the polymer in the solution. The amount of light that a sample backscatters and how it changes over time gives an indication of how the concentration of the sample is changing. By using the results of how the concentration of the suspensions changed with time and further experiments into the height of sediment formed by different concentrations of sand, graphs were produced showing the height change of the sediment over time. This method avoids some of the drawbacks that are present in previous research of settling in support fluids.

It was found that increasing the concentration of sand increased the rate of sedimentation due to an effect known as clustering where particles in close proximity to each other are able to settle at a rate much faster than they could have done on their own. These clusters formed channels analogous to a slipstream that enabled many particles to settle faster than the bulk. The concentration of the polymer was found to have a significant effect upon the settling rate. A combination of the increased viscosity of a higher concentration polymer solution and the shear thinning nature of the polymer greatly reduced the settling rate.

Nomenclature

Roman Symbols

BS	Backscattering
d	Mean particle diameter
$\mathrm{d}u/\mathrm{d}y$	Shear rate
F_g	The force acting on the particle due to gravity
F_d	The drag force operating on the particle
g	Acceleration due to gravity
$\mathscr{g}$	Asymmetry factor
h	Height of sediment
h_s	Height of slurry
K	Consistency index
k	The permeability of the sediment
ℓ^*	Photon transport mean free path
m	Mass
n	Flow behaviour index
∇P	The pressure gradient over the sediment
Q_s	Scattering efficiency factor
q	The flux of fluid out of the sediment
R	The radius of the particle
t	The time it takes for 1 US quart (946 ml) to flow out of the Marsh funnel
V_l	Volume of liquid
V_s	Volume of solid
v	The velocity of the particle
v_s	The terminal settling velocity of the particle

Greek symbols

Θ	The volume of sand in the sediment as a per cent of total slurry volume at time ***t***
μ	The viscosity of the fluid
μ_p	Plastic viscosity – the viscosity of a Bingham plastic
μ_s	The viscosity of a suspension
ρ	Density
ρ_p	The density of the particle
ρ_f	The density of the fluid
τ	Shear stress
τ_0	Yield stress
ϕ	Volumetric concentration of particles
ϕ_1	Initial concentration of particles in suspension

1 Introduction

Construction is one of the world's largest industries and is extremely important for the United Kingdom; the gross value added to the economy in 2008 was approximately £75 billion (ONS, 2010). It is also an industry that has proven to be one of the most resilient, being one of the first to return to growth after the recession. Research in the construction industry is extremely important; it is an industry where things have to be done right on the first try and where mistakes can be exceptionally costly. Project managers tend to stick to the tried and tested techniques and it makes it very difficult for new technologies to break through. With legislation driving up the cost of certain methods there is now a push for change to newer technologies. Laboratory research is important as it enables a technology to be tested on a small scale and provides a basis to develop a technology more economically than carrying out all tests at full scale.

There are few situations where the phrase "working from the ground up" is more fitting than in construction, but in fact arguably one of the most important aspects of a structure begins underground: the foundations. The whole of the rest of the structure relies on the foundations and if they fail it will jeopardise the entire construction. There are many different ways of constructing foundations for large structures and one of the most important methods is piling. Pile foundations work by transferring the load of a structure through soil which cannot provide adequate support to a layer which can, or they go to a sufficient depth that friction on the pile can support the vertical load (Prakash & Sharma, 1990), as can be seen in Figure 1.1.

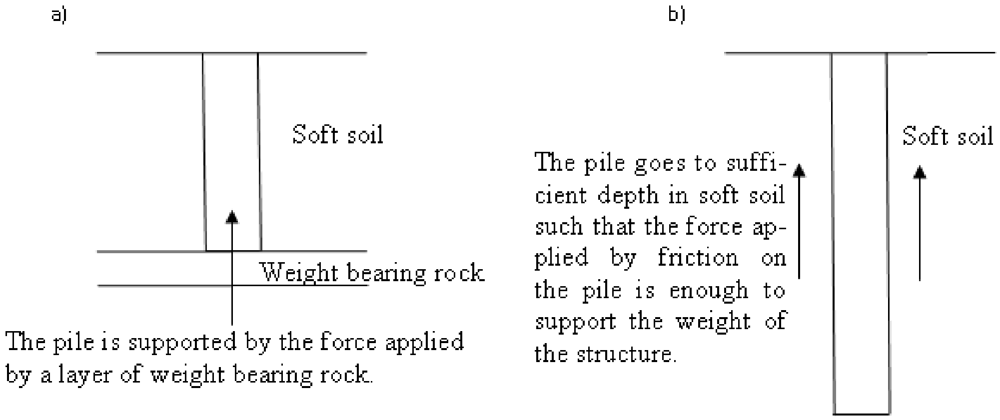

Figure 1.1 The forces acting on foundation piles.

Foundation piles can be made by simply driving the pile into the ground, by hammering or vibrating it into the soil, but this project will focus on what are known as bored piles. A bored pile is constructed by drilling a hole with an auger, such as one shown in Figure 1.2, which is then filled with concrete. One of the issues associated with bored piles is that during drilling in soft or water bearing soils the borehole could collapse if unsupported. One solution to this problem is a support fluid that provides lateral support to the walls of the shaft, limiting any deformation of the soil (Smoltczyk, 2002).

Figure 1.2 A twin flight auger immediately after being extracted from a hole supported by a polymer fluid (Lam *et al.*, 2010).

Bentonite has been the support fluid of choice in the construction industry for many decades. Bentonite is a special type of clay with highly adsorbent properties that is ground up into a fine powder and mixed with water to form a slurry. Originating in oil well drilling it is the fluid that has been in use in the construction industry for the longest time, it is well understood and works very effectively when drilling foundations. Other support fluids that are widely in use today are synthetic polymers such as partially hydrolysed polyacrylamide (PHPA), which this project will focus on. PHPA also originates in oil well drilling but has not been used in the construction industry as long. Bentonite has been used since the early 1960s (Federation of Piling Specialists, 2006) whereas the first uses of PHPA were in the 1980s but Wheeler (2003) states that it was not until the year 2000 that the industry in the UK took much interest in polymer fluids. Because they have not been used as a support fluid for the excavation of foundations for as long, polymer solutions are far less well understood and this holds back their further utilisation within the industry.

There are several key reasons that make it desirable to use synthetic polymer support fluids. The first and possibly the most significant is that the disposal of liquids has come under strict legislation. Due to the European Landfill Directive it is now illegal to dispose of liquids in landfills in the UK (Defra, 2009). This legislation covers all liquids, both the bentonite and polymer fluids, and can make it very expensive to dispose of liquids but the polymer solutions have a very important advantage. Through the treatment of the polymer with very simple chemicals, such as bleach, the polymer can be broken down, causing any suspended soil particles to fall out of the mixture and the viscosity of the solution to be reduced back down to that of water. This means that when the polymer solution has been finished with it can be treated and disposed of into the sewer.

Another benefit of the polymers is that they require much less space on construction sites than the mixing of bentonite slurries. In situations such as construction in crowded and compact cities where space is at an absolute premium this can make the polymer support fluids a very attractive option.

Despite this, uptake of this technology by foundation engineers has been limited. One of the things which stands in its way are that many brands of polymer solutions are proprietary products meaning that engineers know very little about their makeup. There are also a limited number of case histories to support the polymer fluids and there a couple of cases, for example in Texas where the foundations of some bridges, which were supported by polymer fluids during construction, have settled excessively requiring costly repair work (Texas Department of Transport, 2008). What occurs during drilling is that the digging action of the piling auger brings soil and sand particles into suspension in the support fluid. The sedimentation of these particles leads to soft deposits building up at the base of the boreholes while they are being supported by the polymer solution. The sediment layer reduces how effectively the load on the pile is transferred to the underlying rock and it is this which has led to the excessive settling of foundations in cases such as in Texas.

It is this problem of sedimentation in pile bores which this project aims to investigate. Bentonite slurries do not flow like fluids such as water because they are a Bingham plastic. A Bingham plastic requires a certain amount of force to be applied to it before it moves; the magnitude of the force that needs to be applied before it flows is called the yield stress. Small particles in bentonite do not experience a great enough force under gravity to exceed this yield stress, therefore they do not settle, they remain in suspension and very little sediment forms. The polymer fluids on the other hand do not possess a yield stress, which means that suspended soil particles in the solution settle out very quickly and form a layer of sediment at the base of the bore.

In modern construction bored piles have become deeper and larger in diameter. This means that it takes longer for concrete to be placed in the shaft and gives greater opportunity for sedimentation to occur (Brown, 2004). For this reason it is important to gain a good understanding of the settling behaviour of soil particles in these polymer solutions to ensure that future piles will not settle beyond their design limits. The objective of the project is to characterise the sedimentation and be able to predict the extent to which it will occur in bored piles.

The rest of this project is split into six sections; the first is a literature review to look into previous work relevant to the subject. With a solid understanding of the existing knowledge in the area and the experimental methods that have been utilised in previous studies the objectives and methods of this work will be set out. The results of this work will be discussed and then conclusions will be drawn, looking into the implications of this work. The final part of this report makes some recommendations for future research.

2 Literature review

This literature review builds upon the overview presented in the introduction to provide a detailed summary of the principal technical and fundamental knowledge in this area. The review is structured into sections discussing the functions of support fluids, the settling of particles and concentrated suspensions, previous work on settling in support fluids, the methods that can be used for observing settling and finally describing some of the methods used in the industry to characterise support fluids.

2.1 The functions of support fluids

An outline of how support fluids operate is provided below to provide an insight into why certain properties of the fluids are important to their function. Support fluids are an extremely important method for ensuring the stability of boreholes; the two main types in use today are bentonite and polymer fluids. A multitude of other fluids have been investigated as an alternative to bentonite, such as solutions of xanthan gum and starch, but have invariably been discarded as a replacement due to either unsatisfactory performance or cost (Lam, 2008).

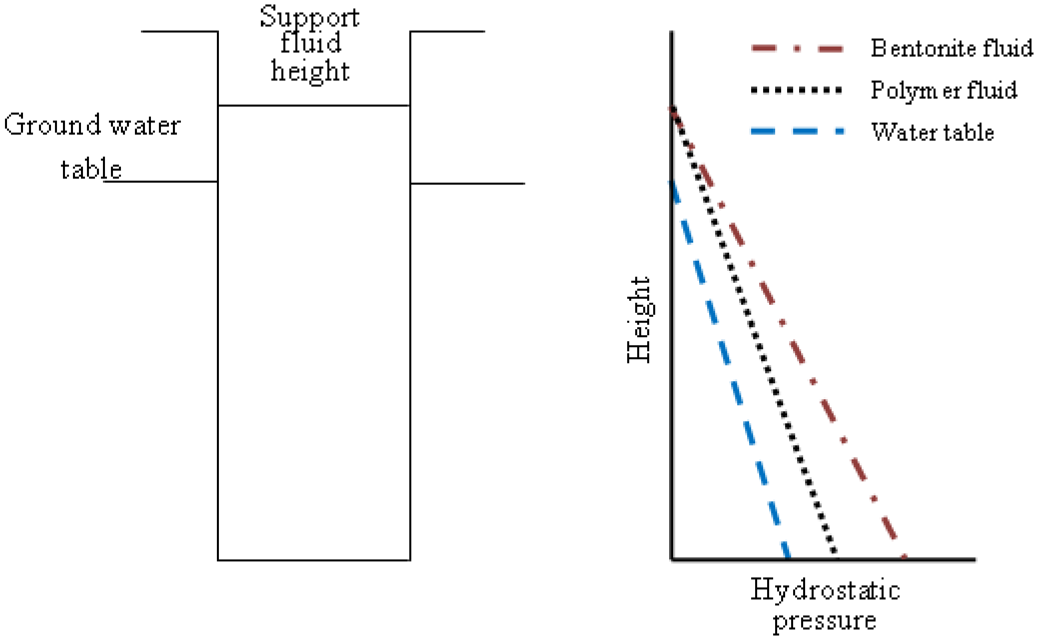

Figure 2.1 Hydrostatic pressure in a pile bore.

Figure 2.1 shows a shaft supported by a fluid and how the hydrostatic pressure of fluids varies over the height of the shaft. By filling the shaft with fluid to several metres above the water table the hydrostatic pressure of the fluid in the shaft will be higher than that of the surrounding ground water; this pressure is transferred to the walls supporting the shaft.

The density of the polymer solution is approximately the same as water so the top of the fluid needs to be kept several metres above the water table to produce the supportive hydrostatic pressure. The density of the bentonite slurry is much higher than water so the pressure change with height is larger. It is essential that the height of the fluid is not permitted to fall below the height of the groundwater or the walls of the shaft could begin to crumble (Brown *et al.*, 2010).

Due to the pressure gradient across the wall, if the hole was filled with water it would very quickly flow through the pores in the soil and its level would reach equilibrium with the ground water. Using the polymer solution, its high viscosity means its flow through the pores is considerably slower; the fluid loss is less so the hydrostatic head remains. The support fluid will still flow slowly out of the shaft and it will need to be topped up to keep the pressure higher in the hole than the ground water.

In a bentonite slurry the pressure gradient tries to force the fluid out of the shaft through the soil walls. The particles of clay that make up the slurry build up on the wall forming an impenetrable “filter cake” preventing any further fluid from flowing out of the shaft. The hydrostatic pressure of the slurry then operates on the walls supporting the shaft (Federation of Piling Specialists, 2006).

2.2 Settling of particles

It is useful to have an understanding of the settling of single particles before considering a suspension where a multitude of different interactions can have a significant influence on sedimentation.

In an infinitely diluted solution a spherical particle settling under gravity experiences three forces, a gravitational force $\boldsymbol{F_g}$, a hydrodynamic drag force $\boldsymbol{F_d}$ and a random Brownian force (Buscall & White, 1987). Brownian motion can have a significant effect on extremely small particles but for anything larger than 10 μm it is insignificant compared to gravitational settling (Allen, 1992). The forces experienced by a falling sphere are described in equations 2.1 & 2.2. $\boldsymbol{\rho_p}$ and $\boldsymbol{\rho_f}$ are the densities of the particle and the fluid, $\boldsymbol{g}$

is acceleration due to gravity, $\boldsymbol{R}$ and $\boldsymbol{v}$ are the radius and velocity of the particle and $\boldsymbol{\mu}$ is the viscosity of the fluid.

$$F_{\mathrm{g}} = (\rho_{\mathrm{p}} - \rho_{\mathrm{f}})g\frac{4}{3}\pi R^3 \qquad 2.1$$

$$F_{\mathrm{d}} = 6\pi\mu Rv \qquad 2.2$$

2.2.1 Stokes' Law

George Stokes derived equation 3.3, known as Stokes' Law, to describe the forces acting upon a particle falling through a fluid for the case of creeping flow. Creeping flow occurs at very low Reynolds numbers i.e. very small particles or flow at very low velocities relative to the particle (Stokes, 1851). $\boldsymbol{v_s}$ is the terminal settling velocity of the particle.

$$v_{\mathrm{s}} = \frac{2}{9}\frac{(\rho_{\mathrm{p}} - \rho_{\mathrm{f}})}{\mu}gR^2 \qquad 2.3$$

It is important to note that Stokes' Law is only applicable to the settling of a particle in a Newtonian fluid under the strict limit of very low Reynolds numbers. As the Reynolds number increases the particle moves into what is known as transitional flow and then into Newtonian flow which require different equations to describe them and to describe a particle falling through a non-Newtonian fluid far more complex equations are required. Stokes' Law is very useful though as an example to highlight the effect different factors have on the settling velocity of a particle.

Particle size and shape

In the Stokes flow regime it is easy to see the large effect particle size has on the settling velocity; doubling the radius of a particle will increase its velocity by four times. Smaller particles will fall more slowly than larger ones due to the fact that they have a larger surface area compared to their volume.

Stokes' Law as it is shown in equation 2.3 applies to spherical particles but the shape of a particle also affects the drag force it experiences. The cross-sectional area presented to the flow of the fluid is one of the most influential characteristics but how angular or smooth a particle is also has an impact on the drag force. A spherical particle is convenient to describe as its orientation in the fluid does not affect the drag force that it experiences but the drag acting on non-spherical particles is far harder to calculate.

Density

The density of the fluid is important because the mass of the fluid displaced by the particle is equal to the buoyancy force operating on it. The density of the particle affects the gravitational pull acting on it and thus the difference between the two densities determines the net gravitational force downwards on the particle.

Viscosity

The more viscous a fluid is the harder it is for the particle to flow through it. The viscosity of the fluid affects the drag force the particle experiences, directly affecting the rate of fall, but it also influences the Reynolds number of the falling particle. This means that a particle settling in the transitional flow regime in one fluid might be in the Stokes regime in a more viscous fluid, also affecting the drag force the fluid experiences.

2.2.2 Rheology

The types of fluid generally used for supporting boreholes can be described as either Newtonian, Bingham plastic or shear thinning. The difference between these different types of fluid lies in their reaction when a force or shear stress ($\boldsymbol{\tau}$) is applied to them.

Figure 2.2 shows how the shear stress of these three fluid types changes with shear rate (du/dy). The gradient of the slopes is the viscosity of the fluid.

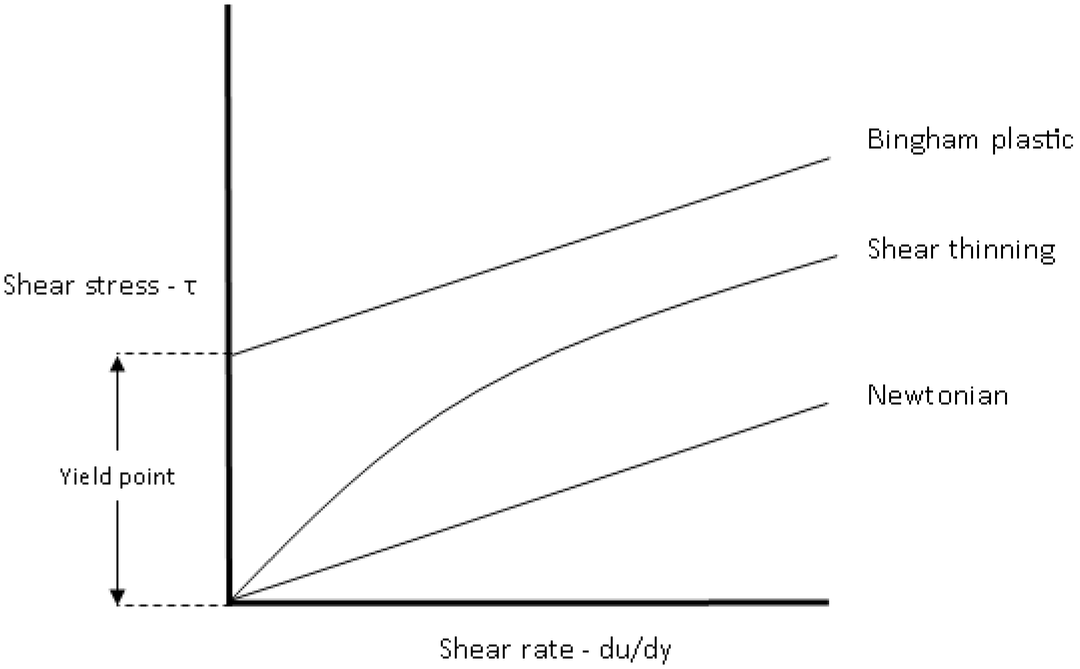

Figure 2.2 Flow of Bingham, shear thinning and Newtonian fluids.

Newtonian fluids

$$\tau = \mu \frac{\mathrm{d}u}{\mathrm{d}y} \qquad 2.4$$

An example of a Newtonian fluid is water, which is occasionally used in drilling. The shear stress acting on a Newtonian fluid varies linearly with shear rate. The only property that is needed to describe a Newtonian fluid is its viscosity (Malkin & Isayev, 2006).

Bingham plastic

$$\tau = \tau_0 + \mu_\mathrm{p} \frac{\mathrm{d}u}{\mathrm{d}y} \qquad 2.5$$

A Bingham plastic differs from a Newtonian fluid in one important way; it requires a particular amount of shear stress to act upon it before it will start to flow, known as the yield stress, $\boldsymbol{\tau_0}$. In a Bingham plastic after the yield stress has been reached the fluid begins to flow and the viscosity appears constant. The Bingham model is shown in equation 2.5; the yield stress and the plastic viscosity ($\boldsymbol{\mu_p}$) are required to describe a Bingham plastic (Malkin & Isayev, 2006).

The affect that the yield point has upon sedimentation is that if a particle is small enough that its gravitational force does not exceed the yield stress of the fluid it will not move and will remain in suspension in the fluid.

Shear thinning fluids

$$\tau = K\left(\frac{\mathrm{d}u}{\mathrm{d}y}\right)^{n} \qquad 2.6$$

The behaviour of a shear thinning fluid can be approximated by the power law model shown above in equation 2.6, where $\boldsymbol{K}$ and $\boldsymbol{n}$ are the consistency index and the flow behaviour index. The model benefits from its simplicity but its drawback is that it is only appropriate across the range of shear rates to which the coefficients were fitted and does not account well for Newtonian behaviour at low shear rates (Malkin & Isayev, 2006). There are alternative models such as that proposed by Carreau (1972), which is able to describe the behaviour of shear thinning fluids at low shear rates far more successfully than the power law model.

The main characteristic of a shear thinning fluid is that as the shear stress applied to the fluid increases, its viscosity drops. Shear thinning fluids can appear to be Newtonian at low shear rates and very high shear rates where the change in viscosity with shear rate is much smaller. If only high shear rates of a shear thinning fluid are investigated it can appear by extrapolating back to the y-axis that that the fluid possess a yield point, termed a pseudo yield point, and it is for this reason that shear thinning fluids are often referred to as pseudoplastics.

Buscall *et al.* (1982) investigated the characteristics of a cellulose polymer, which is a shear thinning fluid, and the sedimentation of latex particles within it. Their results demonstrated that below a critical value for shear stress the fluid behaved as a Newtonian fluid but above it the viscosity begins to drop. However the work of Buscall *et al.* on sedimentation in shear thinning fluids only showed that the rate of settling was proportional to the inverse of the viscosity at zero shear rate, which they defined as the viscosity at very low shear rates where the fluid appeared Newtonian.

Figure 2.3 shows how the viscosity of PHPA varies with shear rate. It can be seen that at low shear rates the polymer solution behaves as a Newtonian fluid, with a constant viscosity, but as the shear rate increases the viscosity drops.

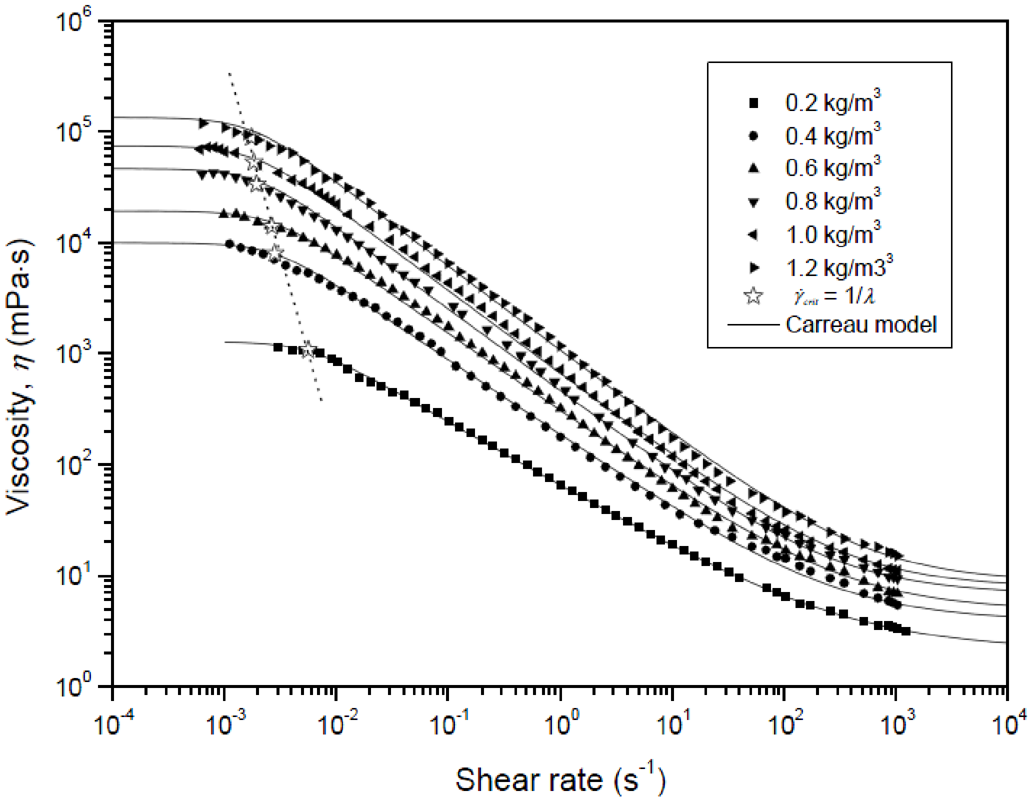

Figure 2.3 The flow curves of various concentrations of PHPA (Lam, 2008).

A shear thinning fluid such as PHPA can affect the rate of settling of different sized particles. Smaller particles will exert a lower shear stress on the fluid thus leading to them experiencing a higher viscosity. This means that compared to the large particles the smallest ones will fall slowly not only due to their size but their velocity will also be retarded by the increased viscosity that they experience.

2.3 Settling of concentrated suspensions

The settling of a concentrated suspension can vary significantly from that of a single particle due to a multitude of interactions. This section looks into the factors that will affect the settling of a concentrated suspension and how they relate to this project.

2.3.1 Types of settling

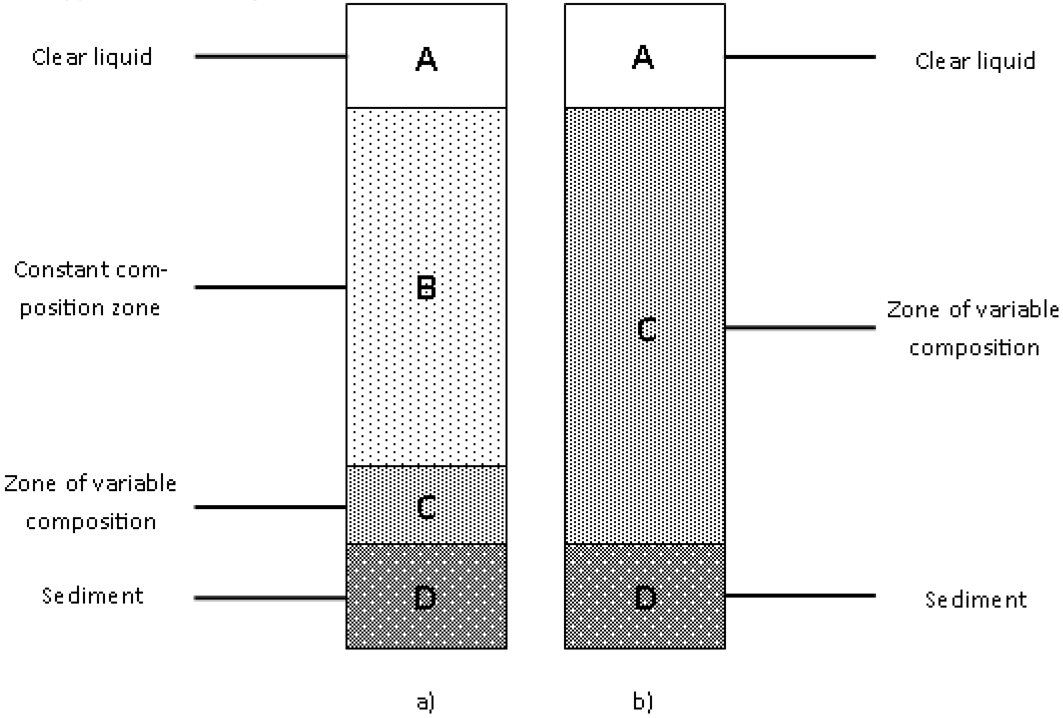

Figure 2.4 a) Type 1 settling b) Type 2 settling.

Coe and Clevenger (1916) determined that the settling of concentrated suspensions could be characterised as occurring in two different ways; type 1 & type 2. Figure 2.4a shows type 1 settling which occurs when the dimensions of the particles are very similar. In this regime there is an initial period of acceleration, as the particles reach their terminal settling velocity. The interface between the clear liquid and the suspension can then be observed to descend at a constant rate until close to the layer of sediment at the bottom where concentration of the suspension steadily increases and its rate of fall decreases. After the clear liquid interface reaches the sediment further sedimentation can occur but only as consolidation of this layer; this process is very slow as it only takes place as liquid is forced out around the particles. The rate of this consolidation also gradually reduces as the particles get closer together and thus resist the flow of the liquid more. This process can be described by separating the sedimentation into different zones where A is clear liquid, B is a zone of constant composition where the particles are in free fall and C is the zone where the concentration varies as the particles reach the sediment layer D.

Type 2 settling, as shown in Figure 2.4b, occurs when there is a large variety in the sizes of the particles. The main difference from type 1 is that the particles will have different velocities, meaning that there will be no zone of constant concentration, and the whole suspension between the clear liquid zone and the sediment layer can be described as zone C (Coe & Clevenger, 1916).

2.3.2 Height of suspension

The height of the suspension does not affect either the rate of settling or the consistency of the sediment. Figure 2.5 displays the height of the clear liquid-suspension interface against time for two different initial suspension heights, what can be seen is that the ratio of 0A':0A'' is equal everywhere (Work & Kohler, 1940). Due to this fact it is possible, once results from one height are obtained, to plot a graph for any height of suspension. This is an extremely important feature as it means that experimental work on the laboratory scale should be able to be scaled up effectively to the size of bore holes in the construction industry.

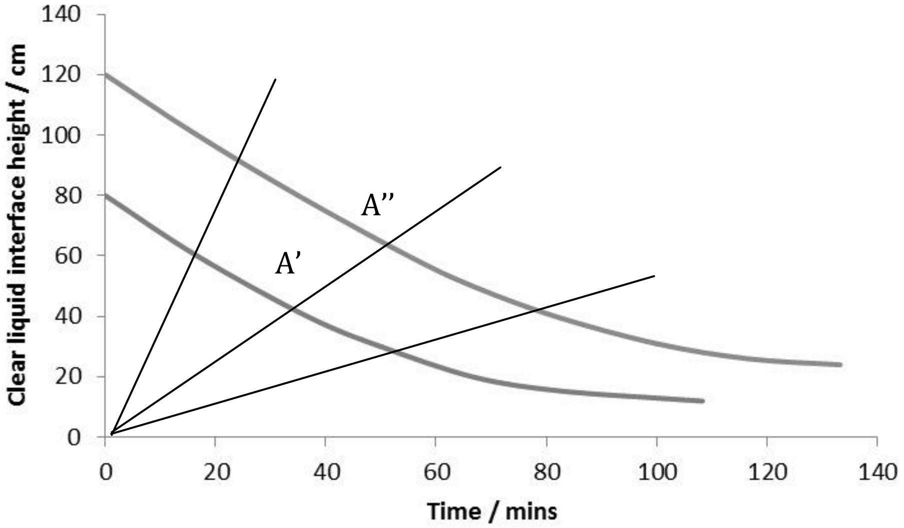

Figure 2.5 The effect of initial suspension height on settling.

2.3.3 Particle effects

Increasing the concentration of particles suspended in a fluid increases the density and viscosity of the suspension. A fluid with sand suspended in it will have a higher density leading to a higher buoyancy force acting on the particles (Richardson *et al.*, 2002). The effect of suspended particles on the viscosity of the fluid can be seen in the work of Lam (2008) who compared the viscosity of suspensions containing different concentrations of sand and it could be seen to increase with particle concentration.

Einstein (1906) looked into the effects of a low concentration suspension of spherical particles on viscosity and developed equation 2.7 to describe it. Equation 2.7 is valid up to concentrations of 2% and similar equations such as that developed by Vand (1948) can be used to describe higher concentrations. $\boldsymbol{\mu}$ and $\boldsymbol{\mu_s}$ are the viscosities of the clean fluid and of the suspension and $\boldsymbol{\phi}$ is the volumetric concentration of particles in the suspension.

$$\mu_\mathrm{s} = \mu\left(1 + \frac{2}{5}\phi\right) \qquad 2.7$$

One of the most important factors which affect the rate of settling is the concentration of the suspension. As a particle falls it must displace a volume of fluid equal to its own. This leads to currents forming within the fluid and as the concentration increases the rate of fall decreases due to the upward velocity of the displaced liquid being greater. The way in which concentration affects the settling rate can be seen in equation 2.8 (Einstein, 1911), it is only a good approximation at low particle concentrations but its simplicity is useful to understand the influence of particle concentration on settling rate. $\boldsymbol{v}$ is the settling rate of the suspension and $\boldsymbol{v_s}$ is the Stokes' settling velocity calculated from Stokes' Law.

$$v = v_\mathrm{s}(1 - 2.5\phi) \qquad 2.8$$

Figure 2.6 shows some of the results of Work & Kohler (1940) who investigated the effect of increasing concentration on the rate of settling by observing the change in height of the clear liquid interface with time.

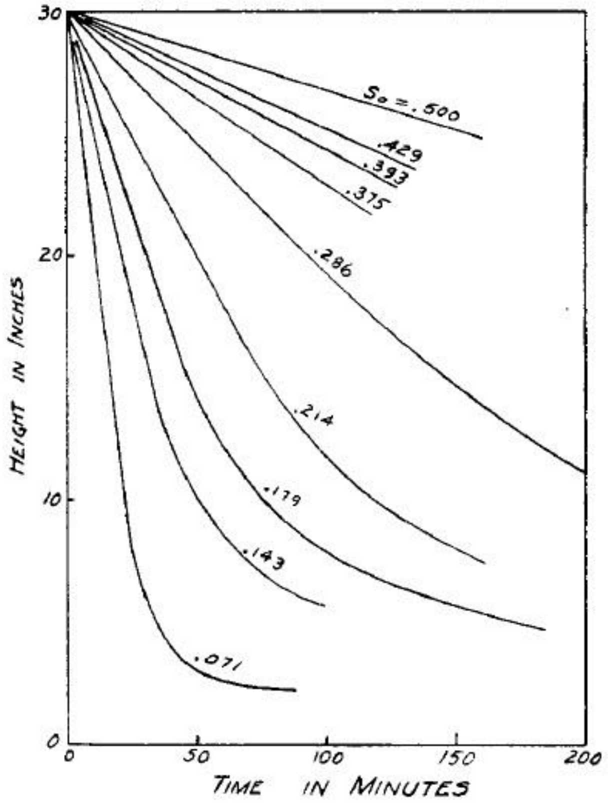

Figure 2.6 The change in height of the clear liquid interface with time for a suspension of calcium carbonate in water at various volume fractions (Work & Kohler, 1940).

Whilst it can be seen that the trend is for the rate of sedimentation to decrease as the concentration of the suspension increases, there has been research that has shown that the settling velocity can be increased to up to 1.5 times the Stokes' terminal velocity of a single particle in low concentration suspensions. This effect is due to the formation of clusters of particles which settle in well-defined streams enabling them to fall faster than they could have alone (Richardson *et al.*, 2002). Bhatty (1986) investigated the clustering effect in dilute suspensions and observed that clusters of spheres, where the particles were at a mean distance of 2.2 diameters apart, would settle faster than a single particle. This shows that this phenomenon is different to flocculation where particles increase in size by sticking together. Barfod (1971) states that the settling velocity of particles is increased as the concentration increases up to a maximum of 0.1% v/v after which the clusters begin to break up, however the work of Bhatty (1986) found that the effect on settling velocity was insignificant at concentrations below 0.83% v/v and increased up until 4.5% v/v. The large difference in the findings of these two papers could be down to the size of the particles observed; the diameters of the particles that Barfod used were 22.5 and 29 μm and Bhatty used particles that were 138 to 650 μm in diameter.

Not only is the concentration of particles important but the sizes of the particles too. A wide range of particle sizes can have a significant effect on the settling of a concentrated suspension. The smallest particles are dragged down by the larger ones leading them to fall faster than they would have otherwise. The largest particles will be settling relative to a suspension of fine particles and as such will experience a different viscosity and density. What a combination of all these factors means is that if the range of particle sizes is greater than about 6:1 there will be no clear interface at the top of the suspension (Richardson *et al.*, 2002).

2.3.4 Diameter of vessel

The walls of a vessel will exert a friction force on the particles directly adjacent to them within the fluid. This reduces the rate of fall of the particles near the wall and reduces the overall settling rate of the suspension. However when the diameter of the vessel is about 100 times greater than that of the particles in the suspension the walls have no significant overall effect on the settling (Richardson *et al.*, 2002).

The modal average diameter of the sand particles is 130 μm and the diameter of the sample vessel is 25 mm. this gives a ratio of nearly 200:1, so the walls will have no effect on the settling and will not need to be taken into account. This is another important factor meaning that the results from these experiments can be scaled up to settling on a larger size.

2.3.5 Shape of vessel

If the walls of the vessel are not vertical, such as in an inclined tube, or the cross-sectional area is not constant, the shape of the vessel can have a significant impact on the sedimentation rate. In some situations bored piles can be constructed with an enlarged base known as underreaming but in the overwhelming majority of cases the diameter of a borehole will remain constant over its entire height. This means that only cylindrical vessels need to be considered for testing.

2.4 Previous work on the settling behaviour of sand particles in support fluids

Whilst no study has been done on the formation of sediment in pile bores, the settling of sand particles in support fluids is a subject that has been investigated previously. The settling of sand is something that influences other considerations for support fluids; such as the formation of the filter cake in pile bores supported by bentonite and settling in support fluids has been studied before for this reason.

2.4.1 Majano and O’Neill

Majano & O’Neill (1993) have previously investigated the effects of support fluids on the settling of sand particles. The focus of their work was on the effect of filter cakes on the transfer of loading in bored piles, investigating PHPA, bentonite and another clay slurry called attapulgite. The sedimentation of sand in the fluids was relevant to their work because support fluids that form an optimum filter cake may have undesirable sedimentation effects.

The aim of their work was to quantify the sedimentation rate of particles and the suspending properties of different support fluids. Majano and O’Neill observed the settling of sand suspensions with a concentration of 0.33 g/ml of particles no greater in size than what could pass through a ♯40 sieve (0.422 mm). They investigated the effects of different support fluids and the concentration of polymer or clay in the fluid. Settling was carried out in a column, shown in Figure 2.7, and over a range of times the concentration of sand was measured by taking a series of samples from the taps on the column and measuring the sand content.

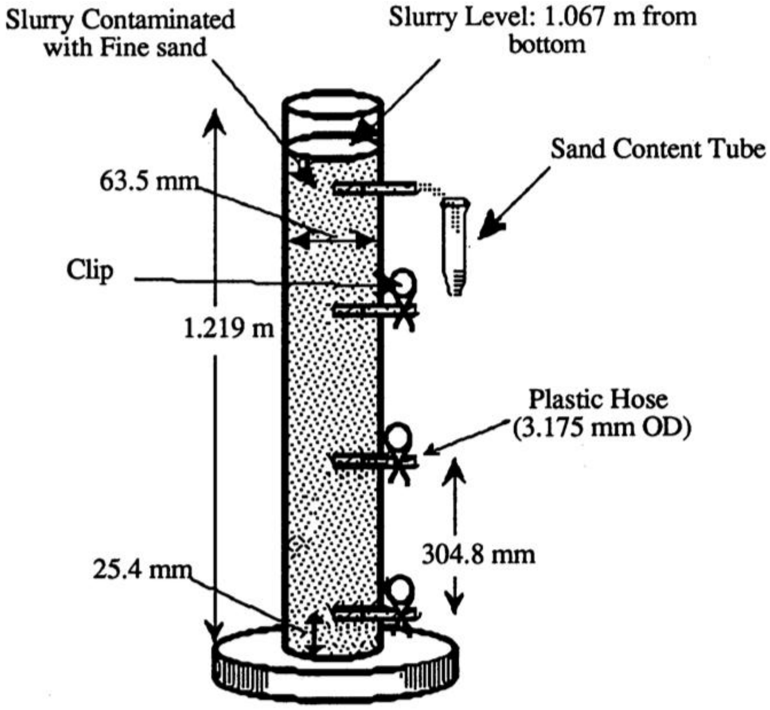

Figure 2.7 A diagram of the settling column used by Majano and O'Neill to observe settling in the support fluids (Majano & O'Neill, 1993).

The rate of settling in the suspension is related to its concentration, so instead of describing an average rate of settling for the whole suspension when it will actually vary over its height Majano and O'Neill describe the rate that a zone of a particular concentration of sand propagates down the column. The average velocity of these concentration zones is calculated by dividing the distance below the surface of the fluid at which the zone occurs by the time at which the concentration measurement was taken. These results are presented as graphs that show the velocity of concentration zones at different times, an example of which is shown in Figure 2.8. The average velocity is divided by the average particle diameter in the results so that they could be adapted for other situations with different particle sizes but the authors themselves admit that relating the results to different situations in this way, particularly if there is a greater distribution of particle sizes, may lead to unrealistic settling times and recommend following their method to obtain results specific to different systems.

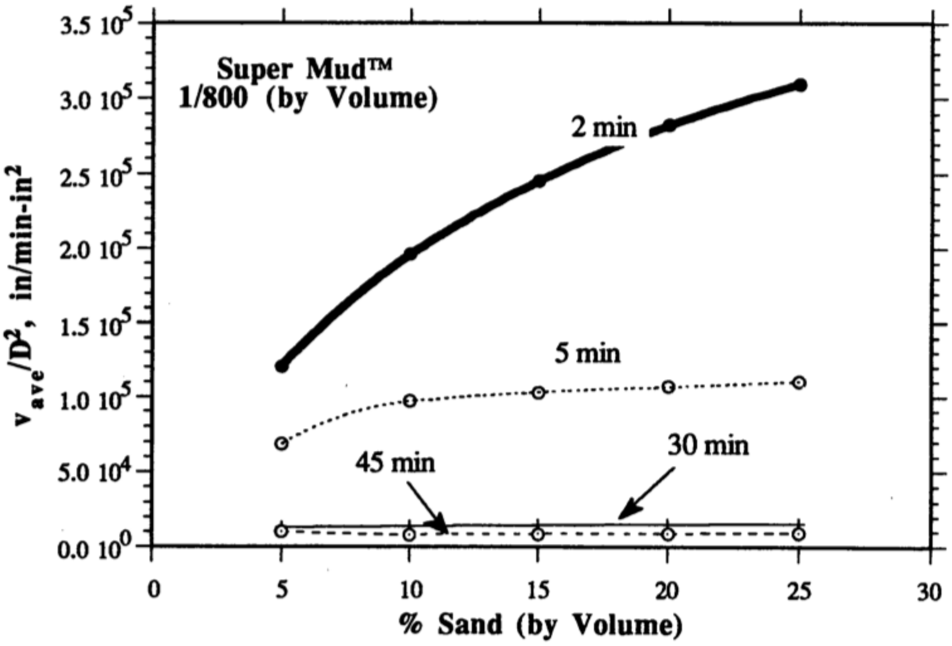

Figure 2.8 The average settling velocities of zones of specific sand concentrations in Super Mud, a brand of PHPA (Majano & O'Neill, 1993).

On the ability of support fluids to suspended particles for extended periods of time Majano and O'Neill concluded that if it was desirable to keep particles in suspension for longer in a polymer fluid that a high polymer concentration is necessary. They also noted that comparing different types of support fluid based on their viscosity alone is not indicative of their particle suspending capability and other rheological properties need to be taken into account.

There are some drawbacks to Majano and O’Neill’s method. Information about the suspension can only be obtained at the points where taps are located and at the times at which they are sampled. Taking a sample from the system disturbs it by removing sand and fluid and by affecting the flow of the liquid; the number of samples taken has to be limited to avoid influencing the system excessively. These problems mean that how the suspension changes with time cannot be observed constantly and limited data points can be obtained.

2.4.2 Kheng *et al.*

The work of Kheng *et al.* (1991) was on rheological and other properties of support fluids and sedimentation on a much larger scale than in Majano & O’Neill’s work, constructing a 20 ft. tall settling column. Kheng *et al.* investigated sedimentation in different concentrations of a clay and a polymer fluid, using sand of two different sizes described only as coarse and fine.

Settling was initially observed in 18 in. high sedimentation cylinders to see whether it was possible to make any predictions about settling in the full sized column by observing it on a small scale. Analysis of these small-scale tests was extremely limited, discussing only whether a fluid had the ability to support a suspension of particles for a period of time or not. It missed an opportunity to determine the scalability of laboratory scale tests to full sized boreholes.

The method of Kheng *et al.* for observing settling in the 20 ft. column was similar to that of Majano and O'Neill, using ten taps to sample the suspension to measure its sand content and density. They collected a huge amount of data on how the concentration, sand content and Marsh funnel times of the suspension changed over 24 hours. The variables were:

- Particle size - coarse or fine.
- Particle volume concentration - 2.5 or 5.5%.
- Fluid type - clay or polymer.
- Fluid viscosity - low, medium or high.

After collecting all this data the analysis was limited to whether the fluid had the ability to hold the particles in suspension and for how long; Kheng *et al.* do not investigate the rate of settling or sediment build up. It was found that the clay slurry could hold a suspension of 5.5% v/v of fine particles for the whole 24 hours and a suspension of 2.5% v/v of coarse particles for 7 hours but in the polymer fluid the sand settled out quickly - 90% of the sediment had formed within 30 minutes and the polymer could not suspend any of the sand particles. This highlights the effect particle size can have on settling as far less of the coarse particles could be suspended in the clay slurry and for a much shorter period. It also shows how the polymer fluid is incapable of holding particles in suspension and preventing them from settling.

The drawbacks to the methods of Kheng *et al.* are very similar to those of Majano and O'Neill except the size of the experiment leads to some further difficulties. It took at least 15 minutes for the samples to be taken from all ten taps, a period of time in which a huge amount of sedimentation could occur and the system could change considerably over that time.

2.4.3 Henry *et al.*

The main interest of Henry *et al.* (1998), like that of Majano and O'Neill (1993), was in the formation and effect of filter cakes in boreholes supported by bentonite. The aim of the settling rate experiments was to investigate the effect different conditions on the particle suspending properties of the bentonite slurry as the amount and size of sand held in suspension effects the formation of the filter cake.

The method employed by Henry *et al.* to examine the settling rate of sand is very different to the other work previously done on settling in support fluids. A column of bentonite slurry was observed using two pressure sensors inserted into the suspension at heights B and C shown in Figure 2.9. The settling velocity could be determined by observing the pressure difference between the two sensors. Whilst the trailing edge of the sand settles from A to B the change in the pressure difference between B and C will be minimal but once the trailing edge passes point B the pressure difference will decrease until it passes point C after which there will be no further change. The change in pressure difference occurs due to the difference in density of the bentonite fluid and the bentonite with sand suspended in it. To calculate the settling velocity of the suspension the distance BC is divided by the time it takes for the trailing edge of the sand suspension to travel from point B to C.

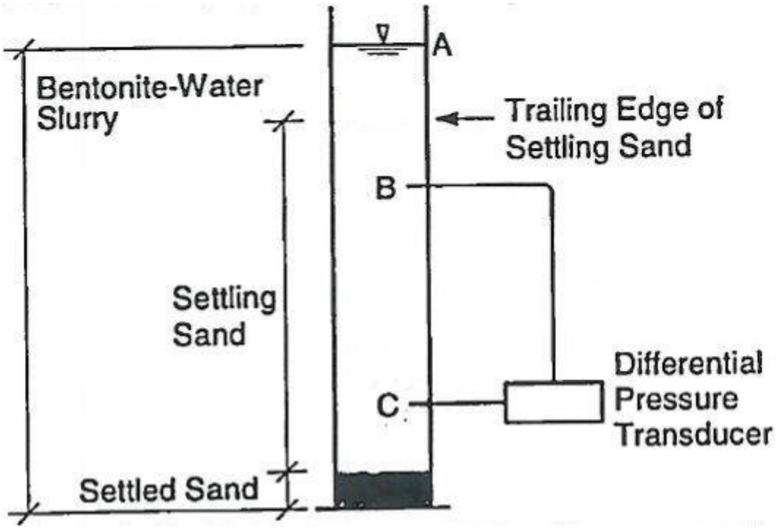

Figure 2.9 The experiment used to determine settling the settling velocity of sand (Henry *et al.*, 1998).

This method works because the particles are uniformly sized and settle at the same velocity; it can fairly accurately measure the velocity of the suspension when it is in free fall but at the bottom of the column the concentration of the suspension will increase as it approaches the surface of the sediment. This means that the settling velocity will gradually decrease at the bottom and that the time it would take for all of the sand to settle out of the suspension will be longer than the height of the slurry divided by the settling velocity determined by this experiment.

Henry *et al.* tested various sizes of particles, different concentrations of bentonite and also looked into the effect fine silty sand suspended in the bentonite slurry had on the settling velocity of larger particles. They found that larger particles settle faster and require a higher concentration of bentonite to keep them suspended. Adding silt to the suspension produced an interesting result that highlights the effects particles can have on each other during settling; the silt increases the density of the bentonite slurry and enabled it to hold larger sand particles in suspension.

The method of Henry *et al.* works effectively for investigating how well bentonite supports particles of different sizes but the drawback to their method for investigating settling velocity and sediment build up is that it only works well for the settling of very uniformly sized particles. If there is a greater distribution in the particle sizes the trailing edge of the settling sand will not be clear and without a clear edge it would not be possible to measure the velocity between points B and C. The sand in actual boreholes is unlikely to be carefully sieved to ensure the particles are of a uniform size so there will not be one value for settling velocity with many particles falling at different rates.

2.5 Observing sedimentation

The settling of suspensions is often observed in settling columns, either by eye if there is a well-defined clear liquid-suspension interface or by using small taps at different points over the height of the suspension to take samples. Innumerable studies of sedimentation have been carried out in this manner, including several studies relevant to this work such as that of Buscall *et al.* (1982) and Kheng *et al.* (1991) who respectively observed the clear liquid interface and took a series of samples over a period of time. There are critical drawbacks to each of these methods that make them unsuitable for this work. It is unlikely that there will be a well-defined clear liquid interface as the range of particle sizes in a sample of sand will be high, making observation by eye impossible. Taking samples of the suspension through taps at different heights and times throughout the sedimentation is not ideal because sampling will influence the sedimentation process.

An alternative method is to use a machine called a Turbiscan. The great strengths of the Turbiscan are that it can take measurements of the sample at a much greater frequency than is possible in the settling columns; it can take measurements over the entire height of the sample and is not restricted by only being able to take samples from taps at particular heights and it can measure the sample without influencing it at all. The Turbiscan and the sample vessel are shown in Figure 2.10.

The Turbiscan works by pulsing an infrared light source into the sample and by measuring the amount of light that is reflected (backscattering) and the amount transmitted straight through, which can be related to the concentration of the suspension. In each scan the sensor takes readings of backscattering and transmission every 40 μm over the entire 55 mm height of the sample vessel and by taking a series of scans over a period of time an understanding of how the suspension is changing can be obtained. Whilst the maximum height that can be scanned is 55mm the operating guide recommends filling the sample vessel only to a height of 42 mm. The Turbiscan can be programmed to scan the sample at set time intervals for as long as desired to build up an idea of the settling. The quickest that scans can be taken is about every 30 seconds but the interval can be set to any time greater than that.

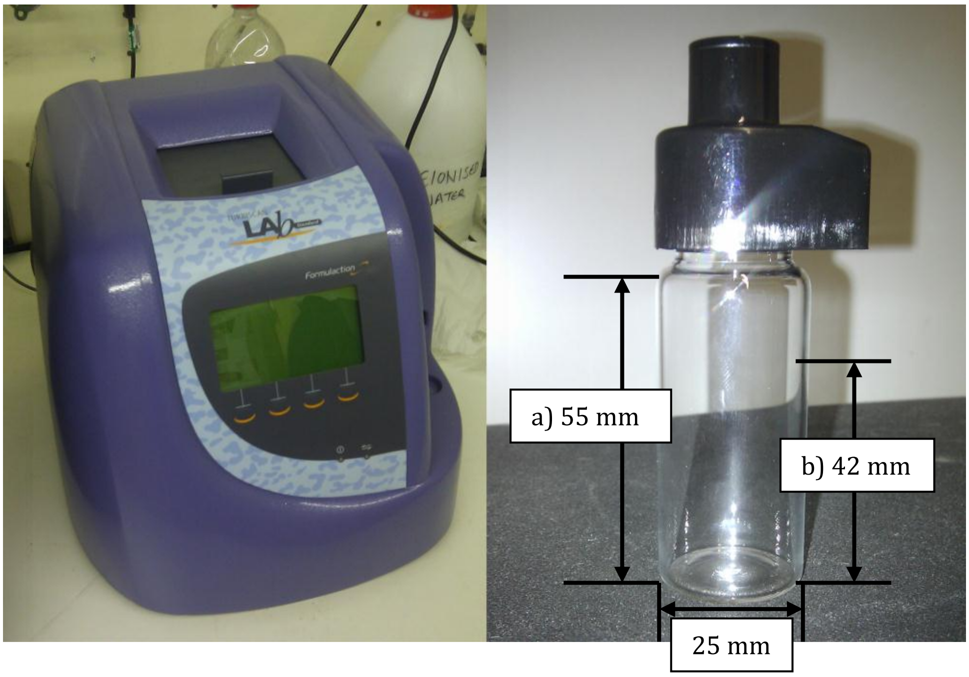

Figure 2.10 On the left is the Turbiscan and on the right is the sample vessel. a) Maximum height scannable b) Recommended scanning height.

2.5.1 Using the Turbiscan to observe Backscattering

The backscattering of light is a technique that has previously been used to examine suspensions of particles. Bemer (1978) created a simple piece of equipment to examine backscattering of suspensions of silicate particles and glass beads. Insight into the concentration and mean size of the particles could be obtained by comparing the intensity of the emitted light to that of the backscattered light. Backscattering is a technique that has been developed to produce the Turbiscan and it has been used recently to investigate suspensions of particles such as in the work of Burgos-Montes and Moreno (2008) who looked into the stability of suspensions of ceramic particles.

Knowledge of how the sample changes with time can be ascertained by observing how the backscattering of the sample changes. Figure 2.11 shows how sedimentation can be observed in the Turbiscan. The top of the sample is on the right and the bottom on the left, the x-axis has a scale describing the height of the sample and the y-axis shows the per cent of light backscattered by the sample. Each line shows the sample at a different point in time and what can be seen is the clear liquid – suspension interface propagating down the vessel and the sediment building up at the base. The profile shown in Figure 2.11 is what would be expected to be seen from the settling of uniformly sized particles.

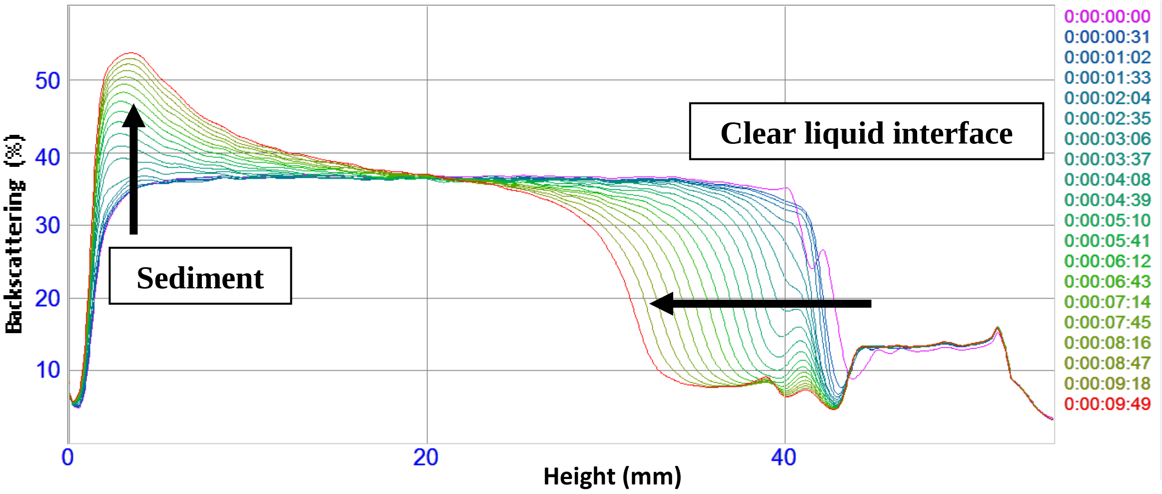

Figure 2.11 The sedimentation of uniformly sized particles in the Turbiscan. The legend displays the time of the scan that each line represents (days : hours : minutes : seconds).

With knowledge of certain characteristics of the sand particles, backscattering can be used to estimate the volume concentration of the particles in suspension (Formulaction, n.d.).

$$\mathrm{BS} \approx \left[\frac{1}{\ell^*}\right]^{\frac{1}{2}} \tag{2.9}$$

$$\ell^* = \frac{2d}{3\phi(1-g)Q_s} \tag{2.10}$$

$$\phi = \frac{2d\mathrm{BS}^2}{3(1-g)Q_s} \tag{2.11}$$

Equations 2.9 and 2.10 can be rearranged to obtain equation 2.11, which can be used to estimate the concentration of particles in suspension. **BS** is the per cent of light that is backscattered by the sample and the photon transport mean free path ($\boldsymbol{\ell^*}$) is how far the photons of light can travel into the suspension before being scattered back out. $\boldsymbol{\ell^*}$ is dependent on the concentration ($\boldsymbol{\phi}$) and the mean diameter ($\boldsymbol{d}$) of the particles and this can be seen in Figure 2.12. $\boldsymbol{\ell^*}$ also depends on two other characteristics of the suspension known as the asymmetry factor and the scattering efficiency factor. The asymmetry factor ($\boldsymbol{g}$) describes the tendency of a particle to scatter light in a particular direction, it ranges from 0 to 1, 1 corresponds to straight forward and 0 to directly back. The proportion of light that hits a particle that is scattered rather than adsorbed is known as the scattering efficiency factor ($\boldsymbol{Q_s}$).

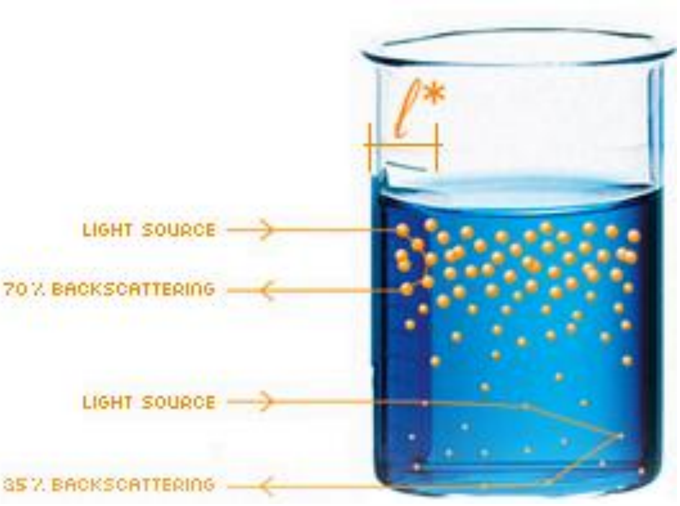

Figure 2.12 The relationship between the photon transport mean free path and backscattering (Formulaction, n.d.).

2.6 Characterising support fluids

There are many properties that affect the performance of a polymer fluid, for example the degree of hydrolysis of the polymer and the yield stress for bentonite. But the property that is generally used to compare support fluids, and the one most relevant to the polymer fluids, is the viscosity.

The instruments that are most commonly used in the industry for measuring viscosity are the Fann viscometer and the Marsh funnel. In a Fann viscometer a rotating tube is enclosed inside another, trapping a thin layer of the fluid; the torque required to rotate the tube is related to the viscosity of the fluid. Different speeds can be used to investigate the viscosity at different shear rates. The Marsh funnel simply measures the time it takes for the fluid to flow out of the funnel and this is used as a comparative value between support fluids.

The drawback of the Marsh funnel is that it only gives a measure of viscosity under one flow condition and for a shear thinning fluid such as PHPA the viscosity over a range of different flow conditions is of particular relevance. The great benefit of the Marsh funnel though is its simplicity, making it extremely convenient for use on a construction site whereas the Fann viscometer is suited only to laboratory work. As this research is not into the rheology of the fluid and to make this study as relevant as possible to the industrial use of support fluids the Marsh funnel will be used to describe the PHPA solution.

2.6.1 Marsh funnel

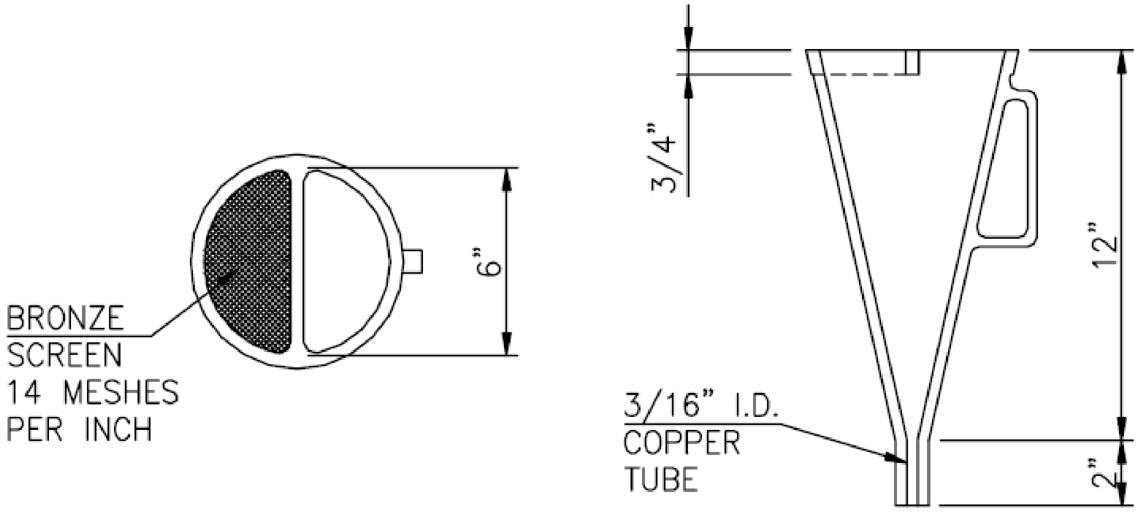

Figure 2.13 The dimensions of a Marsh funnel (Federation of Piling Specialists, 2006).

The Marsh funnel is a device that originated in the oil industry for the testing of drilling muds and is a very practical way of getting a value for the viscosity of the support fluid in a situation like on a construction site. The funnel, shown in Figure 2.13, has two openings at the top, one just a hole and the other covered by a mesh so that slurries with suspended solids can be poured through and the particles removed so that they don't interfere with the measurement. The funnel has a 1.5 litre capacity and is filled to the maximum; it has very specific dimensions such that the time that it takes for 1 US quart (946 ml) to flow out of the nozzle can be used to compare different fluids. It is possible to calculate a value for the effective viscosity using equation 2.12, where $\boldsymbol{t}$ is the time taken for 1 quart to flow from the funnel (Pitt, 2000). Whilst an effective viscosity can be calculated, normally in the industry only the Marsh funnel time is given and this value can be used to compare support fluids of the same type.

$$\mu = \rho_{\mathrm{f}}(t - 25) \tag{2.12}$$

2.7 Sand content tube

In the construction industry a tool called the sand content tube is used to measure how much sand is in suspension (Federation of Piling Specialists, 2006). The sand content tube is shown in Figure 2.14; the tube has a marking on it to indicate to where to fill it with slurry, and another mark above that to top up the slurry with water. The slurry and water are mixed so that the mixture can easily be poured through a sieve as the standard for the test is that the volume measured is only of particles larger than 75 μm. After sieving the sand is washed back into the tube, the bottom of which has a scale to determine the volume of sand the slurry contains. The result is the bulk volume of sand as a per cent of the total volume of the slurry.

It is extremely important to differentiate between the bulk sand volume given by the sand content tube and the actual volume of sand in the mixture. Because of the way particles pack space will be left between them and the bulk sand volume will contain a fraction of liquid. This means that the result is not the same as the volumetric concentration of sand ($\boldsymbol{\phi}$) and to differentiate, the result from the sand content tube will be referred to as the bulk sand volume per cent.

$$\text{Volumetric sand concentration } (\phi) = \frac{\text{Volume of sand}}{\text{Total volume of mixture}} \times 100$$

$$\text{Bulk sand volume per cent} = \frac{\text{Volume of sand} + \text{Volume of liquid between the particles}}{\text{Total volume of mixture}} \times 100$$

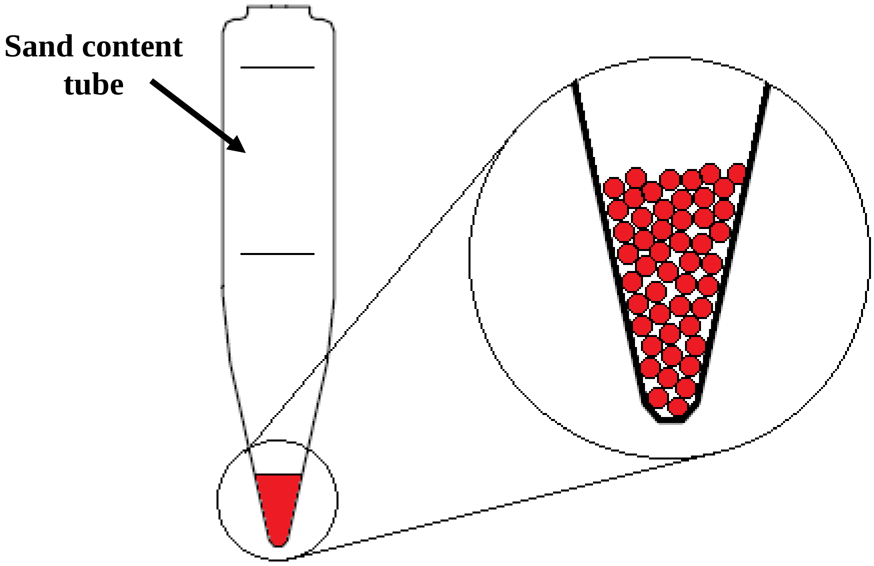

Figure 2.14 The sand content tube and liquid contained between the sand particles in the sediment.

2.8 Summary of literature review

It can be seen from this literature review that there are many important factors that affect the settling rate of particles in suspension: the size, shape, density and concentration of particles and the density, viscosity and rheology of the fluid.

Previous work has given an insight into the settling of sand particles in support fluids but there are many drawbacks to the experimental methods used and none have tackled the issue of the formation of sediment. Investigation of the methods that can be used to observe settling has enabled the benefits and drawbacks of the different methods to be weighed up. The standard industry tests for describing the polymer fluid and the sand suspensions have also been described to ensure the relevance of this work to practical applications in the industry.

This has all made it possible to set out meaningful objectives for this project and then to develop an effective method for studying sedimentation in polymer solutions.

3 Objectives

The previous work on sedimentation in support fluids that has been discussed has focused more on what can be supported in the fluid than what cannot. None of the established literature looks into the rate at which sediment builds up or the amount of sediment produced. The methods that have been used to study sedimentation in support fluids previously have some quite significant flaws and by developing an alternative method greater insight into sedimentation in polymer fluids can be obtained. From a review of the relevant literature the Turbiscan has been selected as the instrument to observe the settling behaviour of the sand particles and an objective of this project is to develop a method using this machine to describe the formation of sediment in sand suspensions.

The primary objective of this project is to investigate and then characterise the formation of sediment in the polymer support fluid. From the literature review it could be seen that there are many factors that affect the settling rate but the ones that have been selected to be investigated in this work are the concentration of sand particles and the viscosity of the fluid. In the industry engineers vary the viscosity of the fluid by changing the concentration of the polymer in solution so the variables in these experiments will be the sand and polymer concentrations.

One of the goals of this experimental work is to be able to scale up the results to describe the settling in a full size bore hole and be able to predict the thickness of a layer of sediment at the base of a pile bore after any period of time within the range that shafts are typically left open for. Additional objectives are to look into the factors that affect the density and thus the volume of the sediment produced.

To summarise the objectives of this project:

- Develop a method to determine how sediment builds up using the Turbiscan.
- Characterise the sedimentation behaviour of suspensions of sand of various concentrations in solutions of different polymer concentration.
- Determine how these results can be scaled up to describe the formation of sediment in full sized pile bores.
- Additionally, analyse the sediment formed and investigate the factors that affect the density.

4 Materials & method

This section describes the materials and methods that were utilised to achieve the objectives that have been set out. It begins by describing the polymer and sand that were chosen for this project and then describes in detail the methods of the main and additional experiments.

4.1 Polymer type: Partially hydrolysed polyacrylamide

Partially hydrolysed polyacrylamide (PHPA) is formed from the hydrolysis of polyacrylamide. This process replaces some of the amides with a carboxylic acid group as shown in Figure 4.1. PHPA is a polymer that has been utilised in several other industries including oil drilling and soil treatment in agriculture. In oil drilling PHPA is used as a shale swelling inhibitor as it helps to ensure the stability of a borehole by holding the shale together and in agriculture it is used to help prevent the erosion of soil.

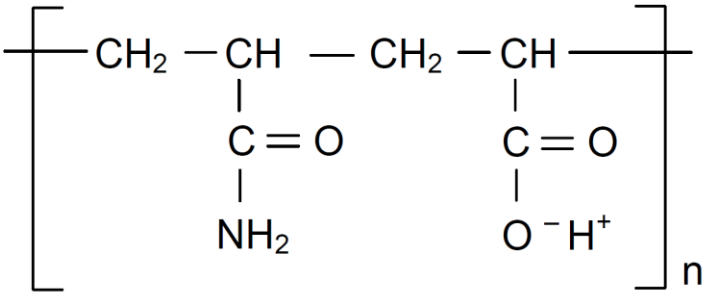

Figure 4.1 The chemical structure of PHPA. The group on the left is acrylamide and on the right is acrylic acid.

When used for supporting boreholes the carboxyl groups on the acrylic acid sections of the polymer interact with the water molecules in the fluid preventing their migration into the soil. The greater the percentage of the polyacrylamide that is hydrolysed, the more effective it will be at inhibiting the flow of water into the soil but this needs to be balanced with the increasing cost of further hydrolysis. In the construction industry the typical percentage of hydrolysis is 30-45% but for other applications it may not need to be so high, for example for soil treatment in the agricultural industry it is normally only 10-20% (Lam, 2008).

One of the factors key to its effectiveness as a support fluid is PHPA’s viscosity. A very high molecular weight is essential to ensure a high viscosity; it typically ranges from 14 to

17 million g/mol (Brown *et al.*, 2010). A high molecular weight corresponds to very long polymer chains; longer chains get entangled with each other and have many points of contact as can be seen in Figure 4.2. This means that they resist flow far more than shorter chains and produce a higher viscosity.

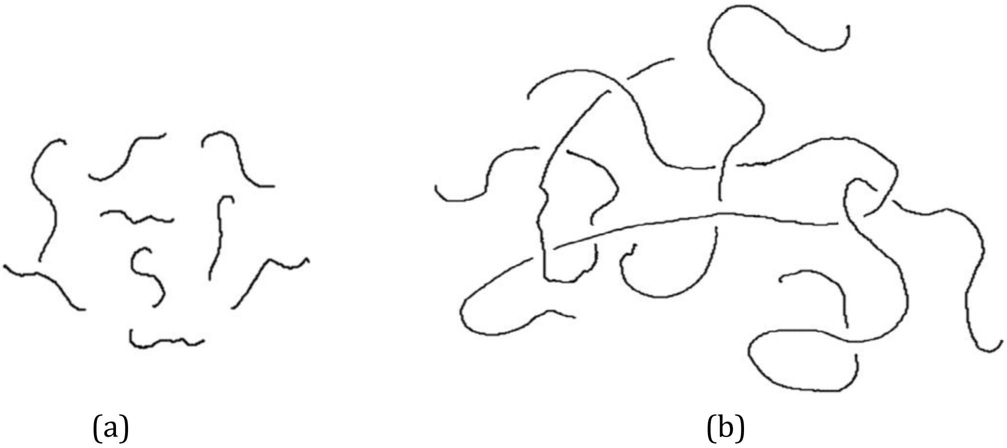
(a) (b)

Figure 4.2 The entanglement of polymer chains (a) Low molecular weight (b) High molecular weight.

The brand of PHPA used was Shore Pac produced by CETCO, it comes as a granular powder and a sample is pictured in Figure 4.3. Shore Pac is a high molecular weight PHPA with a degree of hydrolysis of about 40%.

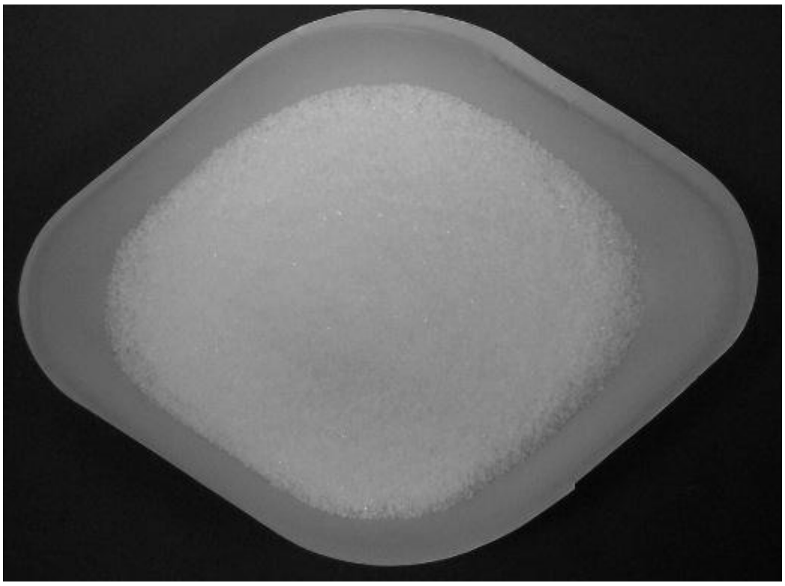

Figure 4.3 Shore Pac - PHPA polymer granules.

4.2 Sand properties

The sand that will be used for these experiments is called Thanet Sand. Thanet Sand is commonly found in the London area at around 20-50 m deep and it has been chosen for this investigation as it is made of fine particles.

To determine the particle size distribution of the sand used in these experiments a particle size analyser called a Malvern Mastersizer 2000 was used. The Mastersizer works by analysing how laser light is diffracted by the particles as they are carried through the machine suspended in a stream of air. The Mastersizer requires certain information about the particles such as their light absorbance but the software contains values of these parameters for many materials and the values for silica were selected.

Before starting the sample tray of the Mastersizer was brushed carefully to ensure there were no particles remaining in it from previous experiments that could have contaminated the results. A sample of 100 g was then placed in the tray, taking care to brush all of the fine particles out of the dish containing the sand sample; this was to ensure that size distribution was not skewed by the smallest particles being left behind. Particles of different sizes have a tendency to separate out into different layers so three different samples of sand were analysed to ensure that the results were repeatable and indicative of the size distribution of all of the sand used in the experiment.

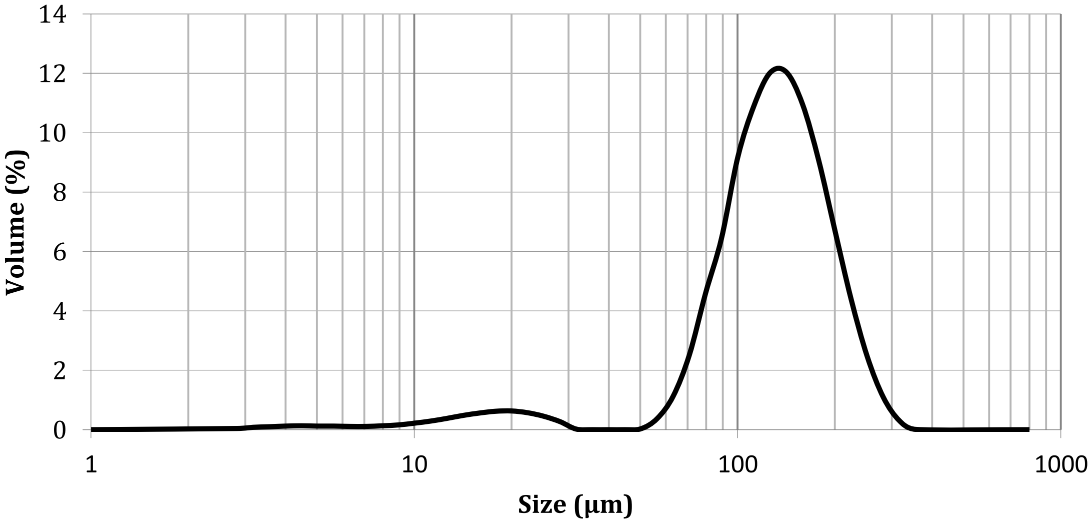

Figure 4.4 The distribution of particle sizes used in testing.

The results from the Mastersizer are shown in Figure 4.4, it can be seen that the particle size distribution is bimodal with 94% of the particles by volume found within the range of 44 and 310 μm and the remainder of the sand was found as a fine powder in the range of 2.5 to 28 μm.

4.3 Method

For the main experiments the settling of a range of sand concentrations was observed in various concentrations of polymer using the Turbiscan. There were several aspects involved with performing these settling experiments that will be discussed in this section: mixing the polymer solution, measuring the viscosity of the solution, suspending the sand and then observing it in the Turbiscan.

The concentrations of the suspensions that were observed using the Turbiscan were 0.25, 1, 3 and 5% v/v, which is the per cent that the volume of the sand particles makes up of the total volume of the suspension. Each concentration of sand was observed in polymer solutions of 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 g/L; a total of 24 tests for the main experiment. With the time that the preparation of the polymer solution took and the amount of time that was required to observe the settling, three of these tests could typically be completed in a week.

4.3.1 Mixing the polymer solution

Great care had to be taken when mixing the polymer to ensure homogeneous mixing throughout the solution. The polymer has a tendency to form concentrated globules, known as “fish eyes”, if added too rapidly. Once formed fish eyes can be very difficult to disperse, leading to an inconsistent solution that could affect settling and would definitely affect flow through the Marsh funnel. The fish eyes would not flow easily through the nozzle of the funnel leading to the time being too great and an incorrect value for the viscosity.

Two litres of polymer solution were mixed for each concentration. The correct mass of polymer granules were weighed out carefully to two decimal places and two litres of distilled water were measured out accurately in a three-litre beaker using an electronic balance.

To mix the polymer an axial flow impeller was placed approximately in the centre of the water in the beaker, at about a 45° angle. Setting the impeller to 300 rpm a vortex was formed in the water to which the polymer was added incredibly slowly, as close to a single grain at a time as was possible, to avoid the formation of fish eyes. Once all of the polymer had been added the impeller was moved to a vertical position and the rpm was reduced to 150. The solution was then left for 45-60 minutes to mix.

After mixing, the solution was covered with three layers of cling film to prevent evaporation and left for at least 12 hours to enable the polymer to dissolve completely and for the long chains to disentangle themselves. Once mixed the polymer had to be used within three days.

Even when the greatest care was taken mixing the polymer solution sometimes the formation of fish eyes was unavoidable, particularly at the higher polymer concentrations. To avoid fish eyes affecting the results of the Marsh funnel test or influencing sedimentation the solution was poured through a sieve with 1 mm holes prior to use.

4.3.2 Marsh funnel viscosity

Three Marsh funnel times were taken for each solution with the first being done with a dry funnel and bucket. Whilst blocking the end of the nozzle with a finger the funnel was filled with the polymer solution to the line at the top. Holding the funnel over the Marsh bucket the stopwatch was started and the finger was removed simultaneously. The time was stopped just as the top of the liquid crossed the line near the top of the bucket denoting 1 quart of liquid. The liquid in the bucket was then poured back into the top of the funnel and the test was repeated for the rest of the measurements.

The time would decrease over the three measurements with the largest being the initial dry funnel time. The actual Marsh funnel time is an average of all three times. The polymer is described in the results by its concentration but how this relates to the Marsh funnel times of the polymer is given in Table 4-1 and Figure 4.5.

Table 4-1 The Marsh funnel times of the polymer solutions.

Polymer concentration (g/L)	Marsh funnel time (Seconds)
0.2	65
0.4	86
0.6	106
0.8	123
1	142
1.2	161

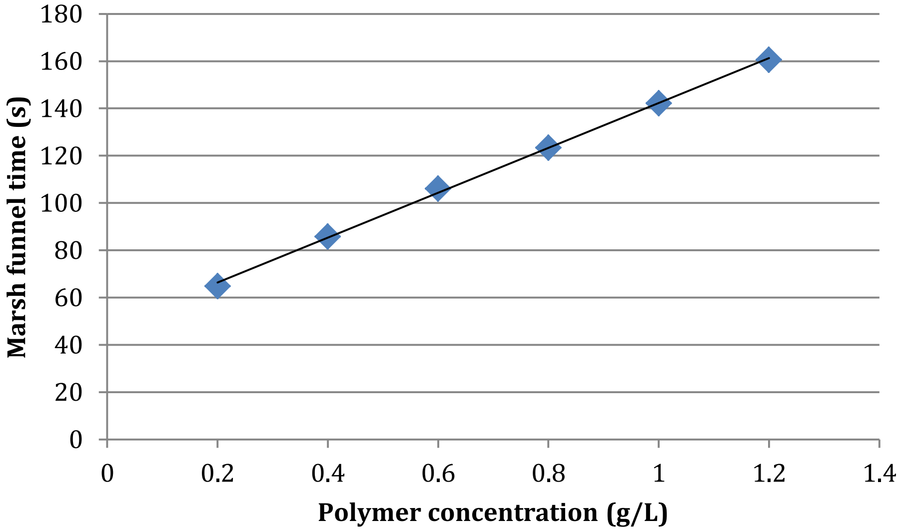

Figure 4.5 Marsh funnel times for PHPA polymer solutions.

4.3.3 Suspending the sand mixture

The definition of the volumetric sand concentration ($\boldsymbol{\phi}$) is shown in equation 4.1 and from this equation 4.2 can be obtained, which was used to calculate the mass of sand required to produce a suspension of the desired concentration. $\boldsymbol{V_{\mathrm{s}}}$ and $\boldsymbol{V_{\mathrm{l}}}$ are the volumes of sand and liquid in the mixture, $\boldsymbol{m}$ is the mass of sand required and $\boldsymbol{\rho}$ is the density of the sand.

$$\phi = \frac{V_{\mathrm{s}}}{V_{\mathrm{s}} + V_{\mathrm{l}}} \times 100 \qquad 4.1$$

$$m = \rho \frac{V_{\mathrm{l}}}{\frac{100}{\phi} - 1} \qquad 4.2$$

Several methods of adding sand to the polymer solution were tried as the sand had a tendency to clump together when added. It could be very difficult to form an even suspension and initial attempts of using a magnetic stirrer were ineffective because of the tendency of the largest particles to settle out very quickly and to remain stuck to the side of the beaker rather than being transferred to the Turbiscan vessel. What proved to be the most successful method was mixing the sample in the Turbiscan vessel by shaking it.

4.3.4 Turbiscan

The settling of the suspension was observed in the Turbiscan. At high sand concentrations and low polymer concentrations a significant amount of sediment could form very rapidly so it was imperative, once the sand had been properly suspended, that the vessel was placed in the Turbiscan and the scan started as quickly as possible. Due to the initially high rate of sedimentation observed scans were made every minute for the first twenty minutes. The rate of sedimentation decreased considerably after this point and scans could be reduced to every half hour or hour. Samples were observed for about 24 hours as the vast majority of sand had settled out by this point and sedimentation after this time is not relevant as a borehole would not be left open for this long.

4.4 Further experiments

Several further experiments were completed to enable the results of the Turbiscan to be analysed and to gain further insight into the sediment produced. These experiments are described below.

4.4.1 Calibration to relate backscattering to sand concentration

To obtain an understanding of how the backscattering relates to the concentration of a sample a series of samples of known concentration were set up to calibrate the results. Thirty samples were used, five of each concentration of sand of 0.25, 1, 2, 3, 4, and 5% v/v. A polymer solution of 1.2 g/L was used so that sedimentation was as slow as possible and the samples were shaken vigorously before scanning to ensure a uniform suspension and so that there was no opportunity for any sand to sediment before the scan. The results of the backscattering calibration curve can be seen in Figure 5.5 on page 51.

For reasons discussed in the results section it was not possible to determine the concentration of a sample below concentrations of 0.25% v/v from the backscattering and for this reason a transmission calibration plot was produced. The same method as for the backscattering calibration was used, only sand concentrations of 0.06, 0.12, 0.18 and 0.25% v/v used. The transmission calibration curve can be seen in Figure 5.6.

4.4.2 Measuring cylinder tests

To enable the height of sediment produced in the Turbiscan experiments to be calculated, suspensions of different concentrations of sand were left to settle in measuring cylinders and the height of the sediment that formed was measured. A polymer solution of 0.2 g/L and sand concentrations of 0.25, 1, 2, 3, 4, 5, 10 and 20% v/v were used and 100 mL of each suspension was used so that sediment heights of each test could be compared. The suspensions were left for two hours to settle after which the height of the sediment was measured and compared to the total height of the fluid. The results of the measuring cylinder tests can be found on page 53 in Figure 5.7. To investigate the effect of the fluid on the density of the sediment formed these tests were also carried out in water and a polymer solution of 0.4 g/L, the results of which are shown in Figure 5.23 on page 65.

4.4.3 Effect of initial slurry height on the rate of sedimentation

To examine the effect that the height of the fluid had on sedimentation two samples of an identical 5% v/v suspension in a 0.4 g/L polymer solution were investigated; one 10 mL and one 20 mL sample. The samples were scanned in the same manner as the main set of experiments and the results can be found in Figure 5.22 and Figure 5.21 on page 64.

5 Results & discussion

To begin the analysis and discussion of the results of these experiments some of the general observations of the Turbiscan experiments are described. The method for analysing the Turbiscan results is then set out. The following sections discuss the factors that affect the sedimentation rate, whether the results of the sedimentation are scalable to full sized pile bores, the compressibility of the sediment and the density of the bulk sand that is formed in the industry standard sand content test.

5.1 Typical back-scattering results

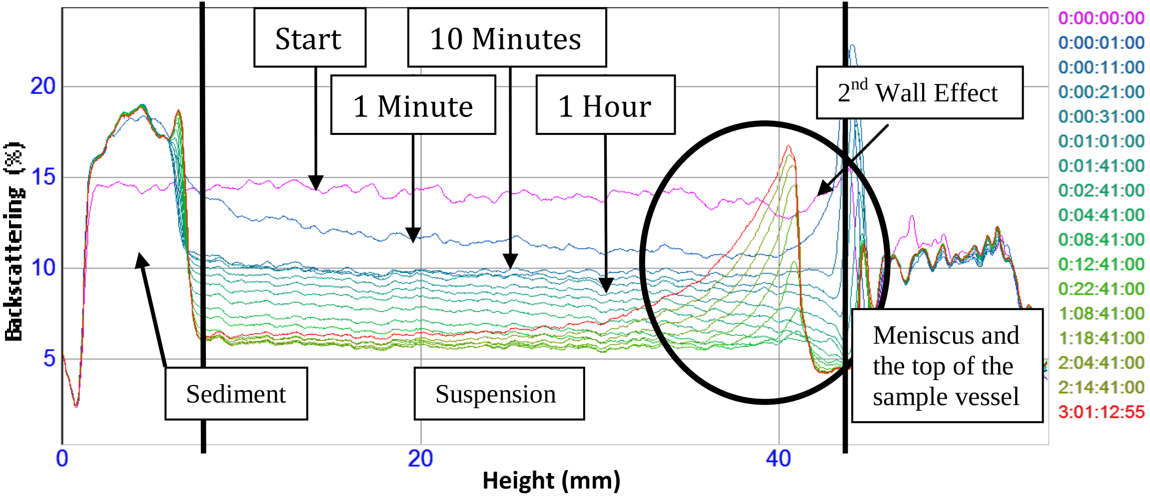

Figure 5.1 The backscattering of a 5% v/v sand suspension settling in a 0.4 g/L polymer solution. The legend displays the time of the scan that each line represents (days : hours : minutes : seconds).

Figure 5.1 shows a backscattering result characteristic of these experiments; it is the sedimentation of a 5% v/v suspension in a 0.4 g/L polymer solution. The backscattering would fall faster in lower polymer concentrations and slower in higher concentrations, but the other experiments all showed a similar shaped graph. One of the most obvious results seen in the backscattering graphs is that they look nothing like Figure 2.11; there is no clear liquid interface seen propagating down the vessel. The wide distribution of particle sizes found in the sand means that there is no clear liquid interface and the settling takes on a different behaviour. It was observed that the backscattering fell at an almost constant rate over the entire height of the suspension.

This behaviour of the backscattering is very similar to what would be expected in a system where a significant amount of coalescence or flocculation occurs. Bru *et al.* (2004) describes how the even decrease of backscattering over the entire height of a sample is characteristic of coalescence and flocculation; the number of particles in a suspension decreases as they come together to form larger ones, giving the impression of a decreasing concentration. However this is not what is occurring in this situation, as sediment builds up simultaneously, meaning that it is not just flocculating. It could be the case that flocculation and sedimentation are occurring together but the fast rate at which the backscattering drops and the sediment builds up initially suggests that it is the pace at which the sedimentation occurs that makes it appear this way.

Figure 5.2 Sedimentation stages in a 5% suspension in a 0.2 g/L polymer. From left to right; top row: start, 30 seconds, 1 minute; bottom row: 10 minutes, 12 hours, 24 hours.

Figure 5.2 is a series of photographs shows the different stages of sedimentation in a Turbiscan sample vessel. It shows how quickly the majority of the sand settles out and how long it takes for the remainder of the sand to settle out of the polymer solution. This series of photos is of a 5% v/v sand suspension in a 0.2 g/L polymer solution and is the fastest settling but all of the other suspensions showed similar behaviour with a rapid initial period followed by a period of much slower settling.

5.1.1 The second wall effect

For some of the samples the backscattering at the top of sample began by decreasing as the concentration of particles fell, as was expected, but after a certain point the backscattering began to increase again as can be seen in Figure 5.1. It was expected that backscattering would continue to decrease with particle concentration so this result seemed counterintuitive. Upon investigation of this phenomenon it was found that it has also been experienced in previous studies using a Turbiscan to investigate suspensions and is known as the second wall effect (Akther *et al.*, 2007).

The glass of the second wall of the Turbiscan sample vessel will itself backscatter a certain fraction of the light and as the concentration of particles drops, more of the glass becomes visible through the suspension. Below a critical point the increasingly visible portion of glass begins to increase the backscattering as the suspension concentration continues to drop.

Due to the second wall effect, data after the backscattering of the sample dropped below 6% was not considered. Most of the results would not be impacted by this as a value of 6% corresponds to a sand concentration in suspension of less than 0.25% v/v; beyond this point settling only occurs extremely slowly. In most cases it took a considerable period of time for a suspension to reach this point, for polymer concentrations of 0.6 g/L and greater it took more than 24 hours before the second wall effect began to appear. For polymer concentrations of 0.2 and 0.4 g/L the second wall effect became prevalent after 5 and 15 hours respectively and in these cases the backscattering results were truncated after this point. The results that this would affect are for the settling of the 0.25% v/v suspensions; for these tests a slightly different method was developed and is discussed in the next section.

5.2 Calibration of Turbiscan results to determine sand concentration and experiments to determine the height of sediment

The sediment can be seen in the graphs of the Turbiscan results and this can be used to estimate its final height but there are two reasons why the Turbiscan graph is not suitable for describing how the sediment builds up over time. During sedimentation there is no clear boundary for the surface of the sediment visible in the Turbiscan graph because the backscattering steadily increases as it approaches the sediment, shown in Figure 5.3. This occurs because above the sediment there is a concentration gradient; the concentration of sand steadily decreases from the concentration of the sediment to that of the suspension and this makes it difficult to define where the top of the sediment is. It can also be seen in Figure 5.3 that the backscattering of the sediment increases with time and this is because the sediment is compressed by its own weight, increasing its density. So not only is it difficult to define where the top of the sediment is but also with the backscattering changing due to sediment compression it makes it even harder to use the Turbiscan graph to determine the height of the sediment. This means it is not possible to describe with any meaningful accuracy what height the surface of the sediment layer is from the Turbiscan graphs.

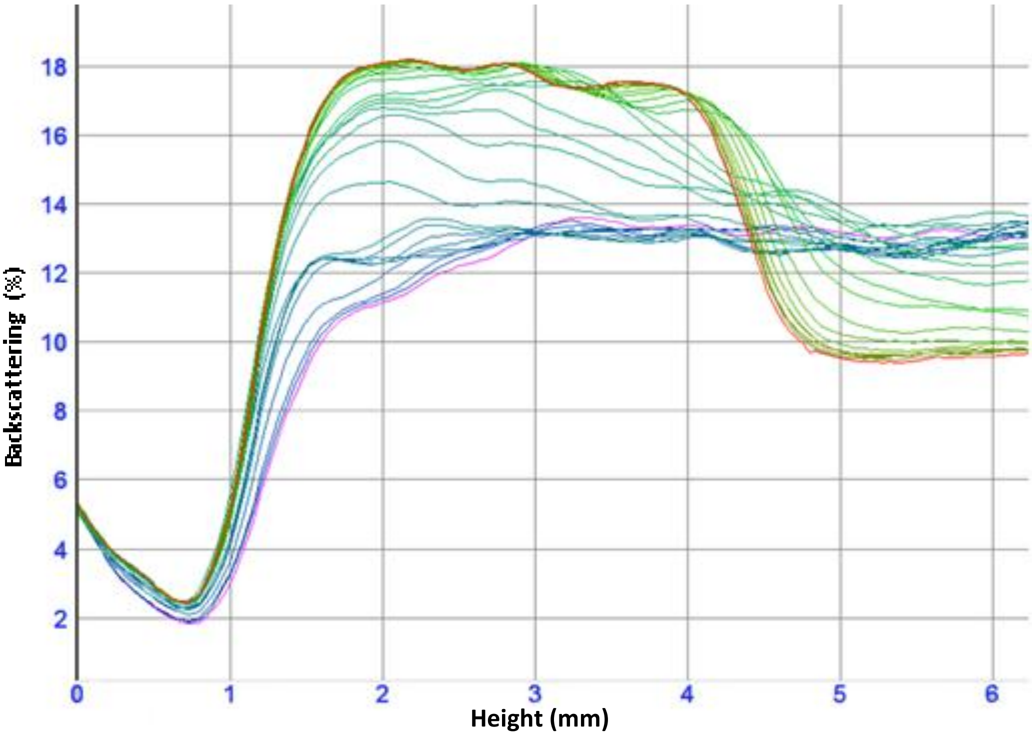

Figure 5.3 Sediment building up in the Turbiscan. 3% v/v sand in a 1.2 g/L polymer solution.

Another method had to be developed to determine how the sediment height changed with time. This method consisted of four stages to convert the results from the Turbiscan into a height for the sediment.

1. Obtain an average value of the backscattering for the suspension at each time.
2. Convert the average backscattering of the suspension at a particular time into the concentration of the suspension using a calibration curve.
3. From the amount of sand in suspension at a particular time calculate the amount of sand that is now in the sediment.
4. Determine the height of sediment that is produced by that volume of sand in the sediment.

How each of these stages was completed is described in detail below.

5.2.1 The average backscattering of the suspension

The first stage in analysing the Turbiscan results is to obtain a single value for the backscattering of the suspension. Between the black bars in Figure 5.1 the section of the graph that relates to the suspension can be seen, and before the second wall effect becomes prevalent, that the backscattering at a particular time is approximately constant over the height of the suspension. The way in which the backscattering of a sample was approximately even over the height of the suspension is used so that a sample can be described at a particular time by the average of the backscattering between the top of the sediment and the surface of the suspension. The software for the Turbiscan has a function that enables the average of one of the lines to be taken between two points enabling the average to be found to a high degree of accuracy. By taking the average of the backscattering over the height of the suspension it takes into account any concentration gradient. When the concentration of sand at the bottom is higher than at the top an average will give an accurate indication of the overall amount of sand still in suspension.

5.2.2 Calibration to convert backscattering to concentration

The Turbiscan gives results showing how much light is scattered back by the particles and how that varies with time, which gives a good indication of how the suspension is changing but it is important to gain understanding of how this actually relates to the concentration of the suspension. Equation 2.11 given in section 2.5.1 can be used to get an idea of how the backscattering should relate to the concentration but it cannot be used to obtain accurate results because equation 2.9 is only an approximate relation and the values of the asymmetry and scattering efficiency factors are difficult to determine without further analysis of the particles. Using estimates for g and Q_s (0.998 and 2 respectively), equation 2.11 was used to plot Figure 5.4 to use as a guide when relating the backscattering to the concentration of particles in the suspension.

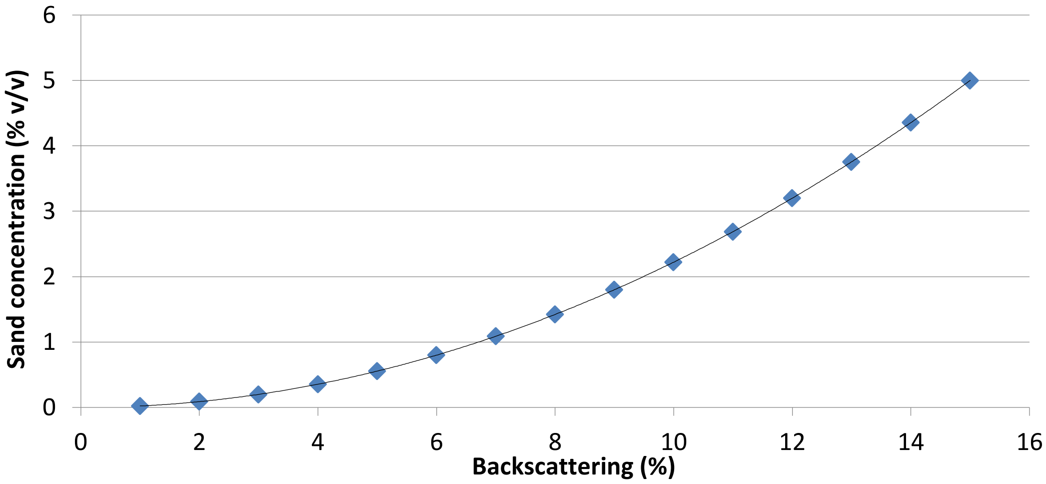

Figure 5.4 Theoretical results of how backscattering varies with sand concentration.

A set of tests was completed to obtain a set of results that relate more accurately to the sand suspensions dealt with in this project. A range of samples of known sand concentration was produced and without giving them any time to settle the samples were scanned to determine the backscattering at that concentration. The average backscattering of the sample was found over the height of the suspension and the value obtained corresponds to that concentration. Five samples were measured for each concentration and the results can be seen in Figure 5.5.

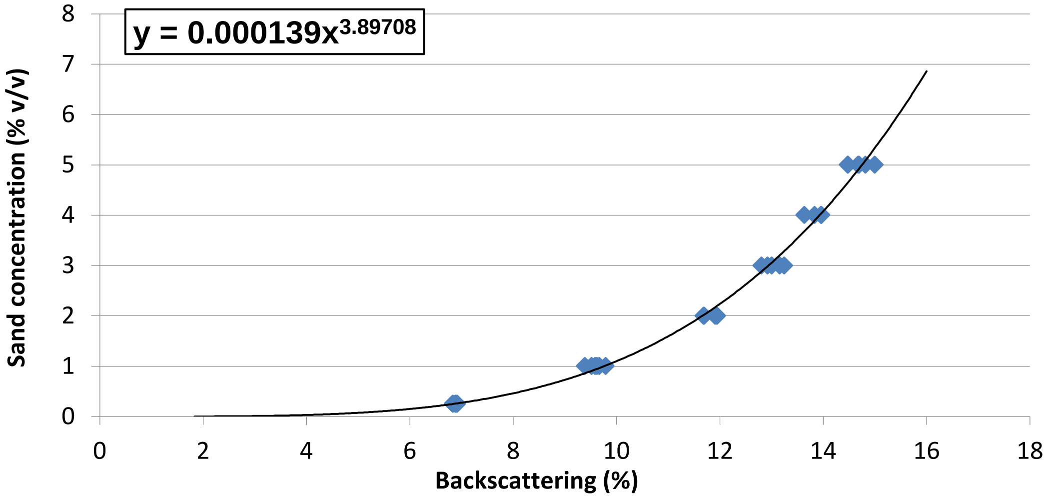

Figure 5.5 Experimental results of how backscattering varies with sand concentration. The equation of the trend line is shown on the graph.

It can be seen that the experimental results correspond well to the theoretical prediction and produces a similarly shaped curve. The concentration of the suspension can now be obtained from the Turbiscan results and the second stage can now be completed. How the concentration of the suspension varies with time can now be described although these results need to be used carefully as different sized particles scatter the light differently. This may mean that after the majority of the sand has settled out, and only the tiniest particles remain in suspension, that the backscattering may not correlate as well with the data collected for concentration.

What occurs when the sand concentration drops below 0.25% is that the backscattering begins to increase again due to the second wall effect. This means that the backscattering calibration curve in Figure 5.5 cannot be used for the 0.25% v/v suspensions because the backscattering begins by decreasing but then goes up again. For sand concentrations of 0.25% v/v and lower a calibration curve based upon transmission was produced, shown in Figure 5.6. The reason a transmission calibration curve was not used for all of the sand concentrations is because for the higher sand concentrations almost the entire time that the suspension is settling the transmission is zero, it is not until the concentration is close to 0.25% that there is any transmission signal.

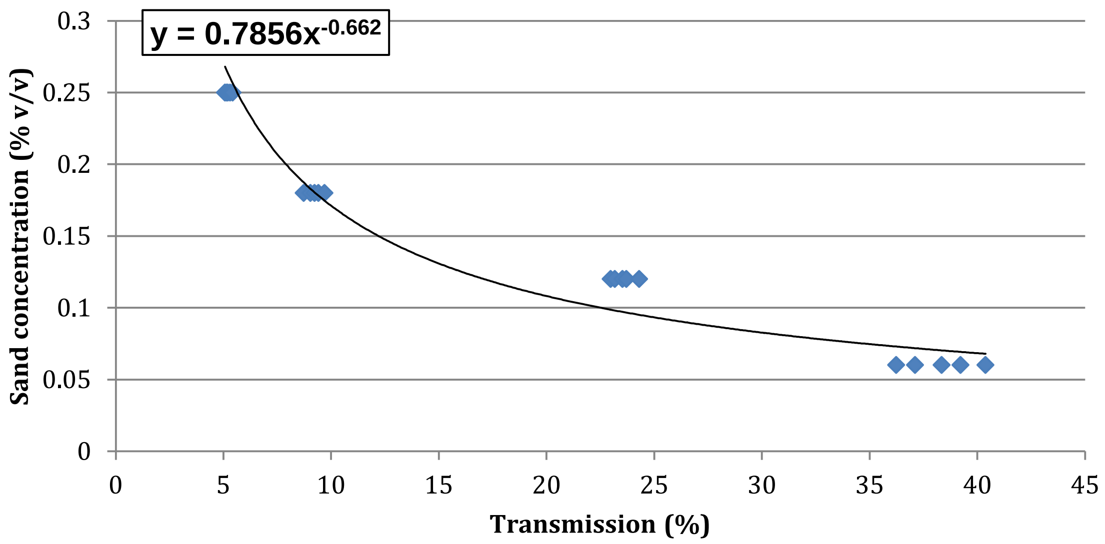

Figure 5.6 Transmission calibration curve.

It can be seen that the fit of the transmission calibration curve is not as good as the backscattering curve and this is due to a combination of effects from the transmission curves and the concentration of the sand. There is a considerable amount of fluctuation in the transmission of light over the height of a sample, which increases at lower concentrations. It is also probable that even with every effort to suspend the particles evenly that the dispersion was not perfect, which would also influence the transmission signal. The difficulty in mixing the samples arises due to the extremely low concentrations of sand and the high viscosity of the polymer, which resisted homogeneous mixing.

5.2.3 Calculating the amount of sand in the sediment

By utilising the results from the previous two stages it is possible to describe the concentration of sand that is in suspension at any point in time. The concentration of sand in suspension can be related to the volume of sand in the sediment through simple calculation using equation 5.1. $\boldsymbol{\phi_1}$ and $\boldsymbol{\phi}$ are the initial concentration of sand and the concentration of sand at time $\boldsymbol{t}$, in % v/v. $\boldsymbol{\Theta}$ is the volume of sand in the sediment as a per cent of total fluid volume at time $\boldsymbol{t}$.

$$\phi_1 - \phi = \Theta \qquad 5.1$$

5.2.4 Measuring cylinder tests to determine the height of sediment formed

The volume of sediment is greater than the volume of the sand alone; because of the way particles pack, space is left between them. To investigate the height of sediment produced by particular concentrations of sand another set of experiments was completed. The height of sediment produced when the sand settles out of suspension was investigated by observing the sedimentation in measuring cylinders of suspensions of known concentration in a polymer solution of 0.2 g/L. Figure 5.7 shows h/h_s, the height of the sediment over the total height of the fluid, over a range of sand concentrations. For comparison the sediment height produced in a 0.2 g/L polymer solution, but observed in the Turbiscan tests, has also been included in Figure 5.7. Although as described previously it is difficult to define the height of the sediment formed from the Turbiscan results and so these heights are less precise than the results of the measuring cylinder tests.

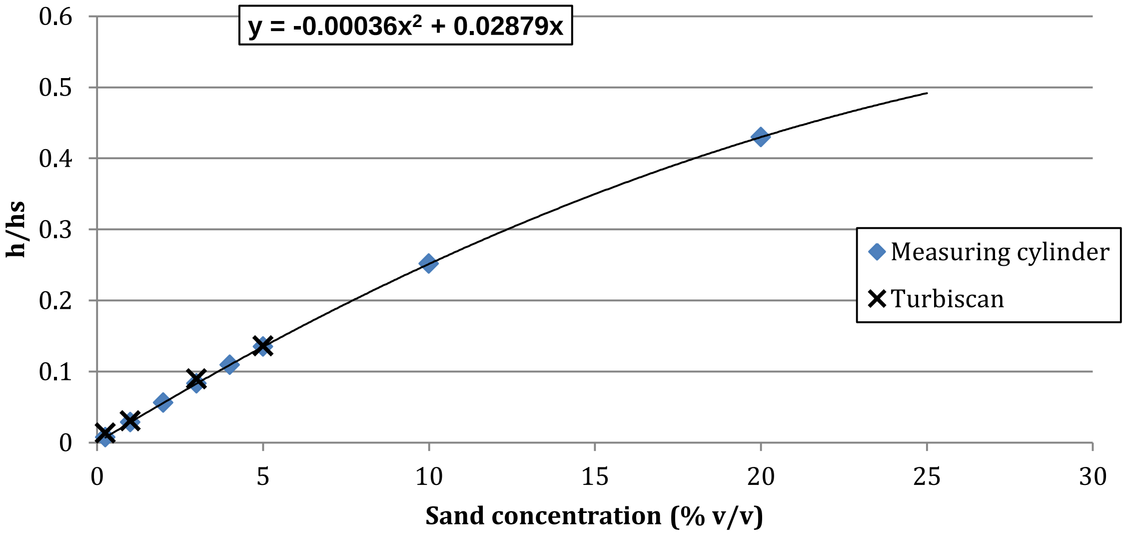

Figure 5.7 The height of sediment formed at different sand concentrations. h_s was 160 mm in the measuring cylinder tests and 42 mm in the Turbiscan.

It can be seen that the relationship between sediment height and the sand concentration is not linear. In the higher concentration mixtures the greater mass of the sediment compresses itself; the fluid is forced out from between the particles enabling them to pack closer together. In a full size pile bore the mass of sediment is going to be many, many times greater and this is likely to lead to greater compression in the sediment and h/h_s will be slightly smaller when h_s is much greater than 160 mm.

5.2.5 Example calculation

The calculation of the height of sediment produced by 5% v/v sand suspension in a 0.4 g/L polymer solution after ten minutes of settling will be used as an example.

The average backscattering of the suspension after ten minutes is calculated from the Turbiscan graph to be 9.85%. From Figure 5.5 the equation of the trend line can be used to calculate the concentration of sand in suspension that it corresponds too.

$$\phi = 0.000139 \times 9.85^{3.89708} = 1.034\%\ v/v$$

Using equation 5.1 it is then possible to calculate the amount of sand in the sediment. This value is the volume of sand in the sediment as a per cent of the total volume of the sand-polymer mixture.

$$\Theta = 5 - 1.034 = 3.966\%\ v/v$$

From this value it is possible by using Figure 5.7 to calculate the value of h/h_s at ten minutes, which is found to be 0.109.

$$h/h_s - 0.00036 \times 3.966^2 + 0.02879 \times 3.966 = 0.109$$

h_s in the Turbiscan experiments was 42 mm and using the value for h/h_s calculated in this example gives a sediment height of 4.578 mm. Estimating the height of sediment from the Turbiscan graph gives a height of about 4.5 mm, which shows that this method makes a good prediction for sediment height.

5.3 Sediment height results

By following the procedure described in the previous section it has been possible to produce a set of graphs describing how the height of sediment changes over time from the Turbiscan results. The sediment height graphs for 0.25, 1, 3 and 5% v/v are shown below in Figure 5.8 to Figure 5.11.

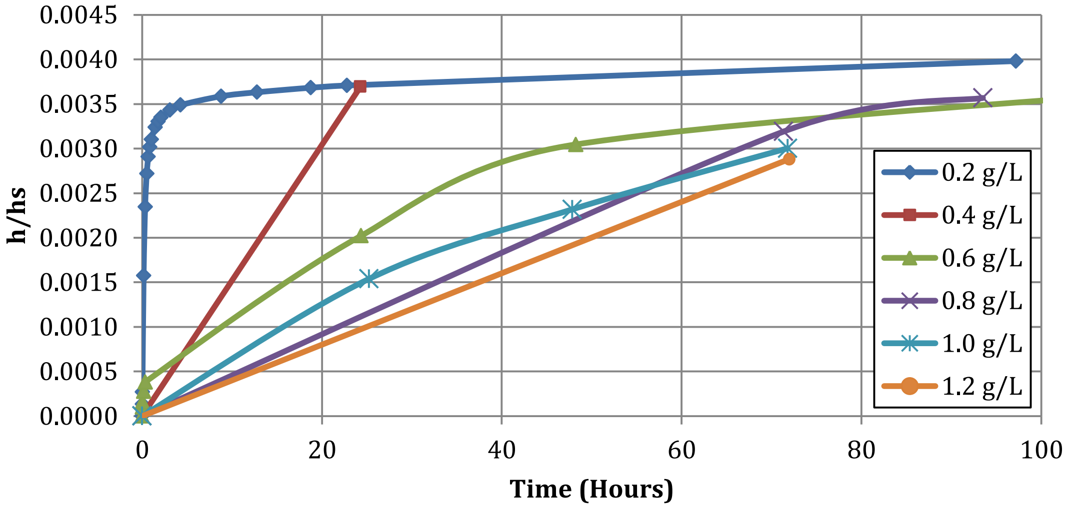

Figure 5.8 Sediment height for 0.25% v/v sand.

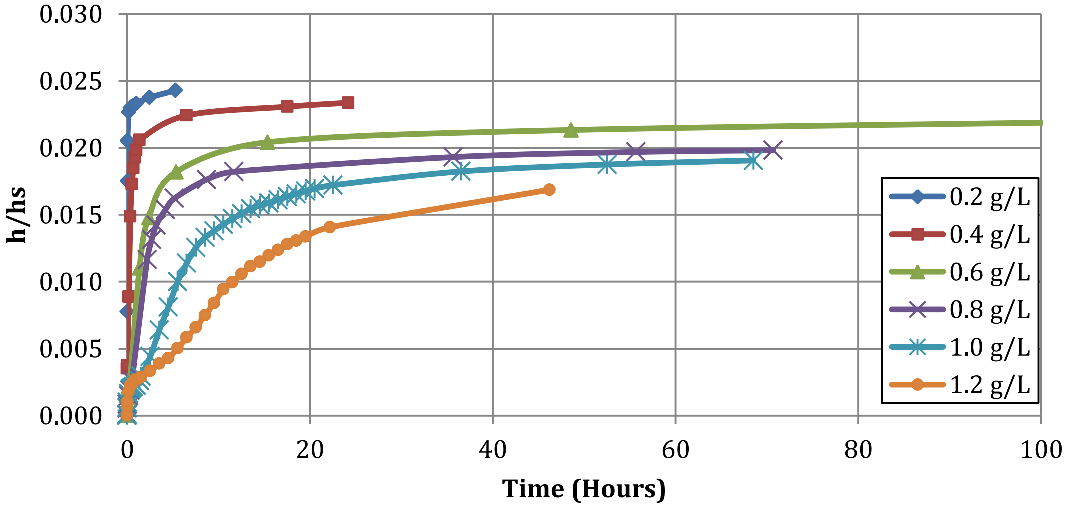

Figure 5.9 Sediment height for 1% v/v sand.

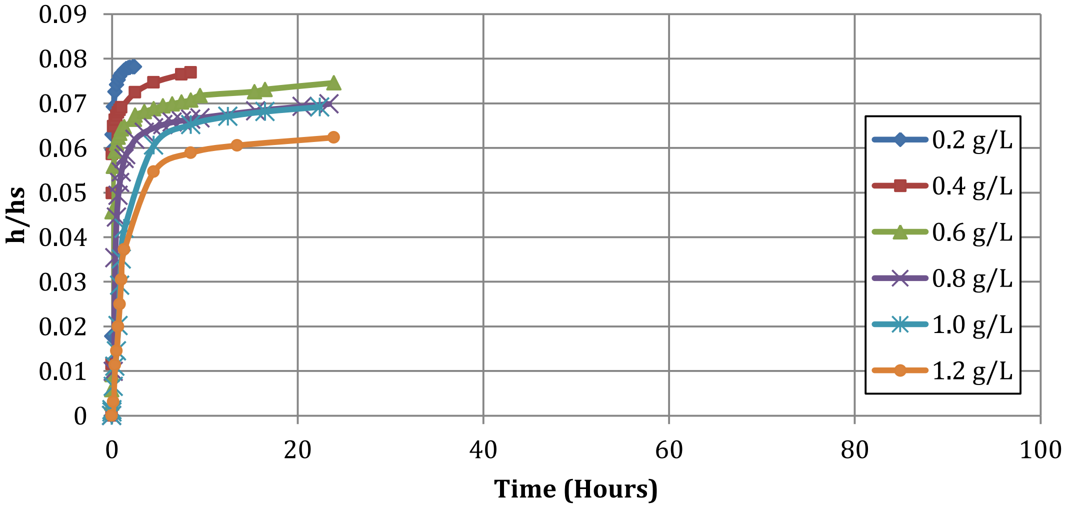

Figure 5.10 Sediment height for 3% v/v sand.

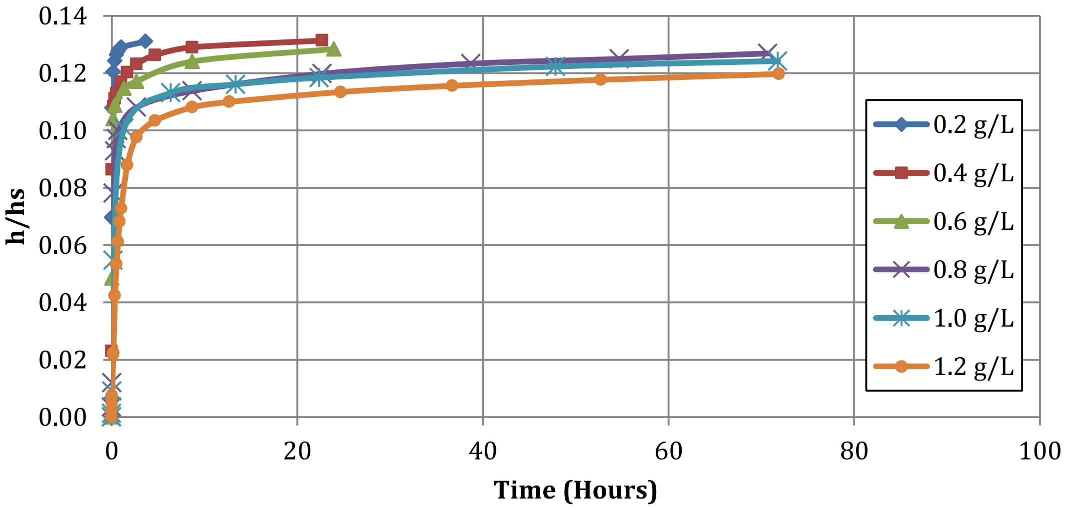

Figure 5.11 Sediment height for 5% v/v sand.

The curves for polymer concentrations 0.2 and 04 g/L always end earlier than the others because settling in these solutions was much faster than at higher concentrations and the second wall effect makes it impossible to collect any further data points. The curves for the 3% v/v sand concentration also end earlier because 3% was the last set of experiments to be completed and it had been seen previously that the rate of change in sediment height was extremely small after 24 hours and there was little insight that could be gained from prolonging the experiments further. There are fewer data points in the graph for 0.25% v/v because the original method developed for analysing the results was based upon how the backscattering of the sample changed with time. The backscattering of the 0.25% v/v samples appeared not to change so fewer scans were taken and the time was dedicated instead to carefully examining the other sand concentrations. It was discovered after the work was completed that a calibration curve of the amount of light transmitted through the sample could be produced to analyse the results of 0.25% v/v, enabling Figure 5.8 to be plotted.

It can be seen in these graphs that height of the sediment for each of the different polymer concentrations does not reach the same maximum. The same volume of sand in a mixture should produce the same volume of sediment and the reason for this discrepancy is that in the higher concentration polymer solutions not all of the sand had settled out over the observed timescale. The extremely fine sand remained in suspension in these solutions for a very long time, upon visual examination of these samples weeks later the liquid was still cloudy with fine sand held in suspension.

Attempts were made to produce graphs with a dimensionless time on the x-axis to condense the curves of all the polymer concentrations into one, but they were unsuccessful due to several reasons. It was very difficult to choose a reference time that related to the results; equations for settling rate such as Stokes' Law made very poor predictions for settling rate of a suspension. Several other equations were tried but with no more success at predicting the settling rate. The main reason why a dimensionless time could not work was that some of the curves are a very different shape and no dimensionless time could condense the data onto one curve.

To highlight the region in which the greatest change to the sediment height occurs and to show a timescale relevant to how long a pile bore will typically be left open for, the first five hours of settling are shown in Figure 5.12 toFigure 5.15 below.

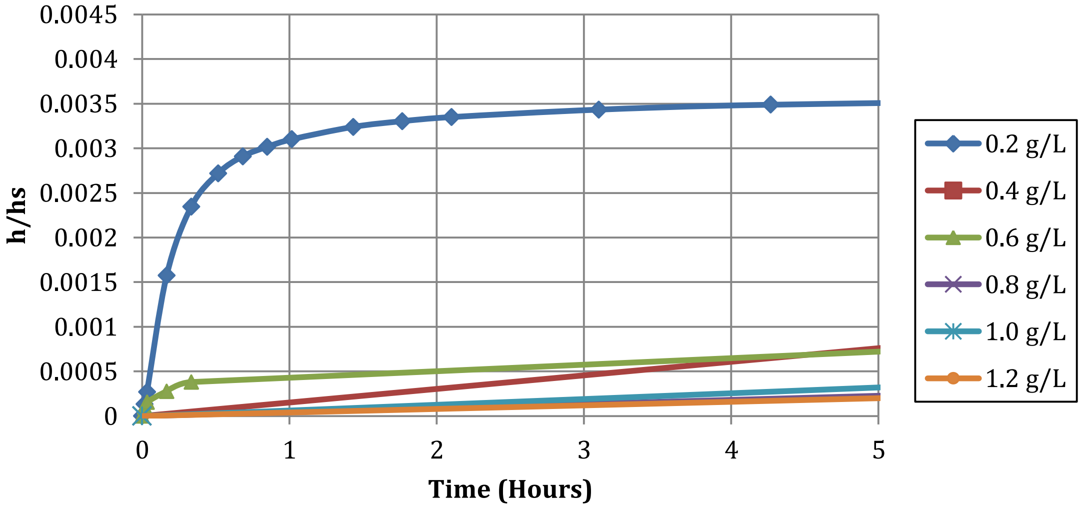

Figure 5.12 The first five hours of settling for 0.25% v/v.

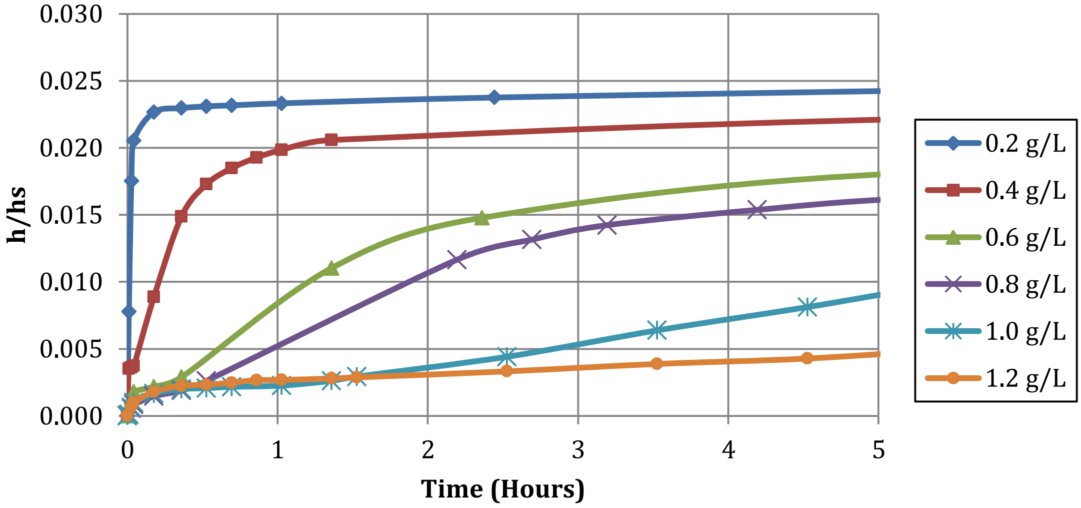

Figure 5.13 The first five hours of settling for 1% v/v.

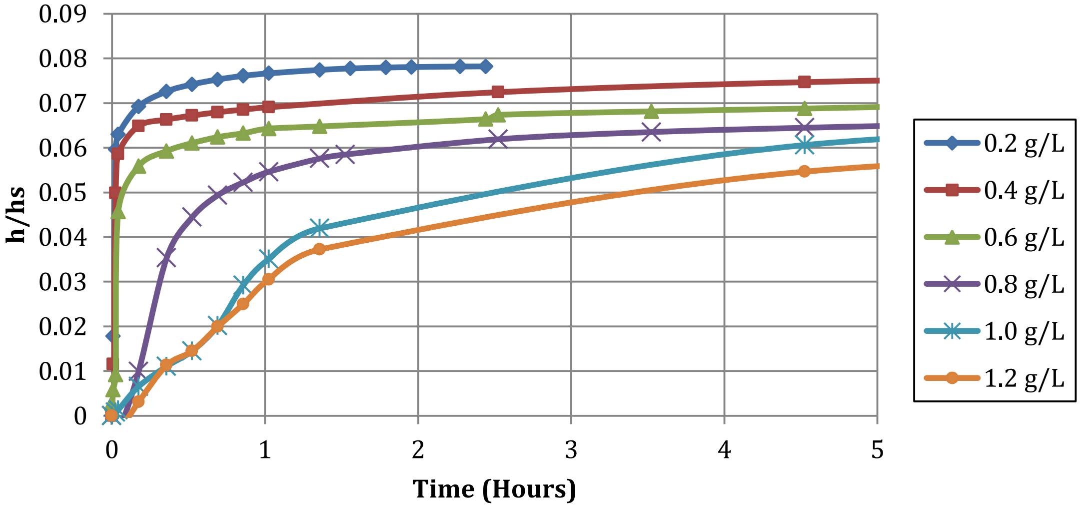

Figure 5.14 The first five hours of settling for 3% v/v.

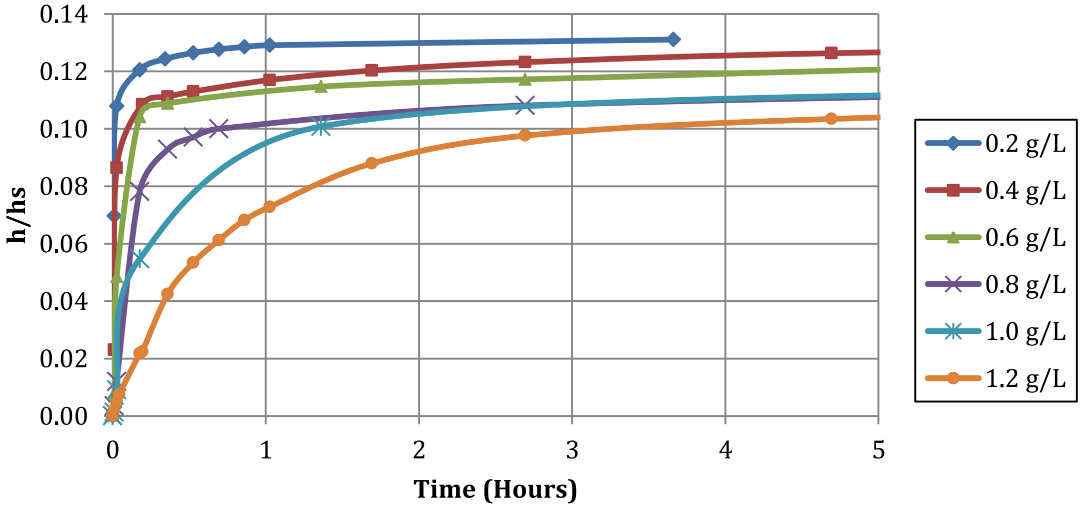

Figure 5.15 The first five hours of settling for 5% v/v.

5.4 Discussion on sedimentation rate

5.4.1 Effects of polymer concentration and particle size

Two factors that are closely linked that influence the sedimentation rate are the concentration of the polymer and the size of particles in suspension. The polymer concentration is directly linked to the viscosity of the solution and it was seen from Stokes' Law in equation 2.3 the great influence on the settling velocity that particle size and fluid viscosity have on settling rate.

It can be seen from the flow curves for the polymer in Figure 2.3 (page 17) the effect that polymer concentration will have on settling rate. By increasing the polymer concentration it will increase the viscosity of the solution causing particles to more slowly. A slower falling particle will also exert a smaller shear rate on the polymer and it can be seen in Figure 2.3 at lower shear rates the viscosity of the polymer is higher. This means that polymer concentration influences the settling rate of particles not only from the direct increase in viscosity but also from the viscosity increase due to the decrease in the shear rate.

From the analysis of the Turbiscan results it could be seen that that there was an initial period of relatively fast settling followed by a period of extremely slow settling. Figure 5.16 shows how the concentration of sand in the suspension changes with time for suspensions with an initial concentration of 5% v/v; the dashed line denotes the change between the periods of fast and slow settling. For a 5% suspension this initial period ranged from under ten minutes for the lowest polymer concentration of 0.2 g/L up to an hour for 1.2 g/L and through visual observation it was seen that it could take weeks for the second period to complete and for all of the sand to have settled out of suspension.

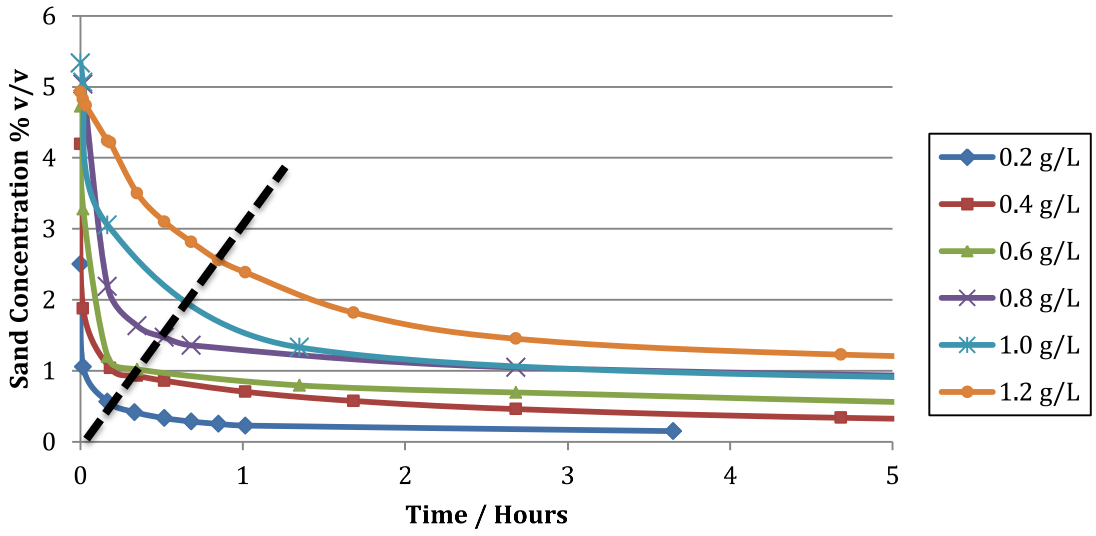

Figure 5.16 The concentration change of a 5% v/v suspension over time.

This phenomenon could be due to the wide range in the size of the particles, where the largest particles settle out rapidly but the finer ones could remain in suspension for a lot longer.

The finest particles take much longer to settle out of the suspension as it can be seen from Stokes' Law their small size will mean that their terminal settling velocity is much lower. This is compounded by the shear thinning nature of the polymer solution, which means that as the smallest particles do not exert a shear on the solution as high as the larger ones they also experience a higher viscosity, further retarding their rate of fall.

One of the effects that can be seen in Figure 5.16 is that as the concentration of the polymer fluid is increased, the period of slow sedimentation begins at a higher sand concentration. The higher viscosity of the higher polymer concentrations could mean that larger sand particles are overcome by the viscous forces.

Figure 5.17 andFigure 5.18 shown below are the same graphs for 1 and 3% v/v and this effect is highlighted paricularly in the graph for 1% v/v suspensions in the curves for polymer concentrations of 0.8, 1.0 and 1.2 g/L. In these curves it can be seen that the sand concentration drops very little in the initial fast period of settling and the majority of the sand settles in the very slow period. It appears from these graphs that the higher concentrations of polymer do not simply reduce the rate of settling overall as the shape of the curves at high polymer concentration is different to that of lower concentrations.

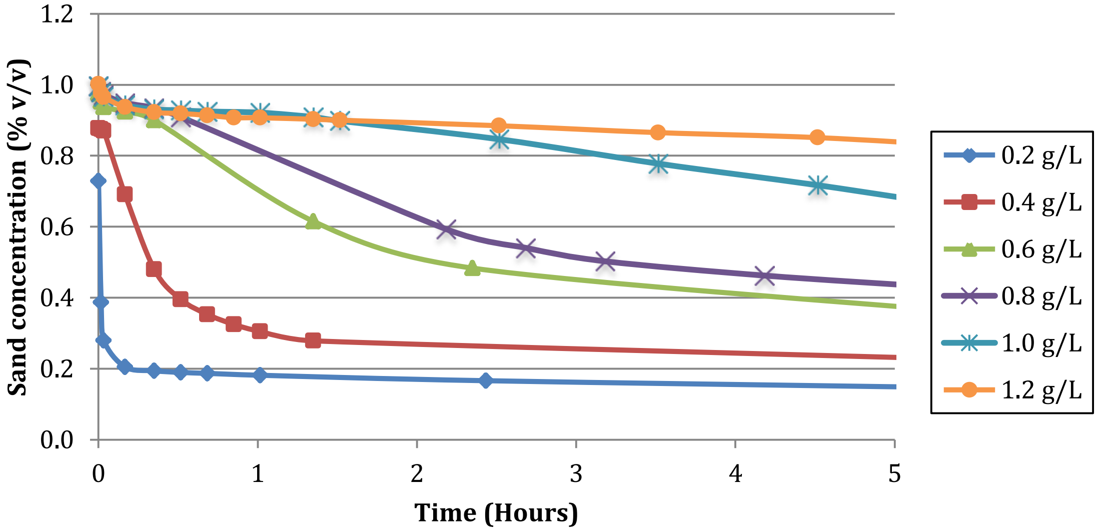

Figure 5.17 The concentration change of a 1% v/v suspension over time.

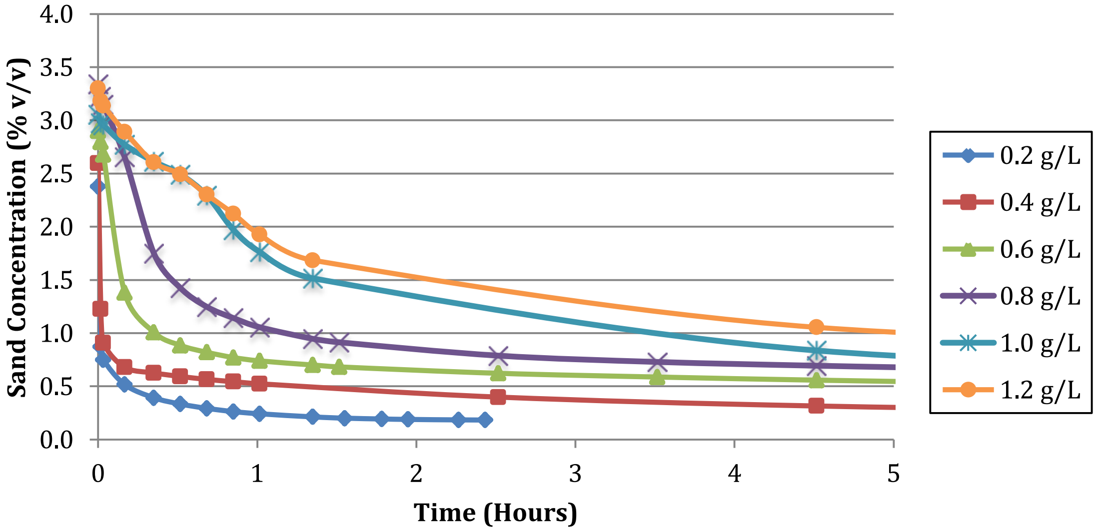

Figure 5.18 The concentration change of a 3% v/v suspension over time.

5.4.2 The effect of sand concentration

As the sand concentration is increased the rate of sedimentation increases; this seems counterintuitive as higher particle concentrations should lead to more hindered settling, slowing the particles down, as the results of Work & Kohler (1940) showed. This has been demonstrated in Figure 5.19, which shows the how the normalised concentration (ϕ/ϕ_1) of four different suspensions varies with time, and it can be seen that the concentration of the suspensions decreases faster for higher sand volumes. Concentrations of 10 and 20%

v/v were tested to investigate the extent of this effect and it can be seen that it is diminished at these concentrations; the difference between the rate of change in 1 and 5% v/v is much greater than that of 5 to 10% and it appears that there is no change when the concentration is increased to 20%.

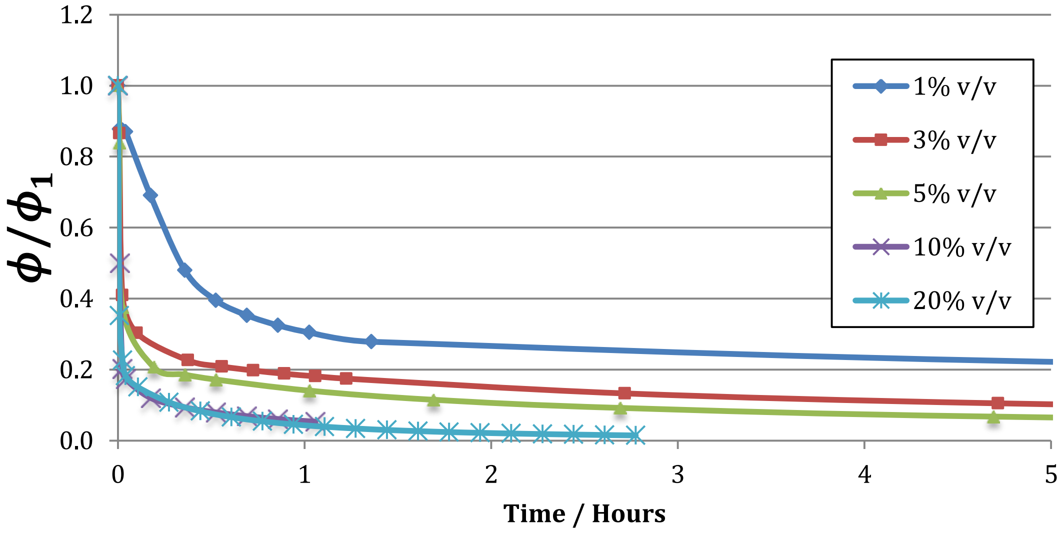

Figure 5.19 Normalised concentration change in a 0.4 g/L polymer solution.

This phenomenon could be explained by the clustering effect described in section 2.3.3 and a visual observation supports this. Richardson *et al.* (2002) describes how the faster falling clusters occur in “well defined streams”; this was observed during all the sedimentation experiments in the polymer solution and an attempt has been made to capture this effect in Figure 5.20. The velocity of particles in these streams was significantly higher than in the bulk of the suspension. Whilst the range of particle concentrations, over which the clustering effect is prevalent, is different to that found by Bhatty (1986) this could be due to the different conditions under which the sedimentation is occurring, such as the size of the particles and the viscosity and rheology of the fluid.

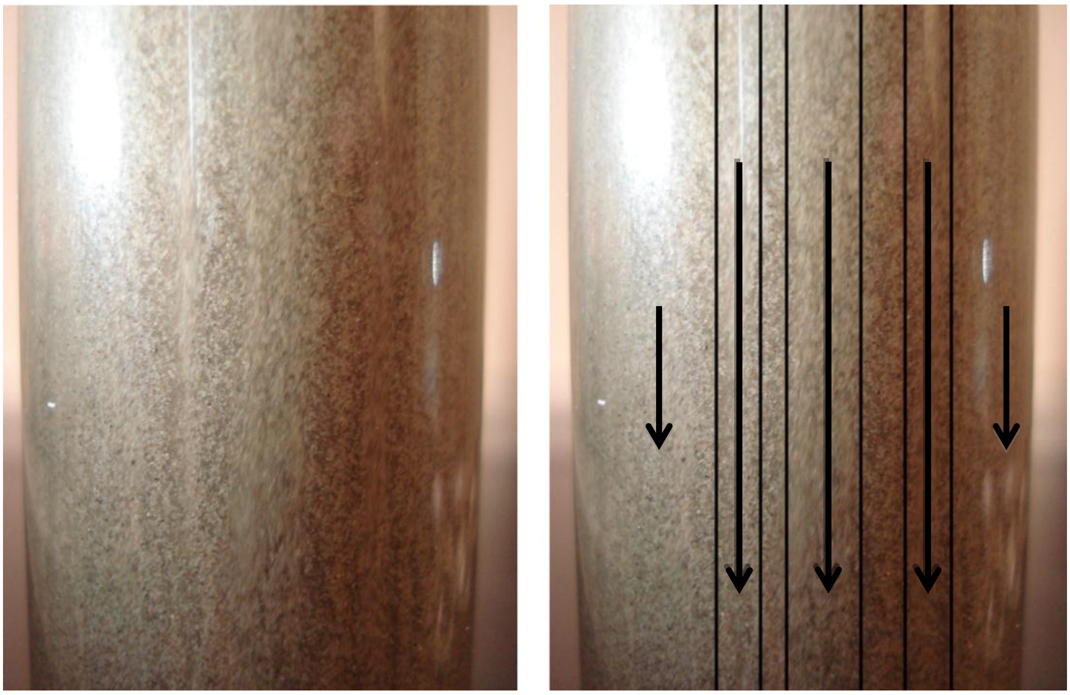

Figure 5.20 Channels of more rapid settling with the channels highlighted on the image on the right. This image is of a 5% v/v suspension in 0.2 g/L polymer solution.

5.5 Scaling the results for different initial suspension height

To confirm whether these results would be valid when scaled up and that the height of the slurry had no effect on how the sediment built up, tests on suspensions of different height were completed. Identical suspensions of two different heights were investigated; the two suspensions were 5% v/v sand in a 0.4 g/L polymer solution, 21 mm and 42 mm high. How h/h_s changed over time in the two different mixtures is shown in Figure 5.21.

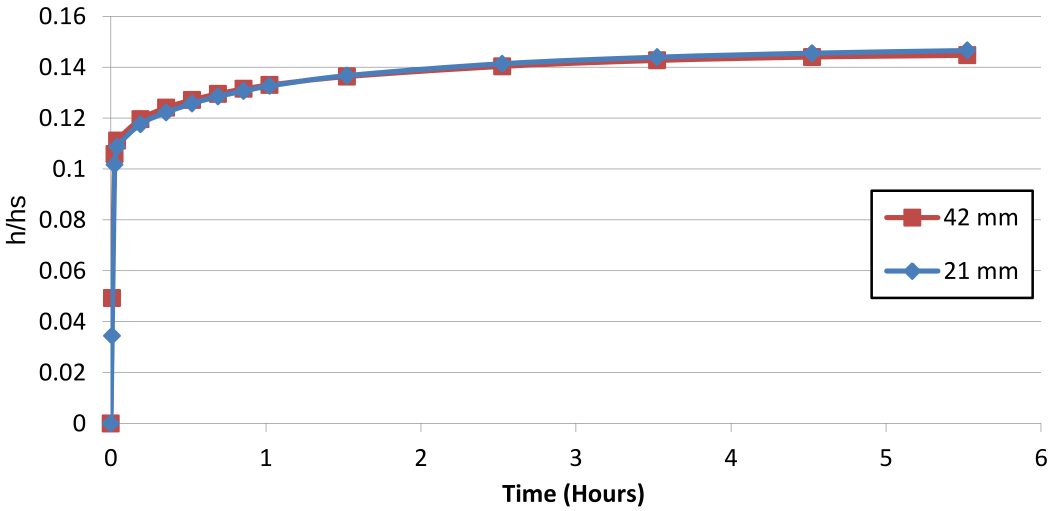

Figure 5.21 Sediment height divided by total suspension height.

From this plot it appears that the results from this project for how the height of sediment changes with time could be scaled to any height. However upon further consideration of the results from this height test it can be seen that, unfortunately, this is unlikely to be the case. By plotting the actual height of sediment against time, as in Figure 5.22, it is easier to see what is occurring in this situation. In a normal situation the settling rate of the two suspensions should be equal and after the smaller suspension has finished settling the large one continues at the same rate until it too has finished. It can be seen that the initial rate of settling (proportional to the gradient of the linear section of the curves in the first 1.5 minutes) for the 42 mm suspension is twice that of the 21 mm one and the settling of the two suspensions finishes at the same time.

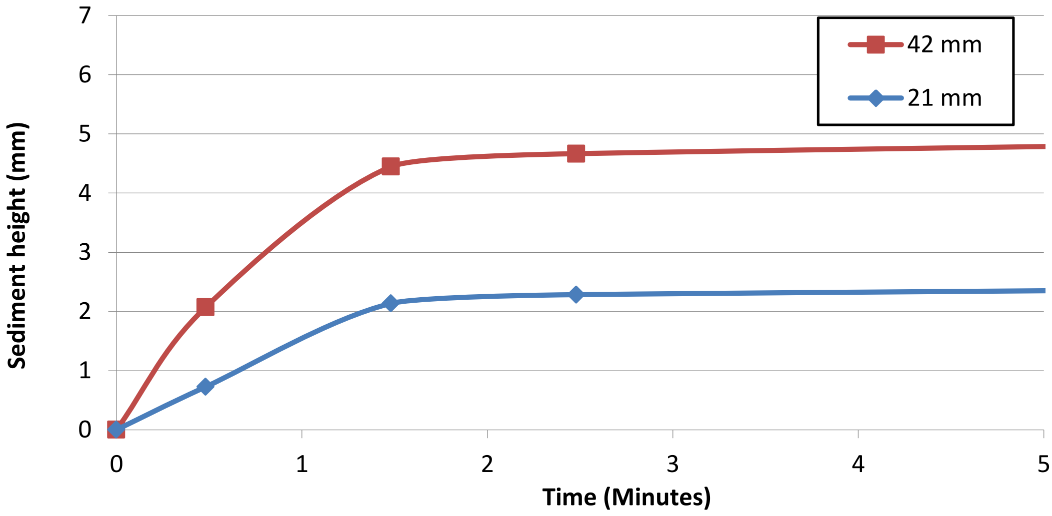

Figure 5.22 The height of sediment in mm for the first five minutes of settling.

Settling rate should be independent of initial suspension height as was seen in Figure 2.5 and the research of Work & Kohler (1940) but the results of this height test show that the settling rate of sand suspensions in PHPA can be dependent on the initial height of the suspension. Reasons for this height dependence could be due to the clustering effect or the shear thinning nature of the polymer solution.

The settling rate cannot increase indefinitely with initial suspension height, so whilst the rate at which sediment builds up appears to be scalable over the height ranges testable in the Turbiscan, without further research into the effect of initial height on the settling rate it is not possible to say exactly how the results of this project will relate to the rate of sediment build up in full scale pile bores.

5.6 Sediment compression

Using the results from the measuring cylinder sedimentation tests in a 0.2 g/L polymer solution and further tests for sedimentation in water, the density of the sediment produced was determined through simple calculation and is shown in Figure 5.23. Sedimentation tests were also carried out on a 0.4 g/L polymer solution to see what effect polymer concentration might have and it can be seen to have very little.

$$\text{Sediment density} = \frac{\text{Mass of sand} + (\text{Volume of sediment} - \text{Volume of sand}) \times \text{Fluid density}}{\text{Volume of sediment}}$$

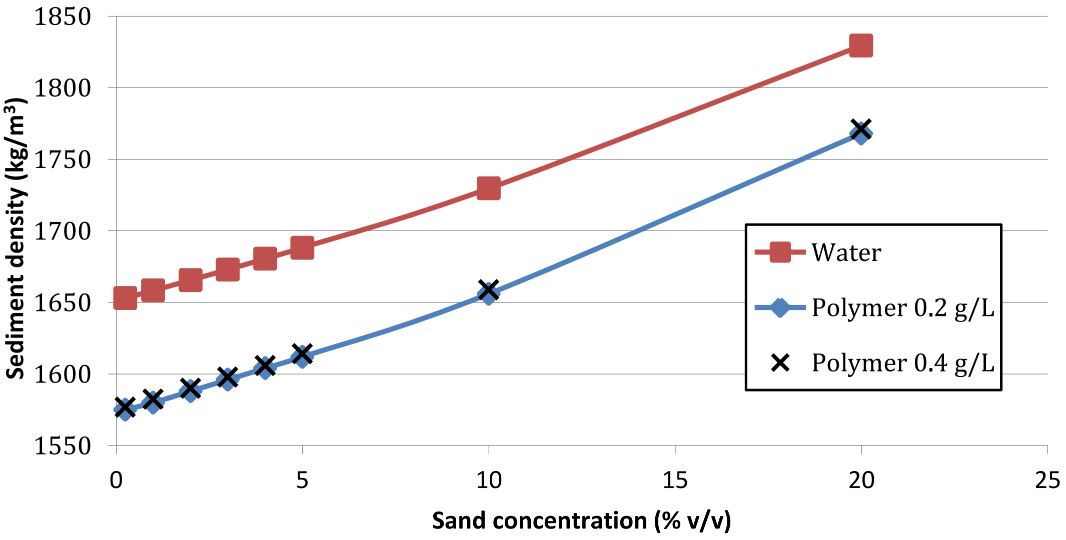

Figure 5.23 The density of sediment produced by suspensions of different sand concentrations in water and a 0.2 g/L polymer solution.

There are two potential reasons why the density of the sediment produced by settling in water is much higher than in the polymer solution. The higher viscosity of the polymer solution means that sedimentation occurs at a much slower rate and Lambe & Whitman (1968) describe how it is possible to achieve a lower density of sediment if the settling occurs slowly, the particles can pack loosely, thus leaving more space between them and leading to a greater volume of fluid in the sediment. Another factor is that as the sediment builds up the fluid is forced out from between the particles under the weight of sand. If the fluid is more viscous it does not flow as easily and it is harder for it to be forced out of the sediment. The effect of viscosity on how the fluid is forced out of the sediment can be seen in Darcy's Law, shown in equation 5.2 (Fanchi, 2000); increasing the viscosity of the fluid will decrease its flux out of the sediment. Whilst Darcy's Law may not be able to be used to calculate the flow of fluid out of the sediment it does give a good indication of what would affect it. $\boldsymbol{q}$ is the flux of the fluid out of the sediment, $\boldsymbol{k}$ is the permeability of the sediment and $\boldsymbol{\nabla P}$ is the pressure gradient over the sediment.

$$q = -\frac{k}{\mu}\nabla P \qquad 5.2$$

5.7 Density of bulk sand

The actual volumetric concentration of sand and the bulk sand volume per cent observed in a sand content tube will differ greatly. In industry the amount of sand in suspension is measured using a sand content tube, so to ensure the relevance of the results of this project a comparison is shown in Figure 5.24.

The sand content tube gives a value for the bulk sand volume as a per cent of the total volume of the suspension and one might assume that it would correspond to the per cent of the total height of the mixture that the sediment makes up (h/h_s) but this is not the case. There are two main reasons why the result from the sand content test will not be indicative of the maximum sediment height. Firstly the standard procedure for the sand content test is to sieve out all particles smaller than 75 μm, which from the analysis of the particle size distribution was found to make up 12% of the volume of the sand. Secondly the density of sediment formed from settling in water is of a higher density and thus a smaller volume than the sediment formed in a polymer solution, as can be seen in Figure 5.23. The density of the bulk sand in the sand content tube can also be unintentionally increased by vibration such as tapping the tube, increasing the density difference. The density of the bulk sand in the sand content tube is shown in Table 5-1 and it can be seen how much larger it can be than the density of the sediment formed by settling in the polymer in the measuring cylinder tests. For these reasons a value for the bulk sand volume per cent obtained from a sand content test cannot alone be used to estimate the maximum sediment height.

Table 5-1 The density of the bulk sand in the sand content tube and sediment in the measuring cylinder tests.

Sand concentration (% v/v)	Density of bulk sand in sand content tube (kg m^{-3})	Density of sediment in measuring cylinder tests (kg m^{-3})
1	1889	1580
2	1873	1588
3	1829	1596
4	1837	1604
5	1777	1612

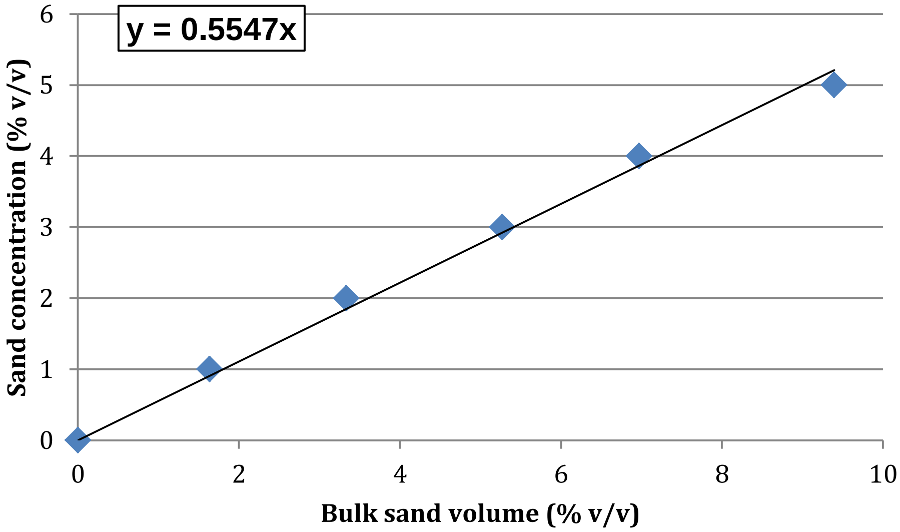

Figure 5.24 A comparison of actual volumetric sand concentration and the result from the sand content tube. The bulk sand volume on the x-axis is the result from the sand content test.

6 Conclusions

In conclusion, a method has been developed to describe how sediment builds up over time in suspensions of sand in polymer solutions. It has been possible to describe how the sediment will build up in a range of sand and polymer concentrations and using the graphs that have been produced it is possible to predict the height of sediment formed in laboratory tests. Insight has also been gained into the density and compression of sediment formed and how this is affected by the fluid in which settling occurs. It has not been possible though to determine how the results of how sediment builds up over time can be directly related to sediment formation on a much larger scale and whether it is possible to predict the height of sediment produced in pile bores.

The method used in this work to convert the backscattering result from the Turbiscan into the sediment height is a fairly accurate one. Taking an average of the backscattering over the height of the suspension using the in-built software is an accurate method of determining the amount of sand still in suspension; any concentration gradient over the height of the sample is balanced to give a value of backscattering relative to the total amount of sand. Using the measuring cylinder tests to determine the volume of sediment produced by different concentrations of sand can be seen from Figure 5.7 to predict accurately the sediment height formed in the Turbiscan. This shows that on the scale of the tests done in this project that the compression of sediment of different heights is not significant.

If there's a weakness in the method it is in the effectiveness of the calibration curves. It can be seen from equations 2.9 and 2.10 how particle diameter relates to backscattering. Once all of the largest particles have settled out of suspension and only the smallest remain, the calibration curve may no longer relate as closely to the actual concentration of particles. It is possible though that as the tiniest particles relate to only 6% of the volume of the sand that this will not affect the results until the vast majority of the sand has already settled.

It is difficult to quantify the accuracy of the method used to analyse the results of the Turbiscan but relating it to the methods used by Majano and O'Neill (1993), Kheng *et al.* (1991) and Henry *et al.* (1998) it is a vast improvement. The drawbacks of these previous methods, as discussed in the literature review, are avoided. Settling can be observed without influencing the sample by removing fluid and sand from taps, the state of the sample can be observed as regularly as desired without affecting the results and suspensions of particles of a range of sizes can be investigated.

Increasing the concentration of the polymer decreased the settling rate as expected, although contrary to expectations it was found that increasing the sand concentration increased the settling rate. Much of the literature suggested that increasing the concentration of particles would reduce the settling rate but it is believed that an effect known as clustering enabled the suspension to settle faster than expected. This hypothesis was supported by observations of settling in which streams of rapidly settling particles could be seen. The concentrations of sand in which this clustering effect was prevalent were higher than those observed in the research of Barfod (1971) and Bhatty (1986) but it is believed that this could be due the different particles and fluid used.

The graphs describing how the height of sediment changed with time could be used to predict the height of sediment that would form after a period of time settling in the Turbiscan vessel. However it was found in the tests on different suspension heights that settling rate was dependent on the height of the suspension, which was unexpected as the literature review had suggested that settling rate should be independent of height. It is unknown what lead to this but it could be linked to the clustering effect, with smaller suspension heights hindering their formation. This effect meant it was not possible to scale these results up to much greater heights but hopefully with further research into the effects of suspension height it would be possible.

If the results of this work could be scaled a source of error that would occur when relating sediment formed in the laboratory to the size of pile bores is that sediment volume is dependent on the suspension height. Due to compression of the sediment its density depends upon the height and total mass of the sediment; this means that the volume of sediment formed in a bore hole will be smaller than that which has been found in these experiments and further research would be required to determine exactly how the density of sediment changes with pile bore size. It has also been shown in this work that other factors can influence the sediment density such as the type of fluid the sand is settling in and the rate at which settling occurs.

7 Recommendations

7.1 Further research

To obtain a more comprehensive knowledge of sedimentation in polymer support fluids such as PHPA there are several areas that would require further research. The two areas that would be most useful would be the height dependence of the settling rate and the compressibility of the sediment. With a good understanding of these factors it should be possible to relate laboratory results to the size of pile bores. Investigation into the detailed effects of particle size and the clustering effect would also be useful.

7.1.1 The height dependence of settling rate

It would be useful to determine to what extent the height of the suspension influences the settling rate of the particles. It would establish whether sedimentation tests in PHPA solutions on a laboratory scale can be related to what occurs in full size pile bores. To understand this properly much greater heights than are observable in the Turbiscan will need to be investigated.

7.1.2 Sediment compressibility

The sediment layer that forms can be compressed under its own weight. To obtain a better understanding of how the concentration of sand in the sediment relates to the volume of the sediment in full scale pile bores it would be necessary to do further research into how two factors affect the density of the sediment; the height and mass of the sediment.

7.1.3 The effect of particle size on sedimentation in polymer fluids

If it is possible to develop the method of this project so that it could be scaled up to the size of pile bores in the drilling industry it would be useful to investigate further the effects particle size have on the rate of settling. A sand with a much larger particle size than Thanet Sand could be investigated.

7.1.4 The effect of clustering on sedimentation rate

Greater concentrations of particles in suspension generally lead to more hindered settling. The observation in this project was that higher sand concentrations lead to an increase in the settling rate and it was hypothesised, due to the effects observed, that this was due to an effect called clustering where particles could settle in a slip stream of the particles ahead of them and channels could form where the settling rate was considerably higher than the bulk.

To understand fully how clustering influences the settling rate it would require further investigation into how sand and polymer concentration affect the channels of particle clusters.

7.2 Suggestions

7.2.1 Using the sand content tube to investigate sedimentation in pile bores

A method that could be used to investigate the rate of sedimentation or to describe the amount of sediment that has formed in a full sized pile bore would be to use the sand content tube to measure the concentration of sand in an actual pile bore. This experiment could be used to investigate how well laboratory work relates to sedimentation in a pile bore or to estimate the height of sediment before concrete is placed.

The sand content would be measured initially when the excavation has been completed and then readings would be taken periodically over the time that the pile bore is supported by the fluid until concrete is placed. As the concentration of sand in suspension will vary quite considerably over the height of the pile bore an estimate of the sand concentration could be made by taking measurements from the top, middle and bottom and taking an average of the results. Then using a similar method to that used for the analysis of the Turbiscan results the concentration measurements could be used to calculate how the sediment height in the pile bore changes with time. By using Figure 5.24 to convert the result of the sand content test to the actual sand concentration (ϕ), equation 5.1 can then be used to calculate the concentration of sand that is in the sediment. From the concentration of sand in the sediment Figure 5.7 could then be used to calculate the height of sediment that has been produced.

This method would be improved by not sieving out all of the particles below 75 μm and by doing further research into the compressibility of sediments of greater height and mass to give a more accurate value of sediment height. It might be possible to improve this method further by producing a graph similar to Figure 5.7 that uses the bulk sand volume determined from the sand content tube on the x-axis. This would mean that there would be no need to convert the sand content tube result to the actual concentration of sand (ϕ).

References

Akther, S., Hwang, J.-Y. & Lee, H., 2007. Effects of the Water Quality on the Dispersion Properties of Bentonites Used for Drilling fluid. *J. Miner. Soc. Korea*, 20(1), pp.21-33.

Allen, T., 1992. *Particle Size Measurement*. 4th ed. p.259.

Barfod, N., 1972. Concentration Dependence of Sedimentation Rate of Particles in Dilute Suspensions. *Powder Technology*, 6(1), pp.39-43.

Bemer, G.G., 1978. A Simple Light Backscattering Technique to Determine Average Particle Size and Concentration in a Suspension. *Powder Technology*, 20, pp.133-36.

Bhatty, J.I., 1986. Clusters Formation During Sedimentation of Dilute Suspensions. *Seperation Science and Technology*, 21(9), pp.953-67.

Brown, D.A., 2004. Zen and the Art of Drilled Shaft Construction: The Pursuit of Quality. *Geotechnical Special Publication No. 124, ASCE*, pp.19-33.

Brown, D.A., Turner, J.P. & Castelli, R.J., 2010. *Drilled Shafts: Construction Procedures and LRFD Design Methods Publication No. FHWA-NHI-10-016*. U.S. Department of Transportation Federal Highway Administration.

Bru, P. *et al.*, 2004. *Particle Size and Rapid Stability Analyses of Concentrated Dispersions*. American Chemical Society.

Burgos-Montes, O. & Moreno, R., 2009. Stability of concentrated suspensions of Al2O3–SiO2 measured by multiple light scattering. *Journal of the European Ceramic Society*, 29, pp.603-10.

Buscall, R., Goodwin, J.W., Ottewill, R.H. & Tadros, T.F., 1982. The Settling of Particles through Newtonian and Non.Newtonian Media. *The Journal of Colloid and Interface Science*, 85(1), pp.78-86.

Buscall, R. & White, L.R., 1987. The Consolidation of Concentrated Suspensions: Part 1. - The Theory of Sedimentation. *The Journal of the Chemical Society, Faraday Transactions 1*, 83, pp.873-91.

Carreau, P.J., 1972. Rheological Equations from Molecular Network Theories. *The Journal of Rheology*, 16(1), pp.99-128.

Coe, H.S. & Clevenger, G.H., 1916. Methods For Determining The Capacities of Slime Settling Tanks. *Transactions of The American Institute of Mining and Metallurgical Engineers*, p.356.

Defra, 2009. *EU Landfill Directive*. [Online] Available at: http://www.defra.gov.uk/environment/waste/strategy/legislation/landfill/ [Accessed 07 December 2010].

Einstein, A., 1906. Eine neue Bestimmung der Moleküldimensionen. *Annalen der Physik*, 19(4), pp.289-306. English translation available at: http://www.ffn.ub.es/luisnavarro/nuevo_maletin/Einstein_1906_thesis.pdf [Accessed 28 March 2011].

Einstein, A., 1911. Correction to My Paper: A New Determination of Molecular Dimensions. *Annalen der Physik*, 34, pp.591-92.

Fanchi, J.R., 2000. *Integrated Flow Modeling*. Elsevier.

Federation of Piling Specialists, 2006. *Bentonite Support Fluids in Civil Engineering*. 2nd ed.

Formulaction, n.d. *Multiple Light Scattering*. [Online] Available at: http://www.formulaction.com/technology_mls.html [Accessed 22 March 2011].

Formulaction, n.d. *Turbiscan Head Image*. [Online] Available at: http://www.formulaction.com/images/turbiscan_head2.jpg [Accessed 10 March 2011].

Henry, L.B., Filz, G.M. & Davidson, R.R., 1998. Formation and Properties of Bentonite Filter Cakes. In *Proceedings of sessions, ASCE Annual Convention, Boston, Massachusette, October 18-21*., 1998.

Kheng, H. *et al.*, 1991. *Slurry Performance in Drilled Shaft Construction*. ADSC: The International Association of Foundation Drilling.

Lam, C., 2008. *Polymer-soil Interactions in Geotechnical Processes. Probationary Research Student (PRS) Transfer Report*. St. Catherine's College, University of Oxford.

Lambe, W. & Whitman, R., 1968. *Soil Mechanics*. John Wiley & Sons.

Lam, C., Troughton, V., Jefferis, S. & Suckling, T., 2010. Effect of support fluids on pile performance – a field trial in east London. *Ground Engineering*, October. pp.28-31.

Majano, E.R. & O'Neill, M.W., 1993. *Effect of Mineral and Polymer Slurries on Perimeter Load Transfer in Drilled Shafts*. ADSC: The International Association of Foundation Drilling.

Malkin, A.Y. & Isayev, A.I., 2006. *Rheology - Concepts, Methods, & Applications*. ChemTec Publishing.

ONS, 2010. *The Blue Book*. [Online] The Office for National Statistics. Available at: http://www.statistics.gov.uk/downloads/theme_economy/bluebook2010.pdf [Accessed 1 April 2011].

Pitt, M.J., 2000. The Marsh Funnel and Drilling Fluid Viscosity: A New Equation for Field Use. *SPE Drilling & Completion*, 15(1), pp.3-6.

Prakash, S. & Sharma, H.D., 1990. *Pile Foundations in Engineering Practice*. John Wiley & Sons.

Richardson, J.F., Harker, J.H. & Backhurst, J.R., 2002. Sedimentation. In *Coulson and Richardson's Chemical Engineering Volume 2 - Particle Technology and Separation Processes*. 5th ed. pp.237-86.

Smoltczyk, U., 2002. *Geotechnical Engineering Handbook, Volumes 1-3*. John Wiley & Sons.

Texas Department of Transport, 2008. *Underwater Drilled Shaft Construction*.

Vand, V., 1948. Viscosity of Solutions and Suspensions. *The Journal of Physical Chemistry*, 52(2), pp.277-99.

Wheeler, P., 2003. *Innovations - Clear as Mud*. [Online] Available at: http://www.foundationworld.org.uk/jsp/effc.jsp?lnk=042&id=17&pageid=36 [Accessed February 2011].

Work, L.T. & Kohler, A.S., 1940. Sedimentation of Suspensions. *Industrial and Engineering Chemistry*, 32(10), pp.1329-34.