University of Southern Queensland

Faculty of Health, Engineering and Sciences

Understanding ballasting agent dynamics when recycled in a ballasted flocculation process and impact on performance

A dissertation submitted by

Mr Cameron Ansell
[redacted]

In fulfilment of the requirements of

Course ENG4111 and ENG4112 Research Project

Towards degree of

Bachelor of Engineering (Honours) (Environmental)

Submitted: October 2022

ABSTRACT

Ballasted flocculation is a process where ballasting agent is added to a conventional flocculation process to increase the density of flocs with the objective to increase settling velocities. With these increased settling velocities it is possible to reduce the footprint of treatment process infrastructure significantly, saving both space and cost of construction.

There is currently limited literature available in relation to the operation and performance of full scale ballasted flocculation processes, particularly where ballasting agent is continually recovered and recycled and how any dynamic behaviour impacts performance. Previously published research has been largely conducted at a laboratory scale where ballasting agent is assumed to be constant in nature.

The objectives of this research were to prove or disprove that ballasting agent properties are dynamic when the ballasting agent is continually recovered and recycled in a full-scale ballasted flocculation process and to apply the known principles of ballasted flocculation documented in previously published research to explain impacts on process performance.

A model was developed in Microsoft Excel to calculate and evaluate coagulation, flocculation and sedimentation processes of the full-scale ballasted flocculation process. Modelling of discrete ballasting agent particle settling velocity was also included. Operating parameters for the full-scale ballasted flocculation process were used as inputs to the model.

The ballasting agent used as stock material to add to the ballasted flocculation process and that found within the process being subject to continuous recycling were both analysed for a range of particle properties. Parameters measured included particle size distribution, d10, d60, coefficient of uniformity, concentration and surface area. For the control period, it was found that ballasting agent within the process featured a distinct absence of particles less than 0.150mm, which is in contrast to the stock material being added to the ballasted flocculation process, which contained a significant portion of particles 0.150mm or less. It was also found that ballasting agent concentration varies both temporally and spatially within the flocculation chamber. It was also found that the particle size distribution is sensitive to flow rates though the full-scale process.

Following ballasting agent analysis, targeted jar testing was undertaken to assist in understanding the impacts on performance which could be expected as a result of the ballasting agent changes that were measured. It was found that for a given ballasting agent concentration by mass, performance would be expected to deteriorate when the particle size distribution is dominated by larger particles. Jar testing also demonstrated that this can be remedied if ballasting agent concentration by mass is increased to attain the same surface are concentration.

This research has contributed to advancing the understanding of ballasting agent dynamics and resulting impacts on performance in a full-scale ballasted flocculation process where ballasting agent is continually recycled.

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LIMITATIONS OF USE

CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Cameron Ansell

Student No. [redacted]

ACKNOWLEDGEMENTS

I would like to extend my gratitude to Dr Antoine Trzcinski who provided the academic supervision and guidance for this research.

Appreciation is also due to my employer who has allowed use of a Water Treatment Plant and laboratory facilities to conduct this research and my colleague Ihsan Hamawand who provided sound advice when I was getting bogged down.

Mostly though, I owe an unpayable debt to my wife Sabrina and children, Claire and Charlotte, who have sacrificed much to accommodate and support my years of study at university, for which this dissertation is the pinnacle achievement. Thank you.

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NOMENCLATURES AND ACRONYMS

BA	Ballasting agent
BF	Ballasted flocculation
CU	Coefficient of Uniformity
d10	diameter which 10% of particles are finer
d60	diameter which 60% of particles are finer
g/L	Grams per litre
Hz	Hertz
L/s	Litres per second
NTU	Nephelometric Turbidity Unit
PSD	Particle Size Distribution
SG	Specific Gravity
TOC	Total organic carbon

CHAPTER 1 - INTRODUCTION

1.1. Outline of the study

This research has included the following activities which are documented in this dissertation:

- A review of the literature related to ballasted flocculation.
- Development of methodologies to investigate ballasted flocculation in selected areas where the literature is not well developed.
- Execution of investigations and experiments to collect data on ballasted flocculation principles and performance.
- Development of conclusions from the data and identifying further work to continue advancement of the literature.

1.2. Introduction

Conventional water treatment includes dosing a chemical coagulant followed by coagulation and flocculation to remove dissolved and particulate contaminants. The chemical floc which forms has a slow settling velocity, typically in the order of 1.25 – 2.5 m/hr (MWH 2012). Ballasted flocculation is a process which introduces a ballasting agent in the flocculation process to artificially increases the floc density, which results in an increased settling velocity. Ballasting agents commercially used include micro sand, where diameters in the range of 100µm - 300µm have been reported (Young 2003) and magnetite which has a very high density of SG = 5.2. Ballasted floc settling velocities have been reported to be as high as 200m/h in the literature and one proprietary system utilising sand as the ballasting agent offers settling velocities of 80m/hr for water treatment. A typical configuration is shown in Figure 1-1.

Increased settling velocities associated with the ballasted flocculation process provide advantages for full-scale water treatment facilities. The higher settling velocity substantially decreases the footprint area of sedimentation processes as the surface loading rate can be increased significantly. The higher floc densities resulting from ballasted flocculation can overcome challenges where flocs have poor settling qualities such as developed in waters with high colour and low naturally occurring solids.

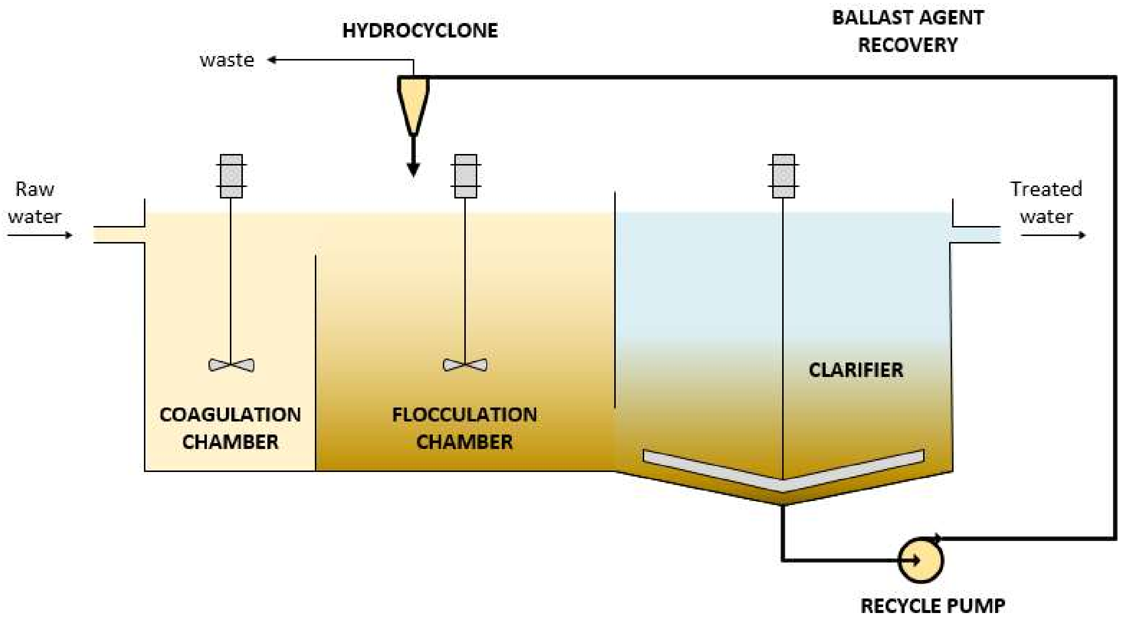

Figure 1-1 Typical ballasted flocculation process

1.3. The need for further research

The literature on ballasted flocculation is limited, with only a small number of researchers publishing works. Any detailed research of the underlying principles has been confined to a laboratory scale. The literature confirms that ballasted flocculation conforms to already well established sedimentation theory. There is however a clear absence of published research on design principles necessary to understand for a full-scale blasted flocculation process, including the behaviour of ballasted floc in the Type II settling phase and the dynamics of ballasting agent properties.

The dynamics of ballasting agent properties is the basis of this research. In the published literature, research has been at the laboratory scale using batched jar tests which treat ballasting agent properties such as concentration, diameter and surface area as being fixed. This however may not apply to a full-scale ballasted flocculation process where the process is continuous flow and the ballasting agent is continuously recovered and recycled. While the literature can inform the expected outcome of varying the ballasting agent properties, it does not inform what variance in ballasting agent can be expected and what design or operating parameters might influence this.

The limited published literature relating to full-scale ballasted flocculation process indicate that ongoing loss of ballasting media is be expected and in some cases to a sufficient scale to be an operational problem. It is hypothesised that ballasting agent properties are dynamic in a full-scale ballasted process and that this may be influenced by a range of design parameters.

1.4. Research objectives

The objectives of this research are to prove or disprove that ballasting agent properties are dynamic when the ballasting agent is continually recovered and recycled in a full-scale ballasted flocculation process and to apply the known principles of ballasted flocculation to explain impacts on process performance.

1. Measure the change in ballasting agent properties over time in a full-scale ballasted flocculation process that includes ballasting agent recycle/recovery with respect to concentration, diameter and surface area.
2. Evaluate the ballasted flocculation process performance with respect to changes in ballasting agent properties using both observation of a full-scale process and through jar test experiments.

1.5. Research scope

With limited literature on this topic the potential avenues of research are numerous. The scope of this research is limited to reflect the time and resource constraint of the project and was detailed in the Project Specification included in Appendix A and summarised as follows:

- Design a methodology and undertake programme of sampling and measurement of ballasting agent properties (particle size distribution, mass per volume unit (g/L) dosed, surface area) in a full-scale ballasted flocculation process.
- Develop a process model (Microsoft Excel) of the full-scale ballasted flocculation process to inform jar testing parameters and evaluation of data.
- Design a methodology and undertake programme of jar testing to compare flocculation and settling performance between the control ballasting agent and the 'operating' ballasting agent.

The following activities could not be undertaken due to time constraints:

- Evaluate the performance of the full-scale process for the time period where ballasting agent properties were studied, using ballasting agent property data, the process model and using process setting and water quality data captured through operational monitoring by the owner.
- If ballasting agent dynamics are found to impact process performance, identify and evaluate solutions to manage ballasting agent dynamics in a full-scale ballasted flocculation process.

1.6. Research site

This research had access to and utilised a full-scale ballasted flocculation process installed and operating within an existing Water Treatment Plant. The upstream treatment processes included lime/CO_2 dosing (for alkalinity and pH adjustment) and coagulation, while downstream of the ballasted flocculation are buoyant media clarifiers, ozone contact and Biological Activated Carbon filtration.

The full-scale ballasted flocculation process utilises silica sand as the ballasting agent.

The facility is designed for a maximum production of 28 ML/d.

The raw water quality is characterised by elevated concentrations of Total Organic Carbon, low turbidity and low alkalinity.

The facility also included suitable laboratory facilities onsite suitable for the conducting the jar testing and analysis of ballasting agent properties.

CHAPTER 2 - LITERATURE REVIEW

2.1. Introduction

The literature review has been undertaken in the context of ballasted flocculation for the treatment of drinking water. The literature review has discovered research on the underlying principles and connection to treatment process design considerations. The literature review was not able to discover many documented research projects on the application of knowledge in a full scale process. The literature review content has been extensively used from previous work for ENG4110 Engineering Research Methodology by the author.

2.2. Coagulation and ballasted flocculation

Coagulation is necessary to remove colloidal and suspended particles from water through the water treatment process. These particles would not otherwise settle or be removed by filtration as the negative surface charge repels the particles and they cannot aggregate to increase in size. A coagulant is added consisting of positively charged ions that destabilise the negative surface charge on particles (MWH 2012).

Coagulation chemistry does not appear to be impacted by the addition of a ballasting agent as they typically have a much lower charge density compared to colloidal materials (Young 2003). Additionally, as an observation schematics of ballasted flocculation processes in all cases indicate ballasting agent is added following the coagulation reaction. Through experimentation Young (2003) concluded that ballasting agent was not involved in coagulation chemistry.

2.3. Flocculation

Flocculation is of particular interest as this process is critical to the ballasted flocculation concept, especially as there is some inconsistency with regard to understanding how the ballasting agent is incorporated in the flocculation process. One line of understanding explains that floc particles adhere to the ballasting agent by using polymer as the “glue”, with further floc growth achieved through mixing and particle collision (Metcalf and Eddy 2014). An understanding in the 1980’s was that the mass of ballasting agent entrained suspended solids following addition of a coagulant (Sibony 1981). It is perhaps that these understandings may be correct where ballasting agent mass is significantly greater than that of the coagulant precipitate and solids to be removed.

Informative research that explains the interactions between ballasting agent and the flocculation process has been undertaken by Ghanem (2007). The aforementioned understanding was discussed and experiments were undertaken to observe the flocculation process with ballasting agent at a microscopic level. It was observed that instead of the ballasting agent acting as a ‘seed’ it was actually incorporated into already formed flocs through momentum resulting from mixing energies. Ghanem (2007) also found that due to random particle collision not all micro-floc may contain ballasting agent and that ongoing flocculation was necessary to create larger ballasted flocs.

The amount of ballasting agent that can be incorporated into formed flocs is dependent on the coagulant dose as described by numerous researchers. Young (2003) found that increasing the concentration of chemical coagulant precipitate increased the amount of ballasting agent that could be incorporated. It has also been observed through experiments that ballasting agent will continue to be incorporated into flocs until the flocs are unable to hold anymore (Ghanem 2007).

Polymers assist in flocculation as they act as a bridge between floc particles and create larger and stronger floc (MWH 2012). While the importance of polymer addition is understood to be critical in ballasted flocculation processes (Desjardins 1991), the literature does have inconsistency on the reasoning. Metcalf and Eddy (2014) states that polymer coats the ballasting agent and this allows floc to adhere, while Young (2003) describes that the ballasting agent is enmeshed in floc and that large floc is necessary for this. In the same research it was demonstrated that the timing of ballasting agent did not have to occur at the time of polymer addition, which would indicate the understanding that the polymer coating on ballasting concept may not be accurate.

The literature does not provide an optimal polymer dose for ballasted flocculation, rather they are for specific waters at the time. Each water type will have a different optimum type and dose of chemicals (Young 2003).

Research has also been undertaken with respect to mixing energy for flocculation incorporating a ballasting agent. The literature includes observations that with a ballasting agent, floc is more resistant to shearing from high velocity gradients and when floc breaks up the resulting smaller floc is rounder and denser than it would be without ballasting agent (Young 2003). The literature is consistent that mixing energies are much higher compared to non-ballasted flocculation processes (Young 2003, Lapointe 2016). Lapointe (2016) summarises that non-ballasted flocculation process utilise G values between $20s^{-1}$ and $50s^{-1}$, however notes in other research the G value was as high as $700s^{-1}$ without causing floc break up. The research by Lapointe (2016) found a lower maximum G value of $300s^{-1}$ before floc break up and attributes the difference in maximum G values to the variety of polymer charge and molecular weight combinations available. A major factor in needing higher mixing energies is to keep the ballasting agent suspended. Lapointe (2016) found that for a ballasting agent of silica sand with a diameter range of 45um-300um with mean diameter of 140um, the minimum mixing energy to maintain suspension was a G value of $165s^{-1}$, however ultimately concluded that the ballasting agent size and density will determine minimum mixing energies.

Lapointe (2016) also found that with higher mixing energies not all floc had embedded ballasting agent. In that research at a G value of $165s^{-1}$ all grains were embedded, however at a G value of $300s^{-1}$ grains greater than 190um were not embedded. Ghanem (2017) found that excessive mixing energies resulted in loss of ballasting agent that had been incorporated into flocs.

2.4. Sedimentation

The sedimentation process is where ballasted flocculation has significant advantages over conventional non-ballasted systems. Typical settling velocities for aluminium hydroxide precipitate flocs range from 2 m/h to 5 m/h (MWH 2012), whereas ballasted flocs can achieve settling rates of up to 85 m/h (Lapointe 2018). Research by Young (2003) recorded settling velocities up to 380 m/h.

The settling velocity of discrete particles is governed largely by the floc density, diameter and shape as described by equations initially developed by Isaac Newton (Davis 2013). Research by Young (2003) includes provision for a shape factor which can be significant for fractal shaped floc. Ultimately higher settling velocities occur with higher floc density, larger diameter and more spherical shapes.

The equations final form is:

$$V_s = \sqrt{\frac{4g(p_s - p)d}{3C_D \varphi p}}$$

Vs = terminal settling velocity (m/s)
g = acceleration by gravity (9.81 m/s/s)
ρ_s = bulk density of particle/floc (kg/L)
p = density of water (kg/L)
CD = drag coefficient
Φ = shape factor

Where:

$$C_D = \frac{24}{Re} + \frac{3}{Re^{0.5}} + 0.34$$

$$Re = \frac{V_s dp}{\mu}$$

Young (2003) described that the shape factor of over 20 for fractal floc. Lapointe (2017) states that density of non-ballasted floc has a density range between 1.03 and 1.05 and for ballasted flocs the density can range between 1.2 and 2.0, being cited from others research.

With respect to ballasted flocculation, Young (2003) attributed the high settling velocities of ballasted flocs to high densities, larger floc sizes and lower shape factor resulting from more spherical shapes as opposed to typical fractal shapes of unballasted flocs.

Higher floc densities are easily explained by the incorporation of the ballasting agent during the flocculation process. Ghanem (2007) found that increase in density is linearly proportional to the amount of ballasting agent incorporated.

The larger floc size of ballasted flocs may be attributed to the high polymer additions necessary for this process. Experiments by Ghanem (2017) found that floc size was smaller and larger ballasting agent was not incorporated when a lower molecular weight polymer was used in comparison to a higher molecular weight alternative. Young (2003) observed that ballasted flocs resist shear forces due to their roundness in comparison to fractal shaped un-ballasted flocs and a tighter ‘binding’ of the flocs. The explanation of ’binding’ is not adequately addressed in the research.

With regard to optimising sedimentation of ballasted flocs, Ghanem (2007) found that a greater floc diameter had the most beneficial impact on settling velocities in comparison to floc density and shape, so much so that process control should target this parameter.

2.5. Ballasting agent concentration

Research by Young (2003) studied the formation of flocs and settling rates using ballasting agent concentrations of 1.25g/L, 2.5 g/L and 5.0 g/L. The summary of results in the paper appears to include inconsistencies. One observation is that settling rates were significantly responsive to increased ballasting agent concentrations, whereas within the same paragraph it is observed that settling rates are independent of ballasting agent concentrations. Given the context of the particular summary, it may be the author should have noted the settled water turbidity was independent of ballasting agent concentration.

Experiments by Lapointe (2017) using surface waters found that a sharp decrease in settled water turbidity was achieved when ballasting agent is first added at low concentrations up to approximately 0.5mg/L and then following that further increases in ballasting agent concentrations provided much lower benefits. These experiments were across a range of ballasting agents.

As discussed in the literature review on flocculation, Young (2003) observed that beyond the capacity for floc to hold ballasting agent, additional ballasting agent will remain unincorporated.

Lapointe (2017) provides a helpful summary of optimal concentrations of ballasting agent (silica sand) by numerous researches; Lapointe (2017) 1-2 g/L, Sibony (1981) 0.8-1.8 g/L, Young (2003) 1.25g/L, Ghanem (2007) 5-7 g/L.

Upon review of the literature there is no concise data on the relationship between ballasting agent concentrations and settling velocities. It is suggested though that a minimum concentration is required for efficient sedimentation and beyond a maximum concentration there is little benefit.

2.6. Ballasting agent diameter

It was discussed in considering flocculation that floc characteristics and mixing energy can impact the particle size of ballasting agent that can be incorporated into flocs (Ghanem 2017).

Young (2003) undertook flocculation and sedimentation experiments with silica sand ballasting agent in size ranges 0.044-0.075mm, 0.075-0.11mm, 0.11-0.21mm and 0.21–0.3 mm. At a concentration of 5g/L all sizes provided acceptable flocculation and settling, although settling rates were not quantified. It was observed that a significant amount of the largest particles were not incorporated into flocs and that the smallest size contributed to settled water turbidity by remaining in suspension.

Lapointe (2018) found that when simulating a high rate clarifier of 30m/h (sampled at 12s), that increasing the ballasting agent mean equivalent diameter resulted in decreased settled water turbidity. This was less pronounced when sampled at 60s and 180s. These experiments used particle size ranges of 80-125um, 125-160um and 160-212um. In all cases the surface area of ballasting agent was kept constant at 0.045m2/L.

From the literature review it is suggested that an optimal ballasting agent diameter is the largest which can be successfully incorporated into the flocs, which is linked to floc characteristics, including polymer dosing and mixing energies.

2.7. Ballasting agent density

It was previously established that Lapointe (2016) found that minimum mixing energies were required to maintain ballasting agent in suspension and that the values were ultimately driven by the density and diameter of the ballasting agent.

Lapointe (2018) found that when simulating a high rate clarifier of 30m/h, that increasing the ballasting agent specific gravity decreased settled water turbidity due to higher settling velocity. This was most distinct between Granular Activated Carbon/Anthracite and silica sand. With ballasting agents denser than silica sand the trade off was un-ballasted flocs caused by the high mixing energies required service the heavier particles. In this work particle size distributions and surface areas were the same the across the different ballasting agents and only the density changed.

2.8. Ballasting agent surface area

Of particular interest is research undertaken by Lapointe (2018) which through experimentation investigated normalising ballasting agent concentrations to surface area instead of mass. The studies found that equivalent surface areas of ballasting agent (m^2/L) diminished the importance of ballasting agent concentration by mass, diameter and density. It is noted this finding was a better fit for simulating lower rate clarifiers and not as good when simulating higher rate clarifiers. For high rate clarifier situations the data does appear to be useful for silica sand, but not across a range of different ballasting agent densities.

Lapointe (2018) also described in the experiments that increased floc growth in terms of particle diameter increased proportional with increase ballasting agent surface area.

2.9. Full scale plant operation

The literature is significantly weighted toward investigating ballasted flocculation through laboratory scale experiments and aimed at understanding the underlying principles. Literature on investigating these underlying principles at full scale operation of a ballasted flocculation system is sparse.

One investigation that has been documented on a full-scale ballasted flocculation process in has been in California where the process was suffering operational difficulties (Pierpoint 2005). At full scale operation, there were difficulties with carryover of flocs and excessive sand loss. Investigations considered the underlying principles of flocculation mixing energies and hydraulic conditions as well as ballasting agent diameter and settling velocity (through surface loading rates). The investigations found a number of factors that when remedied resulted in better incorporation of ballasting agent, less unballasted floc carryover and sand loss.

The process parameters evaluated for the operational problems had good consistency with the underlying principles investigated and documented in other research at a laboratory scale and results reflected the expected outcomes based on the underlying principles.

Young (2003) states that research by others reported sand losses of less than 3mg/L of treated water. Pierpoint (2005) described for a full scale process with operational problems, the design sand loss was 22lb/million gallons (approx. 2.6 mg/L) treated water, however losses of 110lb/million gallons (approx. 13 mg/L) were experienced.

It is worth noting that while the underlying principles documented in laboratory scale experiments can be transferred to full scale process operations, the values may not. Young (2003) summarised that the optimum mix of coagulant, polymer and ballasting agent depended on the water quality being treated.

2.10. Knowledge gaps

From review of the literature it appears that there is a lack of documented research in how the underlying principles can be applied to full scale treatment processes. The laboratory scale experiments have been useful to research a number of important variables for ballasted flocculation including coagulation chemistry, flocculation and the effect of a number of ballasting agent properties with respect to these.

One gap in the research appears to be sedimentation, especially in relation to settling velocities for type II settling. Some research has considered ballasted flocs in the context of Type 1 discrete particle settling to demonstrate the theory of ballasted flocculation improving settling velocities such as Young (2003). Other research has considered turbidity removal in typical jar test experiments, typified by Lapointe (2018). The limitation in this approach is that the beakers are short and not representative of settling conditions in a full scale clarifier. In addition, the modelling of Type II flocculant settling is not reliable (MWH 2012).

It is proposed that to properly understand settling velocities and contaminant removal efficiencies in ballasted flocculation processes, it is necessary to undertake column settling experiments. These tests are described in Metcalf and Eddy (2014), and is essentially a tall column where sampling can be undertaken at time and distances (height/depth) in conditions more representative of a full-scale clarifier.

Another gap in the research appears to be the impacts of loss of ballasting agent from a full scale process. Laboratory scale experiments have a constant ballasting agent property profile, whether it be concentration or diameter. Of note is that published research to date has not included the consideration that full-scale systems recycle ballasting agent and what change may occur over time when sand loss occurs. In full-scale processes ballasting agent loss is expected and has been recorded. What is not documented is evidence of how this impacts the ballasted flocculation process. The literature explains that ballasted flocculation performance is not sensitive to ballasting agent concentration (above the minimum required), however it does explain that ballasting agent diameter and surface area are important factors. It is hypothesised that loss of ballasting agent may not be constant cross the range of particle distribution and that diameter and surface area may be significantly varied when loss occurs.

In summary, further research should be undertaken with respect to settling velocities and performance for Type II settling for ballasted flocculation and also with respect to the dynamics that sand loss from a full scale system and the impacts of this on the process.

CHAPTER 3 - RESEARCH METHODOLOGY

3.1. Introduction

This chapter describes the methodologies for sampling, measurement and modelling used for the examination of a ballasted flocculation process, particularly focused on dynamics of the ballasting agent.

Experiments and investigations for this research have been designed in a way to produce data that is directly relevant to the research objectives. Some of the theory and engineering practice is already highly developed and is included to quantify parameters of the particular ballasted flocculation process being investigated. Where the literature is silent, the methods for sampling and analysis have been developed for this research.

3.2. Analysis of ballasting agent properties

The ballasting agent was analysed for physical properties and quantities that may change over time in a full-scale ballasted flocculation process where ballasting agent is recycled continuously, including:

- Particle size distribution of ballasting agent in the process and the supply stock.
- Concentration of ballasting agent on a mass per volume basis in the process.
- Surface area of ballasting agent on an area per mass basis.

A sampling program was developed to produce sufficient data for analysis as summarised in Table 3-1.

Table 3-1:Sampling summary

Ballasting agent property	**Sampling requirements**
Particle size distribution (stock supply)	Minimum of weekly while particle size distribution in process is being sampled
Particle size distribution (process)	4 samples for each scenario • Fixed flocculation mixer speed and two different flow rates • Fixed flow rate and two different flocculation mixer speeds
Ballasting agent concentration	Target of 4 hourly samples over 12 hour period of operating full scale ballasted flocculation process. At two different flow rates through process.
Surface area of ballasting agent	The surface area of ballasting agent is to be calculated for all particle size distribution data

As ballasting agents consist of small granular materials, the definition and analysis of their physical properties is well established though methodologies used for geotechnical investigations of soils. The methodologies for sampling and preparing ballasting agent material from a full scale ballasted flocculation process however has not been documented in the literature. Methods to sample and prepare ballasting agent for analysis have been developed for this research.

3.2.1. Sample locations

A number of sample locations were selected for this research, in part to attain samples representative of the full-scale process and also to allow comparison where sample locations provide different results. The first location is for collection of samples for analysis of particle size distribution and surface area. Ideally this would be collected directly from the flocculation process, however this was not determined to be practical through initial investigations. The ballasting agent concentration was in the order of 5mg/L and to attain a suitable quantity of ballasting agent for analysis a sample of 10-20 Litres would need to be collected. This was found not to be practical as the amount of polymer contained in this sample size made concentrating and separating the ballasting agent difficult. The sample point chosen is the hydrocyclone underflow as it is representative of the ballasting agent being returned to the process and is at high concentrations, resulting in less sample volume being required. During initial investigations it was discovered that the concentration of ballasting agent in the hydrocyclone underflow is variable. It was observed that concentration variability was cyclic and corresponded to the sludge rake rotation.

This sample location was also used for one of two ways adopted to measure ballasting agent concentration and is the recommended location in the Operations and Maintenance Manual for this purpose.

The second sampling location is for collection of samples to analyse ballasting agent concentration in the process. This has been undertaken as initial investigations found the recommended methodology from the Operations and Maintenance Manual was difficult due to the high hydrocylcone underflow flow rates and the observed underflow variabilities.

The alternate sample location was used in this research to allow direct sampling from the flocculation process, thereby reducing effects of hydrocyclone underflow concentration variability. Initial investigations used a sample location within the maturation chamber in a well mixed area, however it was found that the concentration was variable depending on depth. A sample at 100mm below surface was 6.85 mg/L however a sample at 600mm was 7.19 mg/L. With the maturation chamber being 4m deep, there is potential that concentrations continue to increase with depth, in which case attaining a representative sample may require a more rigorous method. In addition, should there be very large particles of ballasting agent in the lower sections that do not contribute to the ballasted flocculation process (i.e. not being incorporated within the floc), the inclusion of these particles in the concentration statistics may mislead the research. The sample location selected for this research is at the midpoint of the narrowing between the maturation and sedimentation chambers, at a depth of 1200mm from the top of the structure (depth from surface level of water is dependent on flow rate through the process and is approximately 1000mm). At this point it is proposed that the sample will be representative of ballasted floc being introduced to the sedimentation process.

3.2.2. Sampling method for ballasting agent concentration

As previously discussed, two sampling methodologies have been selected to measure the ballasting agent concentration.

Initial investigations found that washing the sample over a 45 micron sieve was difficult due to flocculated particles blinding the apertures. The addition of Aluminium Chlorohydrate to the sample was found to assist. It is proposed that this occurs as an extreme dose of a cationic coagulant results in surface charge reversal and the particles are then re-stabilised (Metcalf and Eddy 2014, p. 470).

Methodology 1

This methodology has been adapted from the Operations and Maintenance Manual to use a much larger receiving vessel for the sample. Instead of the 1L graduated cylinder recommended, a 100L vessel on a trolley had been previously constructed by the equipment operator to improve this exercise and this was used in the research. The vessel dimensions are Width = 0.412m, Length = 0.412m, Height = 0.55m.

The apparatus required is:

- 100L vessel on trolley
- Stopwatch
- Measuring tape

The sampling procedure is:

- Remove pipework from hydrocyclone underflow
- Place vessel under hydrocyclone
- Start timing
- Fill vessel approximately 70L – 90L
- Remove vessel from underflow
- Stop timing
- Allow to settle for 3 minutes
- Using drain at vessel bottom, drain water out
    - Some sand will be lost at the drain outlet, however the remaining sand will be consolidated sufficiently
- Measure distance from top of vessel to sand surface
- Calculate volume of ballasting agent in sample, using the known vessel dimensions.

Methodology 2

This methodology was designed for this research as an alternative to the first methodology which has challenges with variability of the sample from the hydrocyclone underflow. As noted however, this methodology also has challenges as the ballasting agent appears to develop a concentration gradient across the flocculation chamber depth.

The apparatus required is:

- Sampling spear consisting of:
    - 12mm PVC pipe 1.2m in length.
    - 12mm PVC elbow and hose connector.
    - 12mm rubber hose 10m in length.
- 45 micron sieve.
- 1L graduated cylinder
- 10L bucket

The sampling procedure is:

- Place sampling spear in sample location with hose over side of ballasted flocculation structure
- Start siphon through sampling spear, drawing a continuous sample.
- Take samples from hose end on ground level.
- Take 100ml sample every 10 seconds from sample stream and combine in a container (e.g. 10L bucket) until 800mL – 1000mL is collected.
- Measure liquid component of sample in a 1L graduated cylinder, allowing ballasting agent that has settled to remain in container
- Return contents of 1L graduated cylinder to container
- Add 5mL Aluminium Chlorohydrate to container, stir and leave for 5 minutes to reverse flocculation and degrade polymers
- Wash liquid component of sample over 45 micron sieve thoroughly, allowing ballasting agent that has settled to remain in container. Wash ballasting agent again in container and wash over sieve.
- Gently disturb any polymer residue by hand and continue washing until no evidence of polymer remains
- If polymer is not degrading, repeat soak in Aluminium Chlorohydrate with ballasting agent and repeat wash over 45 micron sieve
- Wash ballasting agent from container onto 45 micron sieve and wash sample thoroughly.
- Allow to drain on 45 micron sieve.

3.2.3. Sampling method for ballasting agent particle size distribution

The method for sampling ballasting agent in a full-scale ballasted flocculation process has not been previously described in the literature. The sampling methodology for this research has been determined though experimentation and a composite sampling approach is proposed.

The apparatus required is:

- 4 x 120 mL plastic sample jars with lids.
- Stop watch.

The procedure is:

- Take four composite samples at a time interval of T_S.

$$T_S = \frac{\left(\frac{T_R}{A}\right)}{4}$$

Where:

T_S = time interval between samples
T_R = time for full rotation of sludge rake
A = number of arms of sludge rake

- The first sample is to be taken when the ballasting agent return is highly concentrated due to the sludge hopper being filled. The three subsequent samples are to be taken at the calculated frequency and be completed before the ballasting agent becomes concentrated again.
- Fill each 120mL sample bottle carefully, using the lip to intersect the ballasting agent return stream. Do not allow sample bottles to spill over.
- Combine the supernatant of the four composite samples in a 1L beaker and allow the majority of ballasting agent to remain in the sample bottles
- Add 200mL Aluminium Chlorohydrate to the 1 L beaker and stir
- Add 5mL Aluminium Chlorohydrate to each of the sample bottle where the ballasting agent will largely be retained, replace lids and shake vigorously.
- Allow all sample components to sit for 10 minutes
- Wash sample thoroughly over a 0.045mm sieve until only the ballasting agent remains, not allowing any ballasting agent to be washed out of the sieve.
- Allow to drain on sieve.

3.2.4. Analysis method to calculate ballasting agent concentration

The analysis requirements are different for the two methodologies used.

Methodology 1

The ballasting agent concentration is then calculated by:

$$C = \frac{V * 1700 * 1000}{Q * t}$$

Where:

C = ballasting agent concentration (g/L)
V = volume of ballasting agent (m^3)
1700 = bulk density of ballasting agent used (kg/m^3)

Q = process inflow (L/s)
t = time to take sample (s)

Methodology 2

- Dry ballasting agent sample retained on 45 micron screen (from sampling method previously described) in oven at 110°C until constant weight is attained.
- Place clean dry container on balance
- Transfer sample retained into container, lightly brush out any residues and weigh contents. Record weight.
- Calculate the concentration
    - Sample weight / sample volume = concentration g/L
    - Noting sample volume is the liquid sample volume from the sampling methodology previously described.

3.2.5. Analysis method to calculate Particle Size Distribution (sampled from process)

Methods to measure particle size distribution are well established and multiple standards are documented in the literature. For this research the following Australian Standards were referred to:

- AS 1141.11.1-2020 Methods for sampling and testing aggregates – Method 11.1: Particle size distribution – Sieving method.
- AS 1141.12-2015 Methods for sampling and testing aggregates – Method 12: Materials finer than 75um in aggregates (by washing).

The Australian Standard procedures were adapted to for this research to reflect the equipment being used, increase safety and rationalise the methodology to increase acceptance operational staff in future scenarios. The procedure modifications are described in Table 3-2.

Table 3-2: Departure from AS114.11.1 summary

Australian Standard procedure	**Modified procedure**	**Comments**
AS114.11.1-2020 Section 6.1 Minimum mass of test portion for fine aggregate to be 150g	Test portion to be between 80g – 100g	This limits the mass of sample retained on individual sieves so as not to require second secondary sieving as per Table 2 of AS114.11.1-2020. The potential for error from smaller portions of sample retained on individual sieves is managed by using a balance with an accuracy of +/- 0.1g rather than the +/- 0.5g recommended in AS114.11.1-2020. This also reduces the time which hand agitation is required, reducing manual handling associated injuries.

AS114.11.1-2020 Section 6.6 or AS1141.12-2015 All materials finer than 75 micron are to be measured by washing through a 75 micron sieve.	Materials finer than 75 micron to be mechanically sieved through 75 and 45 micron sieves.	The Australian Standard methods do not allow differentiation of particle sizes less than 75 micron. This research requires particles retained on a 45 micron sieve to me measured. The ballasting agent consists of discrete and rounded particles that are unbound and by observation are able to freely pass through sieves when dried.

The apparatus used in this research is:

- 200mm diameter sieves (in microns - 850, 425, 300, 250, 150, 75, 45 and pan).
- Balance with +/- 0.1g accuracy.
- Sieve brush.
- 2 x 1L beakers.
- 1 x 50mL beaker.

The procedure as adapted is:

- Dry ballasting agent sample retained on 45 micron screen (from sampling method previously described) in oven at 110°C until constant weight is attained.
- Transfer to 1L beaker and mix the dry sample well
- Measure out between 80g-100g of sample, not seeking an exact target mass, into a separate container
- Record sample weight
- Assemble sieve stack
- Remove lid of sieve stack and transfer weighed sample to 850 micron sieve, lightly brush out any residues and replace lid.
- Agitate sieve rigorously by hand for 2 minutes 30 seconds
- Place clean dry container on balance
- Starting with 850 micron sieve, transfer sample retained into container, lightly brush out any residues and weigh contents. Record weight.
- Repeat for all other sieves and pan, recording the accumulating weight as the contents of each sieve is measured.
- Calculate the percent passing for each sieve size
    - (Sample weight – accumulated weight) / sample weight x 100
- Plot the percent passing.

3.2.6. Analysis method to calculate Particle Size Distribution (stock product)

The method to measure particle size distribution for the stock product is the same as described for samples taken directly from the ballasted flocculation process. However the sample is taken directly from the bulk bag as delivered and will not require the same preparation and washing as samples taken from the process will.

3.2.7. Analysis method to calculate surface area

The method of determining surface area of the ballasting agent has been adapted from work undertaken by Lapointe (2018) to allow comparison of the research outcomes with the existing limited literature. It is important to note the method assumes a particle size that is the mean size of the large and smaller sieve apertures used to separate the particles and also that particles are spherical.

The following steps are followed in order to calculate the particle surface area.

$$D = \frac{d_1+d_2}{2}$$

$$V = \frac{\pi * D^3}{6}$$

$$M_1 = V * SG$$

$$N_0 = \frac{M_T}{M_1}$$

$$S_1 = \pi * D^2$$

$$S_T = S_1 * N_0$$

Where:
D = mean particle diameter (m)
d_1 = diameter passing upper sieve for particle analysis (m)
d_2 = diameter passing lower sieve for particle analysis (m)
V = volume of spherical particle with mean diameter D (m^3)
M_1 = mass of particle with mean diameter D and volume V (kg)
SG = specific gravity of particle (kg/m^3)
N_0 = number of particles with mean diameter D
M_T = Mass of ballasting agent sample (kg)
S_1 = Surface area of particle with mean diameter D (m^2)
S_T = Surface area of ballasting agent sample (m^2)

For this research, this method is applied to data attained from analysis of the ballasting agent concentration and the particle size distribution as described in previous sections.

The procedure is:

- Calculate mean particle diameters for each sample portion
- Calculate surface area for each sample portion
- Calculate total surface area for sample (sum of all sample portions)
- Calculate specific surface area
    - Surface area of sample / sample weight = specific surface area (m^2/g)

3.3. Process model

A model of the full-scale ballasted flocculation process being used in this research was required to evaluate, explain and provide context to the data being generated. The model was developed using Microsoft Excel and based on established and well documented engineering principles for water treatment. The model is constrained to the processes relevant to the research.

3.3.1. Input information

The model requires the following input information:

- Flow rate through the ballasted flocculation process.
- Water temperature.
- Ballasting agent properties.
- Dimensions of coagulation, flocculation and sedimentation basins.
- Coagulation and flocculation impeller speed, diameter, power number.
- Sludge waste rate.

3.3.2. Output information

The model provides the following outputs:

- Water properties (density, viscosity).
- Coagulation, flocculation detention times.
- Coagulation, flocculation velocity gradient (S^{-1} and Gt values).
- Surface loading rate in sedimentation basin.
- Minimum particle settling velocity removed in settling tubes

The model also examines the minimum size of a discrete ballasting agent particle that would be retained in the system.

The model includes preliminary work to estimate the ballasting agent particle size that is suspended in the flocculation chamber, though further work is required before this can be applied to the full-scale process.

3.3.3. Coagulation calculations

The formation of floc requires suitable mixing to allow stabilised particles to aggregate and increase in size and density. The engineering parameters to be calculated for the coagulation process are:

- Velocity gradient (G)
- Gt

The full-scale flocculation process parameters are recorded in Table 3-3.

Table 3-3: Coagulation process parameters

Parameter	**Value**	**Source of information**
Chamber dimensions	4.178m (W) 2.379m (L) 3.180m (H)	Drawing.
Motor size	4kW	Electrical load list
Motor efficiency	88.6%	Electrical load list
Power factor	0.83	Electrical load list
Shaft speed (maximum)	70.7 rpm (1.18 rps)	Name plate
Impeller type	4 blades – high solidity hydrofoil	Inspection
Impeller diameter	1.283m	Name plate

The input power to the flocculation mixer is critical to calculate the velocity gradient. Calculations related to input power from the impeller are utilising equation 5-9 from Metcalf and Eddy (2014):

$$P = N_p p n^3 D^5$$

Where:
P = input power (Watts)
Np = Power number
p = mass density of fluid (1000 kg/m^3)
n = impeller speed r/s
D = impeller diameter (m)

Initially the impeller was assumed to be a pitched blade turbine, however the input power calculated at the full design speed was in excess of the motor size provided, indicating the impeller is of a different category. The impeller power number N_P is calculated by rearranging the equation and assuming that the motor capacity is fully utilised at full design speed. This is of particular interest as the mixer motor speed is variable and variable speeds may be selected in the process model.

$N_P = P/pn^3D^5$

$N_P = (4000W) / 1000 \times 1.18^3 \times 1.283^5 = 0.7$

This neatly aligns with the typical value of a high solidity hydrofoil as suggested by Grenville (2017). The velocity gradient in this chamber is calculated using equation 5-3 from Metcalf and Eddy (2014):

$$G = \sqrt{\frac{P}{\mu V}}$$

Where:
G = velocity gradient (s^{-1})
P = Input power from impeller (Watt)
μ = N.s/m2
V = volume of chamber (m^3)

Adjustment of density and viscosity of water based on temperature were taken from Appendix A of Davis (2013)

Gt is simply G multiplied by the detention time in the chamber.

The calculations described in this section have been used in development of a process model in Microsoft excel.

3.3.4. Flocculation calculations

Flocculation is required to allow coagulated particles to be further increase in density and grow in diameter to facilitate settling. The engineering parameters to be calculated in for the coagulation process are:

- Velocity gradient (G)
- Gt

The parameters known are recorded in Table 3-4.

Table 3-4: Flocculation process parameters

Parameter	Value	Source of information
Chamber dimensions	4.178m (W) 4.145m (L) 3.765m (H)	Drawing.
Motor size	4kW	Electrical load list
Motor efficiency	88.6%	Electrical load list
Power factor	0.83	Electrical load list
Shaft speed (maximum)	28.2 rpm (0.47rps)	Name plate
Impeller type	4 blades – high solidity hydrofoil	Inspection
Impeller diameter	2.11m	Name plate

The methods to calculate the impeller characteristics, G and Gt are described in the coagulation section.

$N_P = P/pn^3D^5$

$N_P = 4000W / 1000 \times 0.47^3 \times 2.11^5 = 0.92$

By inspection the mixing impeller is of the high solidity hydrofoil type as seen in Figure 3-1. A typical pump number of 0.7 is suggested for this type of impeller by Grenville (2017).

It is proposed that the calculation method as undertaken could return a high pump number if the motor size was of greater capacity than required. This could be considered likely as electric motor capacities are standardised.

Figure 3-1: Flocculator impeller

3.3.5. Settling tube calculations

The full-scale ballasted flocculation process is fitted with settling tubes above the sedimentation zone. These are 0.120m x 0.05m in cross section per tube and 0.88m in depth. As the tube dimension is rectangular, they are considered to act as inclined plates. Formulas to determine the minimum particle settling velocity removed through the settling tubes have been taken directly from MWH 2012.

$$v_s \geq \frac{v_{f\theta} d}{L_p \cos\theta + d \sin\theta}$$

$$v_{f\theta} = \frac{Q}{A \sin\theta}$$

V_s = settling velocity of particle (m/s).
$v_{f\theta}$ = fluid velocity (m/s).
d = distance between plates (m).
θ = angle of plates (degrees).
Q = flow rate (m^3/s).
A = surface area of sedimentation zone (m^2).

3.3.6. Minimum ballasting agent particle diameter retained in sedimentation zone

As the research is investigating the dynamic behaviour of ballasting agent, the model considers the settling velocity of discrete particles of ballasting agent. While ballasting agent is ideally fully incorporated into flocs before reaching the sedimentation zone, any free particles will need to settle on their own to be retained and returned to the process.

The model calculates discrete particle settling as follows:

Equation 5-18 from Metcalf and Eddy (2014) describes the terminal velocity of a discrete particle when settling.

$$v_{p(t)} = \sqrt{\frac{4g}{3C_d\phi}(sg-1)d_p}$$

Equation 5-19 from Metcalf and Eddy (2014) described the calculation of the drag co-efficient.

$$C_d = \frac{24}{R_e} + \frac{3}{\sqrt{R_e}} + 0.34$$

Equation from 5-21 Metcalf and Eddy (2014) describes the calculation of Reynolds number

$$R_e = \frac{v_p d_p p_w}{\mu}$$

Where:
$V_{p(t)}$ = particle terminal velocity (m/s).
g = acceleration of gravity 9.81 m/s/s.
C_d = Coefficient of drag.
sg = specific gravity of particle.
d_p = diameter of particle (m).
R_e = Reynolds number.

p_w = density of water (kg/m^3).
ϕ = shape factor .
μ = dynamic viscosity of water N.s/m$^{2.}$

The shape factor of 2 for sand has been adopted for the sand ballasting agent being researched to align as this has been reported by Young (2003) and Metcalf and Eddy (2014).

The terminal velocity of a settling particle using these equations is solved through iteration, as the velocity requires the input of a Reynolds number value, which in turn requires a velocity.

The model calculates the minimum particle size that can be retained in the sedimentation zone.

It is most important to note that the model combines the discrete particle settling velocity and calculations for the minimum particle settling velocity removed within the settling tubes.

The process model has been developed to solve this iterative process through the "goal seek" function of Microsoft Excel, which is run by a macro for ease. It appears that for some scenarios multiple solutions may exist however only one is correct. To overcome this two solve functions have been developed, one starting the iterations from a very high particle diameter and the second from a very low particle diameter. The model includes diagnostics to compare the calculated terminal velocity for the particle diameter compared to the upflow velocity of the sedimentation zone to ensure they match.

3.3.7. Ballasting agent suspension

The model considers calculations for suspension of particles in the flocculation chamber. Specifically, the model aims to calculate the impeller speed required which is just sufficient to achieve off-bottom suspension of ballasting agent particles. The Zwietering correlation has been used as described by Kresta (2016).

$$N_{js} = S\frac{v^{0.10}d_p^{0.20}X^{0.13}\left(\frac{g\Delta p}{p_L}\right)^{0.45}}{D^{0.85}}$$

$$X = \frac{100Cp_s}{p_L(p_s - C)}$$

Where
N_{js} = just suspended speed (rpm)
S = Zwietering S factor
v = kinematic viscosity
d_p = particle diameter (m)
X = Zweietering mass ratio
p_s = particle density (kg/m^3)
p_L = density of liquid (kg/m^3)
$\Delta p = p_s - p_L$ (kg/m^3)
D = impeller diameter (m)
C = particle concentration (kg/m^3)

Important factors are the type of impeller, ratio of diameter impeller to tank diameter (D/T) and ratio of the impeller height to the total tank height (C/T). The following were adopted after inspection of drawings for the full-scale ballasted flocculation process.

Flocculation chamber diameter = 4.178m.
Impeller diameter = 2.108m.
Impeller height from bottom = 1.0m (assumed).
D/T = 0.5.
C/T = 0.23.
S = 7.7 (Kresta 2016).

The value of S has been taken from tables of empirically derived constants and provided by Kresta (2016) for D/T = 0.5, C/T = 0.33 for a HE-3 impeller (a 3-bladed, narrow blade hydrofoil which was closest approximation to full-scale impeller in the data set).

The Microsoft Excel model uses the goal seek function to solve for the particle size suspended where N_{js} is equal to the flocculator impeller speed in the model. A macro was developed for ease of running the goal seek function.

3.4. jar testing

Jar testing was undertaken to examine the impact of changing ballasting agent properties has on a ballasted flocculation process. The usefulness of a laboratory scale process is that it can be performed in a controlled setting whereas the full-scale process has variables that cannot be fully accounted for, such as fluctuations in flow, chemical dosing, start-up/shut downs and hydraulic inlet/outlet conditions.

The methodology though has been adapted to mimic the full-scale process as close as possible. The jar testing methodology has been based on operating conditions of the full-scale process as recorded in Table 3-5.

Table 3-5: Typical operating conditions

Parameter	Value
Water temperature (C)	16
Flow rate (L/s)	220
Coagulant dose – ACH (ppm v/v)	120
Polymer dose rate (mg/L)	1.10
Coagulation time – hydraulic mix (s)	390
Coagulation energy – hydraulic mix (Gt)	unknown
Coagulation time – mechanical mix (s)	84.5
Coagulation energy – mechanical mix (Gt)	9264
Flocculation time (s)	287
Flocculation mixing energy (Gt)	20813
Clarifier overflow rate (m/h)	46.1

There are potentially many parameters to observe or measure with respect to how the ballasting agent interacts with the floc. These investigations have been described in the literature. In this jar testing exercise it is the overall performance of the ballasted flocculation process which is of interest.

Settled water turbidity was used as the parameter to represent the overall performance of the ballasted flocculation process. It is proposed that low settled water turbidity will result where a high number of flocs have been successfully ballasted. Conversely, high settled water turbidity would be expected as the result of flocs being poorly ballasted.

3.4.1. Jar test alignment to full-scale process

The differences between the full-scale ballasted flocculation process and the standard jar testing equipment are significant, particularly with regards to scale, geometry, mixer type and process configurations. The jar test equipment therefore cannot be simply set to the same mixer speed and detention time as the full-scale process as the parameters for velocity gradient (G) and Gt will not be correct.

Preliminary investigations found the flat blade turbine impellers of the standard jar test equipment were not suitable to study ballasted flocculation. The rotation speed necessary to suspend the ballasting agent caused excessive velocity gradients and floc could not be properly formed using chemical dose rates similar to the full-scale process. A modified impeller was constructed in the form of a 45 degree pitched blade turbine (2 blades), using aluminium ‘angle’ section. This was found to achieve ballasting agent suspension at lower rotational speeds and floc formation was adequate.

To determine the velocity gradients created with the modified impeller, the power input had to be calculated. The impeller diameter was 70mm and the appropriate power number adopted as 1.6 from Metcalf and Eddy (2014) Table 5-11. The methodology to calculate the power requirement is detailed in section 3.3.

Taking into account the rotational speed of the jar test impellers to maintain suspension of the ballasting agent, the differences between the jar test equipment and the full-scale process and the need to operate the equipment in an efficient and repeatable way, the jar test procedure decided as best on balance is recorded in Table 3-6.

Table 3-6: jar test program

Process	**Jar test impeller speed (rpm)**	**Time (s)**	**Comments**
Add NaHCO3	150	120	
Add ACH	50	240	Gt = 8,867
Condition for flocculation	150	30	
Add ballast agent + poly	150	90	Gt = 17,278
End	0		

The sampling of settled water to measure turbidity also requires consideration as with ballasted flocculation the flocs will settle rapidly. The design overflow rate in the full-scale clarifier process is 75m^3/m^2/d (75m/h or 20.8mm/s). It therefore could be said that all ballasted flocs should be absent from a sample location 50mm below the water surface during settling in 2.4

seconds. Unballasted alum based floc has a settling velocity range between 2m/h and 5.5m/h (0.55mm/s to 1.53mm/s). Therefore the same sample location 50mm below the water surface would need to be sampled within 32 seconds to ensure unballasted flocs were properly represented in the sample.

However, preliminary investigations found that conditions within the jars were highly turbulent immediately after the impellers were stopped due to the high impeller speeds and the down-pumping circulation induced by the modified pitched blade turbine impeller. Under these conditions it was not possible to differentiate well ballasted flocs from poorly ballasted flocs within the very short time frames theoretically derived.

An alternate approach was adopted, where samples were collected 50mm below the surface every 30 seconds from immediately after the impellers were stopped for 2 minutes (6 samples in total). Ideally a resolution less than 30 seconds would be used, however as the sample is taken by hand, a resolution less than 30 seconds would be difficult to repeat with an acceptable margin of error.

Samples were taken using a 50mL syringe, with sufficient syringes so that all samples can be collected and analysed afterwards. It is noted that as samples will sit for some time, the syringes were slowly rotated 10 times to resuspend any particles that had settled and agglomerated. As the sampling requirements require close attention, only one jar can be used per experiment, which is significantly different to the typical practice of running up to 6 jars in a single experiment. Therefore the same experiment is to be run three times.

The apparatus and materials required are:

- Stock solution of sodium bicarbonate (1% strength)
- Stock solution of ACH (1% strength)
- Stock solution of poly (0.025% strength)
- 5mL syringe x 1
- 10mL syringe x 2
- 50mL syringe x 6
- Jar test machine with pitched blade turbine impellers
- 1 L square jars to suit jar tester
- Timer
- Ballasting agent x 1kg
- Sieves – 0.075mm, 0.150mm, 0.250mm (depending on experiment)
- Scales
- Small dishes to hold ballasting agent samples
- Turbidity analyser.

The turbidity analyser used for this research was a Hach TU5200.

The procedure specifically adapted for this research was:

Step	Time elapsed (s)	Process	Jar test impeller speed rpm
1	0	Add NaHCO3	150
2	120	Add ACH	50
3	360		150
4	390	Add ballasting agent + poly	150
5	480	Stop jar test machine	0
6	480	Take sample 1	0
7	510	Take sample 2	
8	540	Take sample 3	
9	570	Take sample 4	
10	600	Take sample 5	
11	630	Take sample 6	
12		Analyse samples 1 to 6 for turbidity	

3.4.2. Jar test experiment scenarios

The following jar tests are proposed to inform the research.

Test 1 – control (no ballasting agent)

The aim of this experiment is to determine what settled water turbidity is expected with no ballasting agent. While this scenario is not anticipated for the full-scale process, it will provide a upper limit for performance that may occur where flocs are poorly ballasted.

The chemical dosing regime has not altered from subsequent jar tests where ballasting agent is added.

Three individual experiments are to be run with one jar each.

Settled water turbidity has been used to measure performance.

Test 2 – performance as designed

The aim of this experiment was to analyse the performance of the ballasted flocculation process using a ballasting agent to mimic the design particle size distribution and concentration by mass as recommended in the Operation and Maintenance Manual for the full-scale process.

To approximate design recommendations as closely as possible, a 6g sample of ballasting agent passing through a 0.150mm sieve and retained on a 0.075mm sieve has been used.

Three individual experiments are to be run with one jar each.

Settled water turbidity has been used to measure performance.

Test 3 – increase in particle size distribution, constant mass

The aim of this experiment was to analyse performance of the ballasted flocculation process when the ballasting agent particle size increases, while the concentration by mass remains constant.

A 6g sample of ballasting agent passing through a 0.250mm sieve and retained on a 0.150mm sieve has been used.

Three individual experiments are to be run with one jar each.

Settled water turbidity has been used to measure performance.

Test 4 – increase in particle size distribution, constant surface area

The aim of this experiment was to analyse performance of the ballasted flocculation process when the ballasting agent particle size increases, while the concentration by surface area remains constant.

The methods of calculating surface area for ballasting agent have been described in section 3.2.7.

6 g/L of ballasting agent with particles in the range between 0.075mm – 0.150mm has a surface area of 0.12 m^2.

To attain the same surface are of 0.12 m^2 with a ballasting agent with particles in the range between 0.150mm – 0.250mm, a mass of 10.7g is required.

Therefore jar tests were conducted with 10.7g/L of ballasting agent with particles in the range between 0.150mm – 0.250mm.

Three individual experiments are to be run with one jar each.

Settled water turbidity has been used to measure performance.

CHAPTER 4 - RESULTS AND DISCUSSION

4.1. Introduction

This chapter describes the data and observations which have resulted from performing the experiments and investigations aligned with the project objectives and previously described methodologies.

The results for ballasting agent properties are presented first as both modelling and jar testing occurred concurrently and afterwards as iterations were necessary to better reflect the data provided by the full-scale ballasted flocculation process.

The data is presented and discussed in this section.

4.2. Ballasting agent Particle Size Distribution

This research has analysed the particle size distribution of ballasting agent both as stock material and in-process after being subjected to continuous recovery and recycling and under a range of operating scenarios. The following ballasting agents were analysed:

- Ballasting agent as specified in Operations and Maintenance Manual for the full-scale process.
- Ballasting agent as purchased and added to make up for loss from the full-scale process.
- Ballasting agent sampled in-process:
    - Control period of stable operation (220 L/s)
    - At a higher flow rate (250 L/s)
    - At higher flow rate (250 L/s) and higher flocculation energy
    - At the control period flow (220 L/s) and higher flocculation energy, AND a change in ballasting agent stock material particle size distribution.

4.2.1. Particle size distribution – design ballasting agent

A proprietary ballasting agent is recommended for use in the full-scale ballasted flocculation process in the associated Operation and Maintenance Manual. It is noted that the design ballasting agent has a very uniform distribution curve with particle diameters ranging between 0.04mm – 0.2mm, with an effective size (d10) of 0.075mm and a Coefficient of Uniformity < 1.7 (name withheld, 2014).

The design ballasting agent is specified as being made from crushed "sea pebble" having a specific gravity of 2.65.

The particle size distribution has been reproduced from data in the Operations and Maintenance Manual in Figure 4-1. This material was not physically measured in this research.

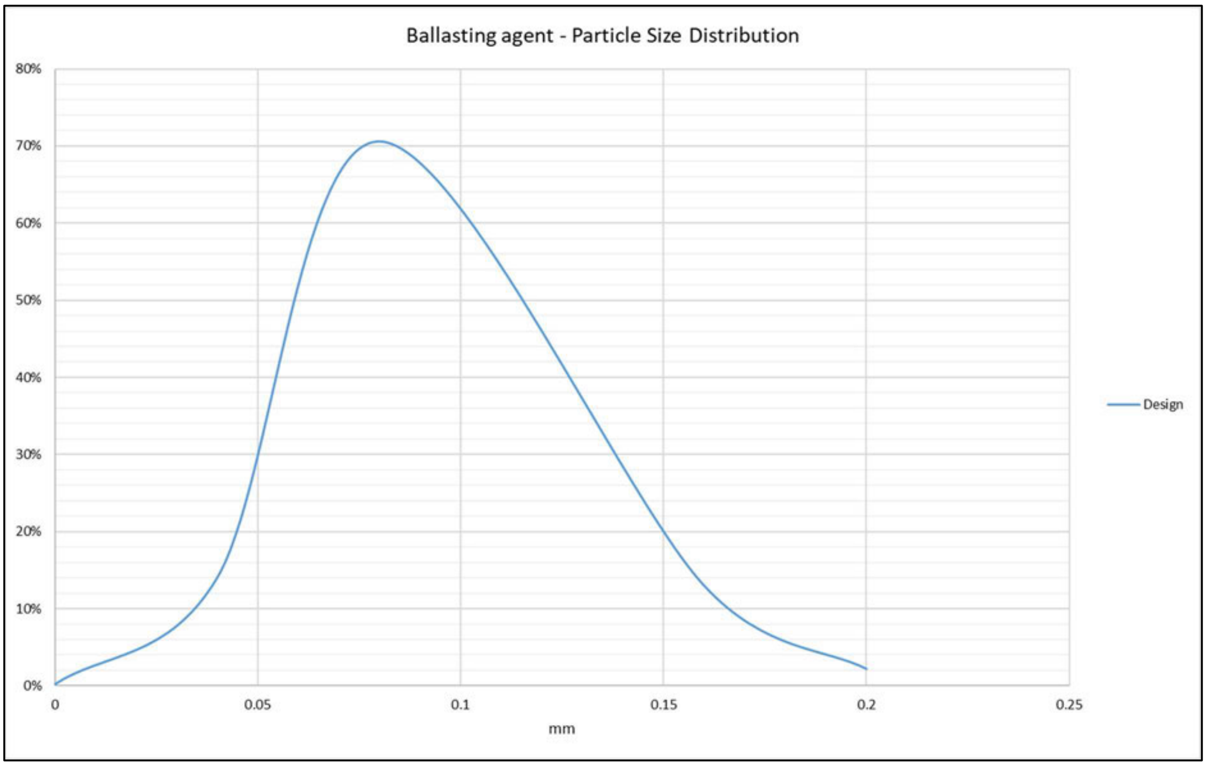

Figure 4-1: particle size distribution as designed

4.2.2. Particle Size Distribution – stock ballasting agent

The stock material added to the full-scale ballasted flocculation process is not the proprietary product and a locally supplied material is used due to lower cost and reportedly a lower mass of ballasting agent being lost on a daily basis (M Little, pers. comm 2022). The ballasting agent is locally sourced sand that has been graded and kiln dried. It is assumed the sand is silica, having a SG of 2.65.

The stock material as used was sampled from the site and the particle size distribution analysed. The data demonstrated that the stock material ranges in size between 0 – 0.5mm. The stock material has a non-uniform distribution curve with the majority of particles (55%-63%) in the range of 0.075mm.

The stock material being used as ballasting agent in the full-scale ballasted flocculation is an approximation of the design ballasting agent, having a higher portion of larger diameter particles and less fines. The stock ballasting agent particle size distribution is compared to the design ballasting agent in Figure 4-2.

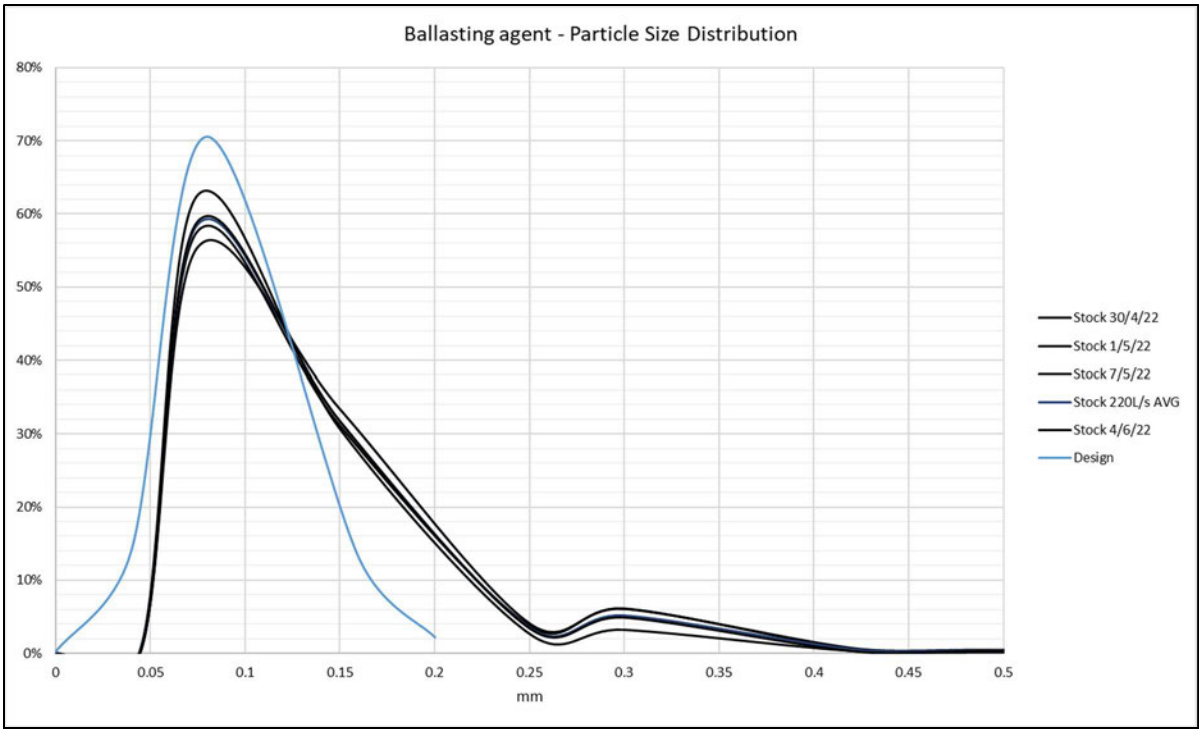

Figure 4-2: particle size distributions - design and stock ballasting agents

4.2.3. Particle size distribution – control period

Ballasting agent was sampled directly from the full-scale ballasted flocculation process which has been subject to continuous recovery from the sedimentation chamber and recycling to the flocculation chamber. Measurements were taken over a period where operational parameters were stable. Flow rate through the process was 220 L/s and the flocculator mixing speed was 25 Hz on the variable speed drive, equating to 14.1 rpm for the flocculator impeller.

Eight samples were collected and analysed over a period of 9 days.

The particle size distribution was found to be different to the stock material being added to make up for ballasting agent loss over the same period. Measurement by sieve analysis has shown that the ballasting agent sampled directly from the process has the same range of particle diameters, however the larger particles become dominant in proportion. The stock material was found to have the highest portion of particles retained on a 0.075mm sieve, whereas the in-process samples had the highest proportion retained on a 0.150mm sieve as shown in Table 4-1.

Table 4-1: particle size distribution - control period

Particle diameter (mm)	**Stock material % retained on sieve**	**In-process (control) % retained on sieve**
Pan	0	0
0.045	0.2 – 0.6	0
0.075	**55.4 – 62.5**	7.0 – 14.1
0.150	30.7 – 33.4	**36.8 – 41.8**
0.250	2.7 – 4.1	20.4 – 22.1
0.300	3.2 – 6.2	24.4 – 29.1
0.425	0.2 – 0.5	1.4 – 2.21
0.500	0.1 – 0.4	1.1 – 1.9
No. samples	3	8

Individual measurements have been graphed in Figure 4-3.

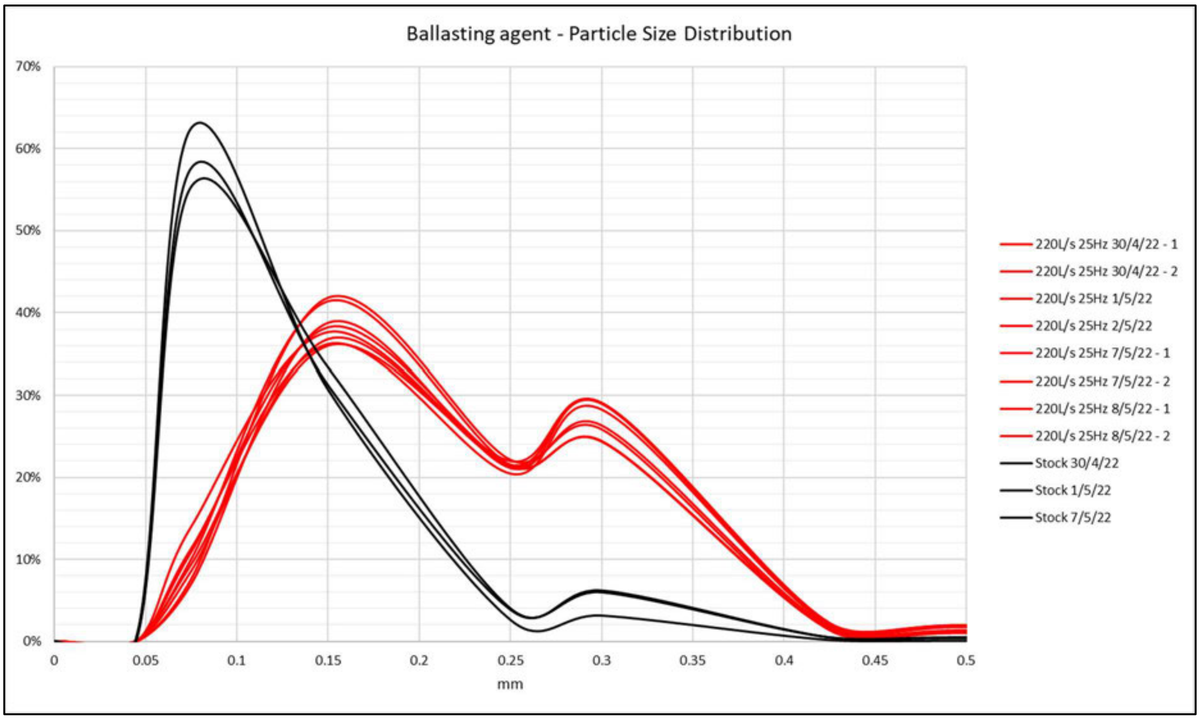

Figure 4-3: particle size distribution - control period

Effective size and coefficient of uniformity have also been calculated as summarised in Table 4-2.

Table 4-2: particle size parameters - control period

Parameter	**Stock material**	**In-process (control)**
Effective Size (d10) mm	0.09	0.13 – 0.16
d60 mm	0.15 – 0.16	0.27 – 0.28
Median Particle Size (d50) mm	0.13 – 0.14	0.25 – 0.26
Coefficient of Uniformity CU (d60/d10)	1.7 – 1.8	1.8 – 2.1
No. samples	3	8

Particles size distribution as percent finer has been calculated as shown in Figure 4-4.

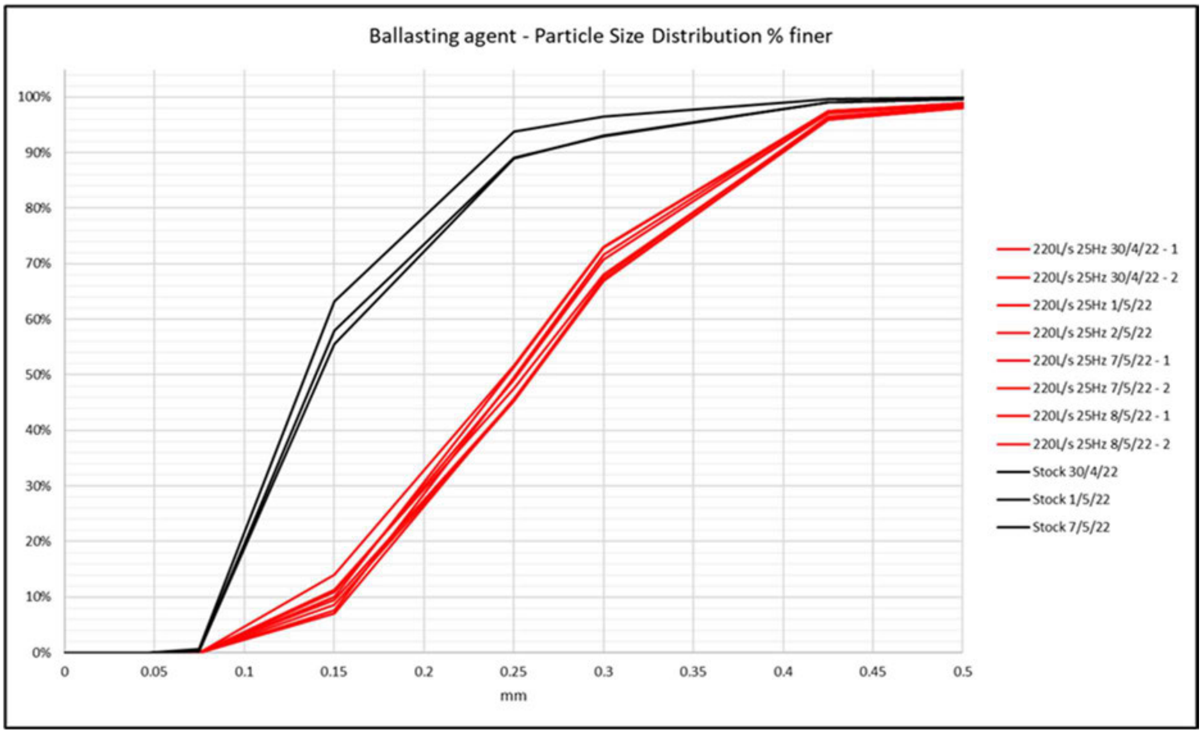

Figure 4-4: % finer curves - control period

4.2.4. Particle Size Distribution – Increased flow rate

The same measurement techniques for the control period were applied following an increase in flow through the full-scale ballasted flocculation process. The flow was increased from 220 L/s as used in the control period to 250 L/s. The flocculator mixing speed was maintained constant at 25Hz on the variable speed drive equating to 14.1 rpm impeller speed. The stock material particle size distribution was measured and it was found to be identical to the average of values measured during the control period. Three samples were collected and analysed over the course of one day.

At the higher flow rate, the particle size distribution of in-process ballasting agent was found to further depart from the stock material particle size distribution, with highest portion being retained on a 0.3mm sieve as shown in Table 4-3.

Table 4-3: particle size distribution 250 L/s

Particle diameter (mm)	Stock material % retained on sieve	In-process (250L/s, 25 Hz) % retained on sieve
Pan	0	0
0.045	0.4	0
0.075	**58.5**	6.4 – 9.2
0.150	31.7	20.6 – 22.4
0.250	3.5	23.3 – 24.6
0.300	5.1	**39.2 – 42.5**
0.425	0.4	2.9 – 3.6
0.500	0.3	2.5 – 3.2
No. samples	1	3

The particle size distribution of ballasting agent sampled from the process at 250 L/s is graphically represented in Figure 4-5, including a comparison to measurements from the control period.

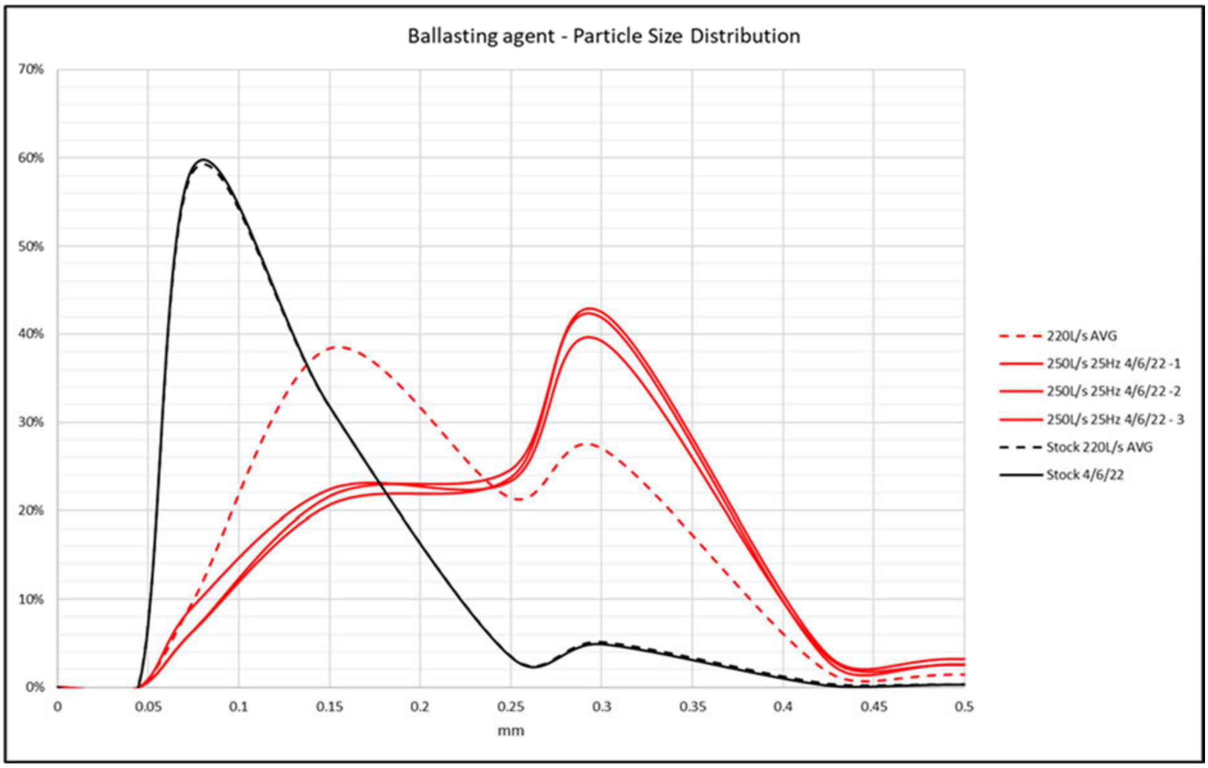

Figure 4-5: particle size distribution 250 L/s

Effective size and coefficient of uniformity have also been calculated as summarised in Table 4-4.

Table 4-4: particle size parameters - 250 L/s

Parameter	**Stock material**	**In-process (250 L/s, 25 Hz)**
Effective Size (d10) mm	0.09	0.15 – 0.17
d60 mm	0.15	0.32 – 0.33
Median Particle Size (d50) mm	0.14	0.29 – 0.30
Coefficient of Uniformity CU (d60/d10)	1.7	1.9 – 2.1
No. samples	1	3

Particles size distribution as percent finer has been calculated as shown in Figure 4-6.

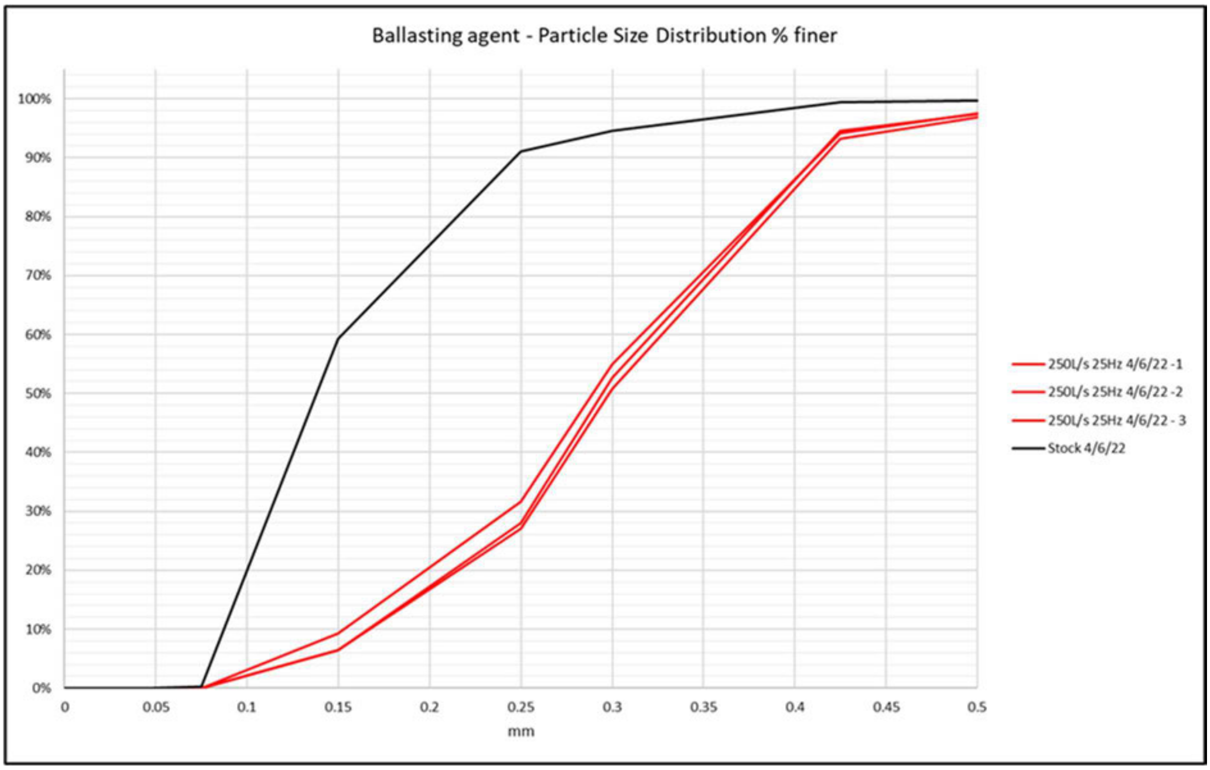

Figure 4-6: % finer curves - 250 L/s

4.2.5. Particle Size Distribution – Increased flocculation energy

The in-process ballasting agent was measured when with the flow rate at 250 L/s and the flocculator speed increased from 25 Hz to 30 Hz on the variable speed drive, equating to an impeller speed of 16.9 rpm. This was an increase of 2.8 rpm and 23 s^{-1} velocity gradient. It was not possible to increase the flocculator speed further without creating a vortex and entraining air in the process.

The particle size distribution was seen to change in response to increased flocculation energy with the dominant portion being retained on a 0.3mm sieve increasing further when compared to when the flocculator speed was 25 Hz. Results are shown in Table 4-5.

Table 4-5: particle size distribution 250 L/s 30 Hz

Particle diameter (mm)	**Stock material % retained on sieve**	**In-process (250L/s, 30 Hz) % retained on sieve**
Pan	0	0
0.045	0.4	0 – 0.1
0.075	**58.5**	3.5 – 6.1
0.150	31.7	19.9 – 20.8
0.250	3.5	22.0 – 23.2
0.300	5.1	**45.2 – 46.1**
0.425	0.4	3.8 – 4.1
0.500	0.3	3.5 – 3.7
No. samples	1	3

The particle size distribution of ballasting agent sampled from the process at 250 L/s is graphically represented in Figure 4-7, including a comparison to measurements when the flocculator speed was set at 25 Hz (14.1 rpm impeller speed).

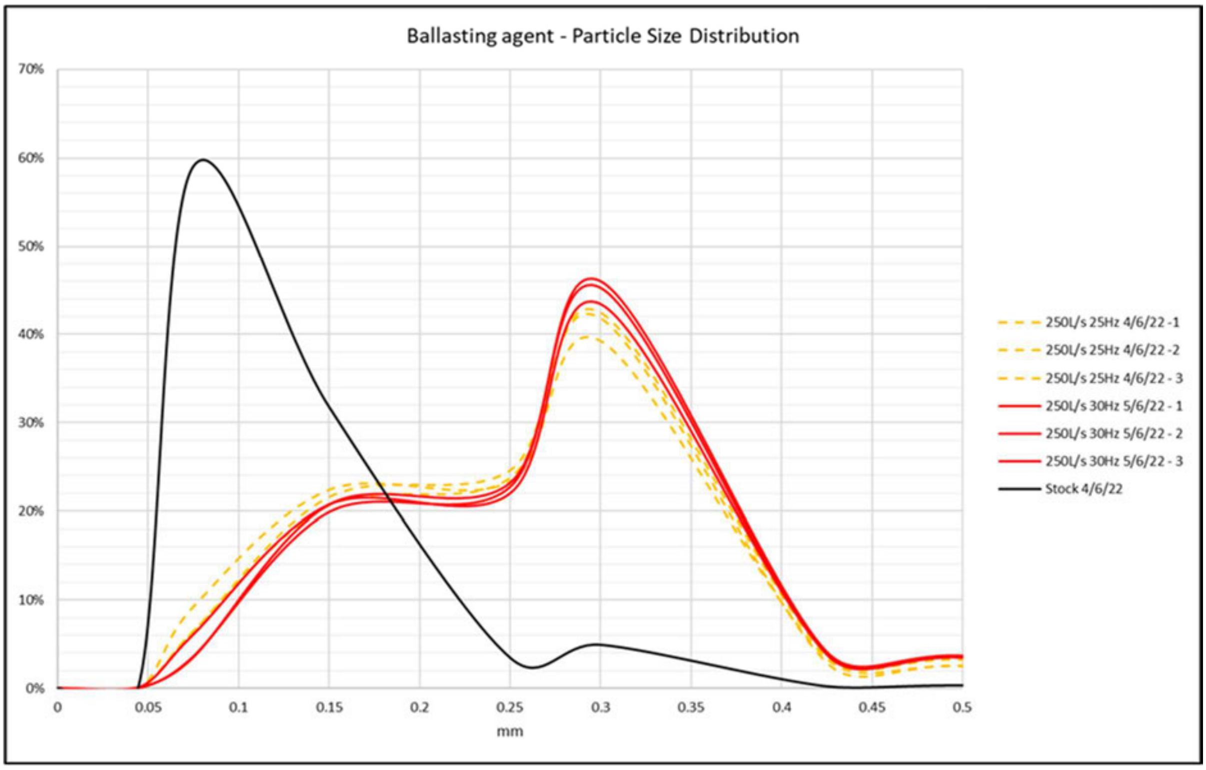

Figure 4-7: Particle size distribution curve 250 L/s 30Hz

Effective size and coefficient of uniformity have also been calculated as summarised in Table 4-6.

Table 4-6: particle size parameters 250 L/s 30 Hz

Parameter	**Stock material**	**In-process (250 L/s, 30 Hz)**
Effective Size (d10) mm	0.09	0.17 – 0.18
d60 mm	0.15	0.33 – 0.34
Median Particle Size (d50) mm	0.14	0.30 – 0.31
Coefficient of Uniformity CU (d60/d10)	1.7	1.8 – 2.0
No. samples	1	3

Particles size distribution as percent finer has been calculated as shown in Figure 4-8.

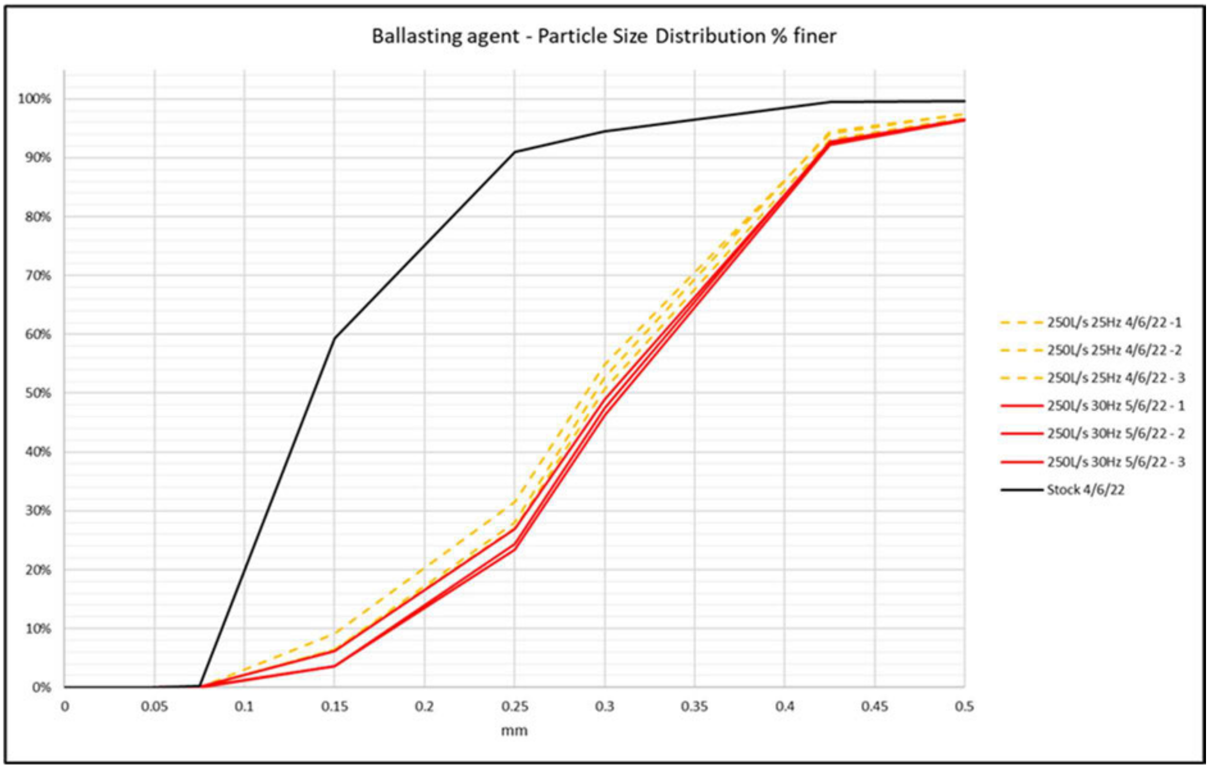

Figure 4-8: % finer curves 250 L/s 30 Hz

4.2.6. Particle Size Distribution – increased flocculation energy and change of stock ballasting agent

Particle size distribution of in-process ballasting agent was analysed with the flow returned to 220 L/s used in the control period but with the flocculator increased from 25 Hz to 30 Hz on the variable speed drive, increasing the impeller speed from 14.1 rpm to 16.9 rpm.

It was also discovered that the stock ballasting agent particle size distribution had changed from that previously seen, possibly due to the supply of the incorrect product or manufacturing error. The stock material measured on 16/7/2022 had a greater portion of particles retained on a 0.150mm sieve and an absence of particles retained on a 0.25mm sieve or greater in diameter as recorded in Table 4-7.

Table 4-7: particle size distribution - new stock material

Particle diameter (mm)	**Stock material 4/6/22 % retained on sieve**	**Stock material 16/7/22 % retained on sieve**
Pan	0	0.1
0.045	0.4	0.2
0.075	58.5	58.8
0.150	31.7	40.9
0.250	3.5	0
0.300	5.1	0
0.425	0.4	0
0.500	0.3	0
No. samples	1	1

Interestingly, as only the larger diameter particles were substantially different, the measurements for d10, d60 and Coefficient of Uniformity were identical between the two stock materials.

Three samples of in-process ballasting agent were analysed and the results recorded in Table 4-8.

Table 4-8: particle size distribution - new stock material and in-process

Particle diameter (mm)	**Stock material 16/7/22 % retained on sieve**	**In-process (220 L/s, 30 Hz) % retained on sieve**
Pan	0.1	0.0
0.045	0.2	0.0 – 0.1
0.075	58.8	13.7 – 20.3
0.150	40.9	31.0 – 35.4
0.250	0	12.2 – 13.7
0.300	0	28.9 – 35.9
0.425	0	2.2 – 3.0
0.500	0	1.6 – 2.5
No. samples	1	3

The particle size distribution of ballasting agent sampled from the process is graphically represented in Figure 4-9, including a comparison to measurements of the average particle size distributions for stock material and in-process ballasting agent during the control period.

Note test 1 was taken before stock ballasting agent was added to the process and tests 2 and 3 were sampled after ballasting agent addition, which shows the effect of adding stock ballasting agent to make up for in-process ballasting agent lost from the system.

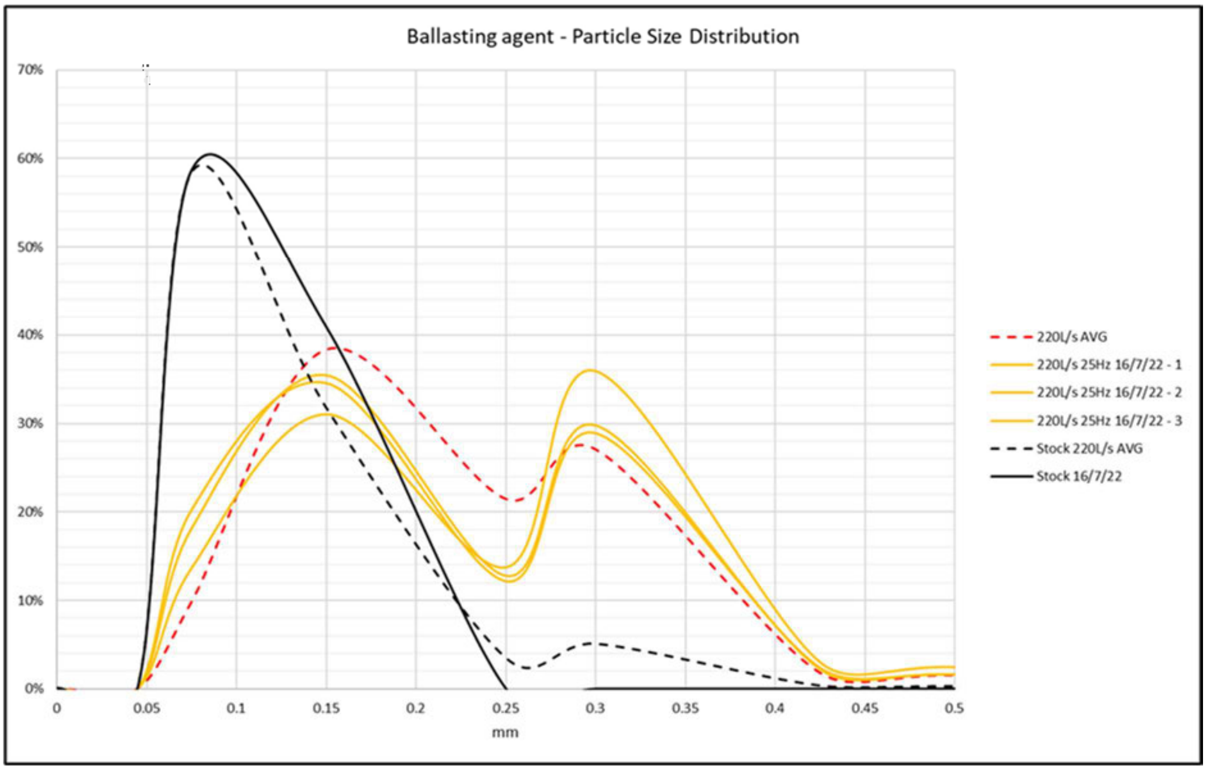

Figure 4-9: particle size distribution - new stock material

Effective size and coefficient of uniformity have also been calculated as summarised in Table 4-9

Table 4-9: particle size distribution – new stock material – 250 L/s 30Hz

Parameter	**Stock material**	**In-process (220 L/s, 30Hz)**
Effective Size (d10) mm	0.09	0.11 – 0.13
d60 mm	0.15	0.27 – 0.30
Median Particle Size (d50) mm	0.14	0.24 – 0.27
Coefficient of Uniformity CU (d60/d10)	1.7	2.4
No. samples	1	3

Particles size distribution as percent finer has been calculated as shown in Figure 4-10.

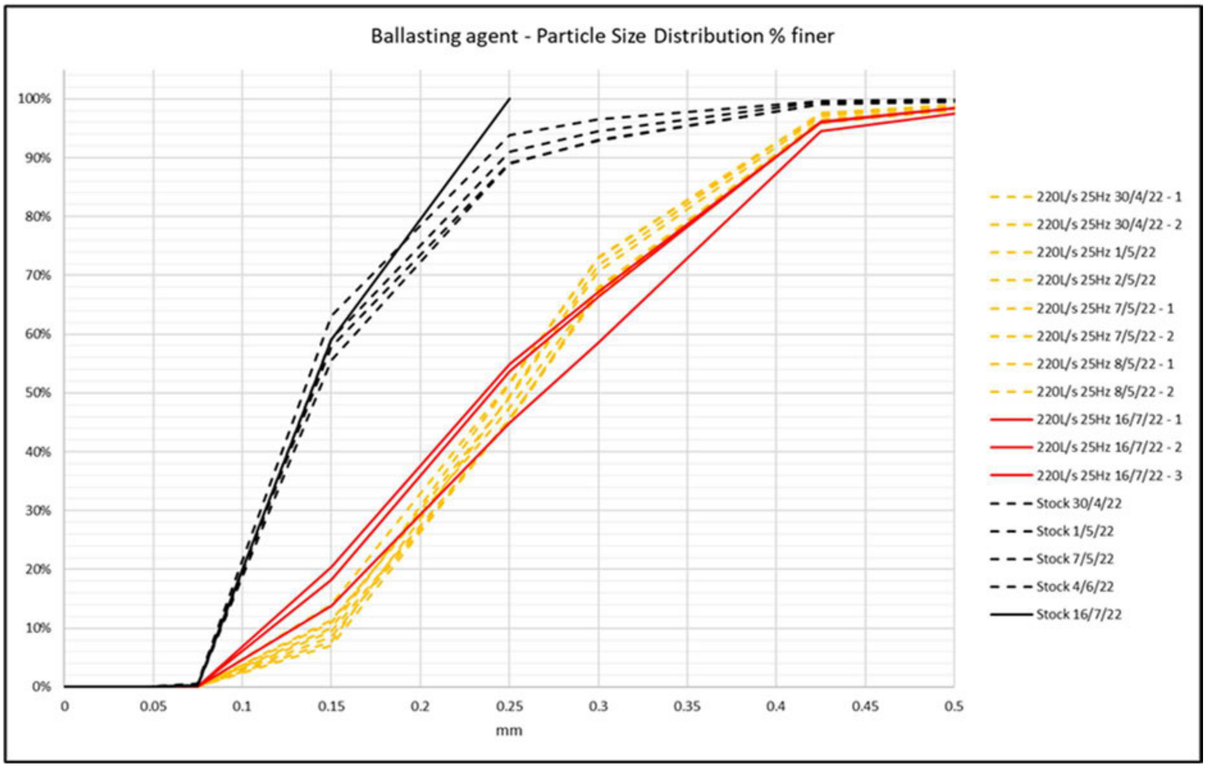

Figure 4-10: % finer curves - new stock material

4.2.7. Discussion

The results attained through analysis and measurement of the ballasting agent particle size distribution are discussed in this section.

4.2.7.1. Change in particle size distribution

The results demonstrate that the ballasting agent particle size distribution as found in-process is significantly different to the particle size distribution of the stock ballasting agent. The in-process ballasting agent that has been subjected to continual recycling has a larger portion of larger diameter particles compared to the stock ballasting agent. Using the control period as an example, the particle diameters for d10 increased from 0.09mm to between 0.13mm - 0.16mm for stock and in-process ballasting agents respectively. The value of d60 also increased from 0.15mm - 0.16mm to between 0.27mm - 0.28mm also respectively (Table 4-2). This transition is visualised in Figure 4-3, where it can be seen that for the in-process ballasting agent, particles smaller than 0.15mm decrease as a portion of the ballasting agent mass and particles 0.15mm or greater in diameter increase as a portion.

The cause of this significant change in particle size distribution has not been specifically determined through analysis for this research, however some possibilities were considered:

- Particle diameter is increasing due to biofilm growth.
- Small diameter particles are being lost from the process due to carryover of flocs from the sedimentation process.

- Small diameter particles are being lost from the process as discrete particles from the sedimentation process.
- Small diameter particles are not being recovered for recycling in the hydrocyclone.

By visual inspection of the ballasting agent recovered from the hydrocyclone is clean sand of discrete particles with no biofilm growth or fouling.

The loss of ballasting agent from the process is expected. The Operation and Maintenance Manual advises that ballasting agent loss will occur from the hydrocyclone overflow (to waste) and through the sedimentation process and that the addition of make-up ballasting agent will be required on a daily basis. The expected loss from each process is not quantified in the Operation and Maintenance Manual, however the mass added to the full-scale process is typically between 100 – 200 kg/d (M Little, pers. comm 2022). As will be discussed later in this section, increasing the flow rate through the process was observed to result in a further reduction of small diameter particles from the ballasting agent mass. It is therefore considered likely that the loss of ballasting agent is predominantly through the sedimentation process.

As it has been proven the particle size distribution of the in-process ballasting agent is different to the stock ballasting agent and with losses of ballasting agent in the order of 100 - 200kg/d, there is a strong indication that the smaller diameter particles are lost at a higher rate than the larger particles. For the control period, the data suggests that particles smaller than 0.15mm in diameter were predominantly lost and those larger were retained.

The ballasting agent specified for the process would be expected to experience higher rates of loss than the current ballasting agent product as the effective size is 0.075mm with a Coefficient of Uniformity < 1.7 and the maximum particle size of 0.2mm.

The impact of the in-process ballasting agent particle size distribution transformation is discussed in section 4.5 of this report as investigated through jar testing.

4.2.7.2. Particle size distribution in response to increased flow rate

It was observed that the in-process ballasting agent particle size distribution also changed in response to a number of operational variables including flow rate, flocculation energy and the ballasting agent stock characteristics.

Increasing the flow rate from 220 L/s to 250 L/s caused further reductions in the portion of ballasting agent particles 0.15mm and smaller, while particles in the range of 0.3mm significantly increased. Particles in the range of 0.25mm were the least impacted. In comparison to the control period, the effective size (d10) increased, as did the value for d60 for the in-process ballasting agent by up to 0.01mm and 0.04mm respectively. The Coefficient of Uniformity was not impacted.

The further reduction in smaller diameter ballasting agent particles indicates the additional loss is occurring though the sedimentation process, as the flow rate through the hydrocyclone remained constant.

4.2.7.3. Particle size distribution in response to increased flocculator speed

Increasing the speed of the flocculator with the flow rate held constant at 250 L/s resulted in the particle size distribution changing further, although perhaps insignificantly. The flocculator impeller speed was increase form 14.1 rpm to 16.9 rpm which was the maximum before a vortex was created and air entrainment occurred. The mixing energy was increased from a velocity gradient of 72 s^{-1} to 95 s^{-1}.

It is proposed that increasing the flocculator speed has increased the mixing energy and therefore a higher portion of larger particles have been brought into suspension which may have otherwise been retained on the floor or in the corners of the flocculator basin. In this manner, the smaller diameter particles may not have been lost from the process and instead make up a smaller portion of the overall mass of ballasting agent given the additional larger particles brought into suspension. It may also be that the particle size distribution would change back when the flocculator speed was decreased, though this was not analysed in this research.

The review of mixing energies and particle suspension are outside the scope of this research.

4.2.7.4. Particle size distribution in response to changed stock ballasting agent

During the period where ballasting agent stock changed, the flocculator speed had also changed.The effects of increasing the flocculator speed can be subtracted from the results obtained by reviewing the results when this occurred when the process was operated at 250 L/s and the only variable that changed was the flocculator speed. In-process ballasting agent particles of 0.3mm diameter and greater are expected to increases as a portion of the overall ballasting agent mass and this has been observed again at 220 L/s. Particles smaller than 0.3mm in diameter are expected to decrease as portion of overall ballasting agent mass and this has again also been observed at 220 L/s.

The stock ballasting agent had an absence of particles 0.25mm or greater as previously described.

The additional effect observed is that in-process ballasting agent particles of 0.15mm diameter or less were the most impacted by the stock ballasting agent being added to the process.

In-process ballasting agent particles of 0.075mm were present in higher portions compared to the control period. When the new stock ballasting agent was added, this further increased these portions.

In-process ballasting agent particles of 0.15mm were lower in portion compared to the control period, however at the higher flocculation speed this is expected in concept. The addition of the new stock ballasting agent also increased the in-process portion of this size.

In-process ballasting agent particles were of a higher portion than the control period, again explained by the higher flocculation speed. With the absence of particles this size in the stock ballasting agent and these particles being retained in the process, it is proposed that in-process ballasting agent of 0.3mm or greater is lost from the process at much lower rates compared to smaller diameter particles.

4.2.7.5. Further work

Further work is required in order to verify the cause and solutions to manage ballasting agent loss. Suggested investigations are:

- Undertake a ballasting agent mass balance, measuring the particle size distribution and concentration in-process, in the hydrocyclone overflow and in the clarified water.
- Investigate if ballasting agent loss in clarified water is through floc carry over or as discrete particles.
- Trial ballasting agents in the full-scale process with an effective size of 0.15mm and greater with a low Coefficient of Uniformity.
- Develop a process model to investigate mixing energy and particle suspension in the flocculation process.

4.3. Ballasting agent concentration

The ballasting agent concentration was measured using two methodologies. In both cases, samples were taken over multiple hours throughout the day to investigate changes that may occur over a period of time.

4.3.1. Methodology 1

Methodology 1 has been described in previous sections, where samples are taken from the hydrocyclone underflow. As samples were collected, it became evident that the effect of the hydrocyclone variability could impact the amount of ballasting agent collected. As previously described, the concentration of ballasting agent in the hydrocyclone underflow varies with relation to sludge scraper position. The vessel being used to capture samples was of insufficient capacity to collect a sample representing the whole variation cycle, which may have resulted in excess of a 200L sample. In response to this, samples were collected and recorded as either not influenced by the high concentration phase (Type 1 underflow) or including the high concentration phase (Type 2 underflow). Samples were taken 1/10/2022 where the maximum concentration measured was 10.1 g/L and the minimum was 7.2 g/L.

The results from analysing samples using Methodology 1 are presented in Figure 4-11.

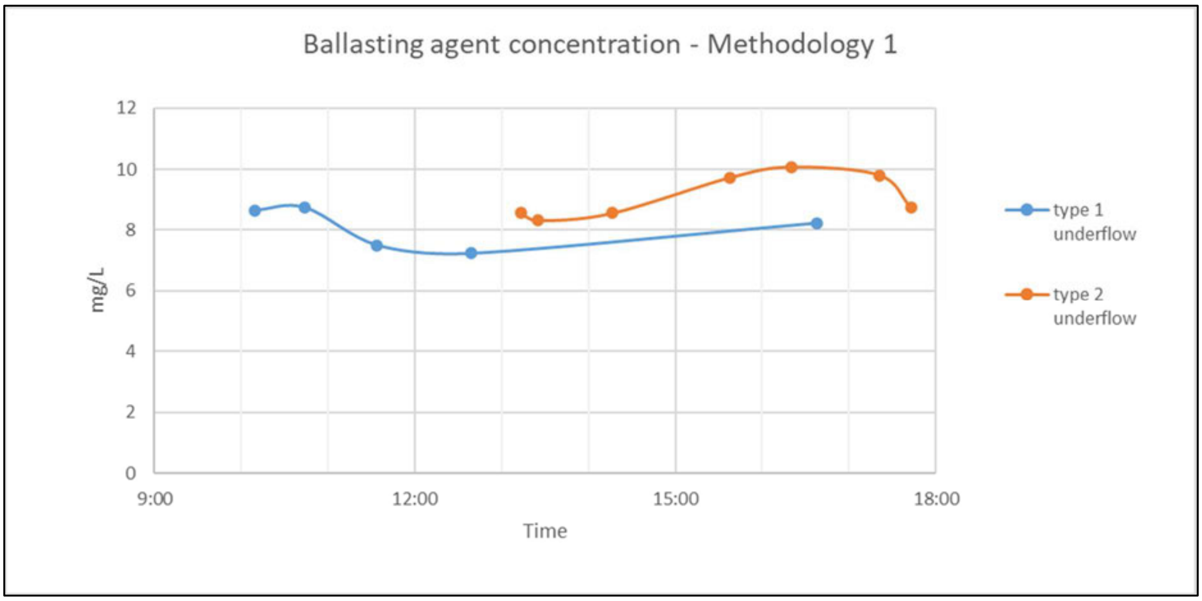

Figure 4-11: Ballasting agent concentration - Methodology 1

4.3.2. Methodology 2

Ballasting agent concentration was also measured using an alternate methodology. Samples were taken directly from the flocculation chamber as previously described. The results from analysing these samples are presented in Figure 4-12. Samples were taken 17/2/2022, where the maximum concentration measured was 5.3 g/L and the minimum was 3.0 g/L.

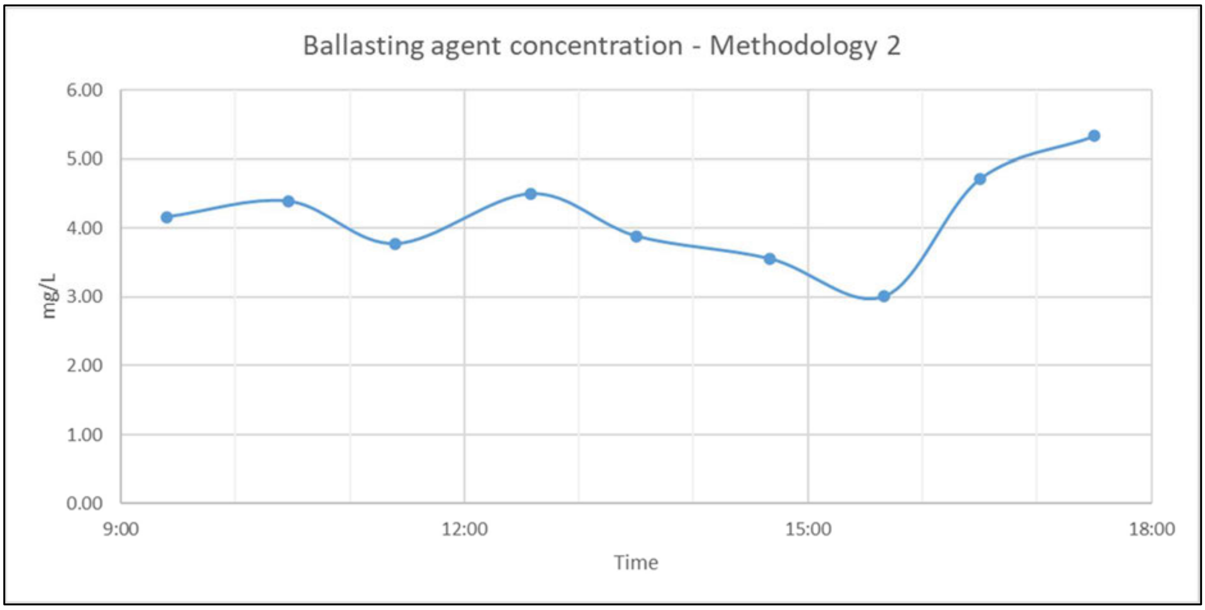

Figure 4-12: Ballasting agent concentration - methodology 2

4.3.3. Discussion

Results captured in this research indicates that ballasting agent concentration is variable within a full-scale ballasted flocculation process both temporally and spatially, when measure in the range between 30 minutes to 1 hour.

4.3.3.1. Methodology evaluation

A large difference in ballasting agent concentration results exist between the two methodologies. One possible explanation may be that the methodologies return different results because the sample locations are different. Another explanation is that the ballasting agent concentrations were actually quite different, noting the large amount of time between when the methodologies were applied.

Methodology 1 was challenged by variations in the hydrocyclone underflow and results in this research may not have adequately accommodated this. Methodology 2 was challenged by the apparent existence of a concentration gradient.

Due to time constraints on the research it has not been possible to undertake replicate or truly comparative sampling and analysis. Therefore it has not been possible to determine which of the methodologies deliver the most accurate results.

4.3.3.2. Temporal variation

It was expected that ballasting agent concentration may have been relatively constant and steadily declined over the course of a day between events where stock ballasting agent is added to make up for ballasting agent loss. The results however indicate the ballasting agent concentration is variable on multiple time scales.

The variability of ballasting agent concentration in the hydrocyclone underflow was observed during preliminary stages of this research, where this occurred over the course of 1 minute or less. The degree of variation was not measured.

It has been shown using Methodology 1, where samples were taken during different phases of the hydrocylone underflow, that the determination of ballasting agent concentration is sensitive to this variability. At a greater time period, this methodology also indicates that the ballasting agent concentration does not steadily decline over the course of a day and that the concentration seems to increase unexpectedly following some time of a decreasing trend. Due to the variability of the hydrocylone underflow, these results should be used with caution.

Samples taken using Methodology 2, which was significantly different in approach to Methodology 1, also returned data indicating ballasting agent concentrations appear to recover after periods of decline. Due to the spatial variability also described in this section, these results should be used with caution.

It is noteworthy that no stock ballasting agent was added during the duration where samples were collected in both cases.

It can be observed that for both methodologies, the unexpected increase in ballasting agent concentration appears to occur at or around 3 O'clock in the afternoon. It has been confirmed that flow rate through the full-scale process remained constant. One possibility could be that particle suspension is being impacted by a change in viscosity and density caused by water temperature variations, whereby the suspension of ballasting agent particles may change. However it would be suspected that the water would increase in temperature throughout the day and the viscosity and density would decrease, therefore suspension would be more difficult for the same mixing energy. The water temperature was not measured during this research.

Ballasting agent concentration does appear to be variable in a full-scale process. This may be partly due to the variability of ballasting agent in the hydrocyclone underflow, however this research has also shown that the accuracy of measurement needs further work before definitive conclusions can be made.

4.3.3.3. Spatial variations

Early investigations during development of methodolgies to measure ballasitng agent concentration taken directly from the flocculaiton chamber found that variabiliy existed in realtion to depth. A sample taken at 100mm below surface was 6.85 mg/L however a sample at 600mm was 7.19 mg/L. With the flocculation chamber being 4m deep, there is potential that concentrations continue to increase with depth. Beyond initial investigations, the concentration gradient within the flocculation chamber was not measured directly in a detailed way.

A concentration gradient may exist in the flocculation chamber if the suspension of particles are not uniformly mixed. A situation may exist where the suspension of particles is classified as *on-bottom motion* or *complete off-bottom suspension* as described by Kresta (2016), where concentration will be greater nearer the bottom of the flocculation chamber. This is partly supported by the particle size distribution being seen to include larger particles with higher mixing energies (Section 4.2), where it is proposed these were not uniformly suspended at the lower mixing energy. Significant review of the literature was undertaken to determine how to calculate particle suspension within the flocculation chamber, however insufficient empirical data was available for the chamber and impeller geometries of the full-scale process to apply methods such as the Zweitering correlation.

The significance of spatial variation of ballasting agent concentration was not considered in this research. There is a potential that ballasting agent particles that are not fully suspended, or do not reach a certain height in the chamber, do not contribute to ballasted flocculation if they are not incorporated into flocs that carry over to the sedimentation process.

4.3.3.4. Further work

This research demonstrated that measurement of ballasting agent concentration in a full-scale process is challenging. Additional works that may advance knowledge of this are:

- Undertake more rigorous sampling of ballasting agent concentrations to gather more data with respect to changes thoughtout the day.
- Design a methodology to capture a more representative sample of ballasting agent returned in the hydrocyclone underflow.

- Investigate ballasting agent concentration gradient in floccualtion chambe in greater detail.
- Investigate ways to reduce variability of ballasting agent in hydrocyclone underflow, including use of a balance tank.

4.4. Process model

The coagulation process was modelled at 220 L/s and a water temperature of 16°C, which was representative of the full-scale process at the time.

4.4.1. Coagulation conditions

The results obtained from the model are recorded in Table 4-10. While this chamber is called the coagulation chamber, in practice the coagulant has been added upstream and been subjected to a degree of hydraulic mixing. The coagulation chamber will therefore more likely provide flocculation prior to the main ballasted flocculation process. The modelled results have been compared with typical design values from MWH (2012) for flocculation.

Table 4-10: coagulation conditions - modelled

Parameter	**Process model value**	**Typical design value**
Coagulation chamber volume (m^3)	18.6	
Detention time (s)	84.5	
Impeller speed (rpm)	28.3	5 – 20
Impeller tip speed (m/s)	1.9	1 – 3
Impeller power (W)	254.6	
Velocity gradient (S^{-1})	110	10 - 80
Gt	9 264	

It can be seen that the full-scale process generally aligns with typical design standards, although the mixing energy is higher by a small amount.

4.4.2. Ballasted flocculation process

The results obtained from the model are recorded in Table 4-11. Typical design values for ballasted flocculation are not readily available in the literature. Metcalf and Eddy (2014) state a velocity gradient of 200 – 400 s^{-1}, which is much higher than calculated for the observed operating conditions of the full-scale process. It is noted that at full mixer speed, the full-scale process would achieve a velocity gradient of 205 s^{-1}, though this does not appear to be required at the observed conditions. This may also be a factor of the mixing energy required for various operating conditions. Davis (2013) explain that higher mixing energies are required for heavier floc and higher solids concentrations, stating G values up to 300 s^{-1} for water softening processes. As observed in the difference the jar testing and full-scale process in this research, the mixing energy can be different compared to the velocity gradient value and it is proposed this is due to a range of factors with impeller configurations and tank/impeller geometries.

Table 4-11: ballasted flocculation conditions - modelled

Parameter	**Process model value**	**Typical design value**
Flocculation chamber volume (m3)	63.2	
Detention time (s)	287.3	
Impeller speed (rpm)	14.1	
Impeller power (W)	377.8	
Velocity gradient (S^{-1})	72	200-400
Gt	20 813	

4.4.3. Sedimentation process

The results obtained from the model are recorded in Table 4-12. The surface loading rate design value has been adopted from the manufacture of the full-scale process. It is noted that at design capacity, the surface loading rate of the full-scale process is 74.7 $m^3/m^2/hr$. Design values for settling tubes/lamellar plates are not available in the literature for such high surface loading rates as seen in this application. For unballasted flocculation, surface loading rates for settling tubes/lamellar plates are stated as up to 6.25 $m^3/m^2/hr$ (MWH 2014).

Table 4-12: sedimentation condition - modelled

Parameter	**Process model value**	**Typical design value**
Surface area (m2)	16.3	
Surface loading rate (m3/m2/hr)	46.1	80
Settling tube angle (degrees)	60	
Minimum particle settling velocity removed in settling tubes (m/h)	5.5	

The available literature does not include design parameters for settling tubes/lamellar plates used at such high rates and therefore it cannot be concluded if the results indicate appropriate operation or not.

4.4.4. Minimum size of ballasting agent retained

The model incorporated calculations for discrete particle settling and also removal through the settling tubes. For the modelled conditions, the minimum ballasting agent particle retained was 0.02mm. This is significantly smaller than the ballasting agent diameter of 0.075mm that appears to be lost from the full-scale ballasted flocculation process.

This may indicate that ballasting agent is not being lost as discrete particles and instead through poorly or partly ballasted flocs.

4.4.5. Ballasting agent suspension

The model was run with the flocculator impeller speed set at 25Hz (14.1 rpm) and using the Zweitering correlation S factor of 7.7 as initially adopted is section 3.3. The model calculated that a ballasting agent particle of 0.000002mm would suspended. This was considered erroneous as ballasting agent particles in the range of 0.3mm are being suspended in the full-scale process.

For the model to show that a ballasting agent particle of 0.324mm would be suspended at the flocculator impeller speed of 14.1 rpm, a Z factor of 0.45 was required. The range of empirically derived S values provided by Kresta (2016) range between 2.7 and 9.9 for a range of impeller types and D/T and C/T geometry ratios.

Constraints to modelling suspension of particles include:

- The available empirically derived values for S do not include 4-bladed high solidity hydrofoil impellers such as the full-scale flocculator impeller.
- It is unknown if the values for S were for a round or square tank.
- The full-scale process includes a draft tube which was not able to be accounted for in the model.
- It is unknown if discrete ballasting agent particles require modelling, or if suspension of ballasted flocs is more appropriate.

The further work required to address these constraints was not possible in this research. The modelling of particle suspension in the flocculation chamber was not considered further.

4.4.6. Discussion

The coagulation conditions were not as expected and not completely accounted for in the model as the coagulant was dosed upstream of the full-scale process and subjected to hydraulic mixing. These conditions were not calculated due to difficulties in measuring head loss over different items of infrastructure and pipework. The model would be improved by taking this into consideration.

The ballasted flocculation process was modelled and the velocity gradient was found to be much lower than recommended in the limited amount of literature available on design values for this process. It is proposed this may be due to differences in impeller styles, impeller to tank dimension ratios and tank geometries that cause difference in mixing energies for the same velocity gradient. The full-scale process has the flocculator impeller located within a draft tube. The impact of these factors were observed in this research also. While the full-scale process has a velocity gradient of 72 s^{-1} in the ballasted flocculation process, which appears to maintain suspension of a large portion of the ballasting agent, a much higher velocity gradient of 195 s^{-1} was required in the jar test experiment, which was geometrically different, to suspend the ballasting agent. It is therefore proposed evaluation of ballasted flocculation processes using only velocity gradient as a measure of adequacy may not fully inform the investigation.

The sedimentation zone was difficult to assess using the model as suitable design values could not be found in the literature for settling tubes at such high surface loading rates. The calculations though were applied and it was found that a minimum particle settling velocity that could be theoretically removed was 5.5 m/h when the surface loading rate was 46.1 m/h. It is interesting that the surface loading rates within the sedimentation process are within the design parameters for ballasted flocculation, even at full design capacity and without the settling tubes. The purpose of the settling tubes may be to capture poorly or partly ballasted flocs not having the optimum settling velocity.

By observation onsite it could be seen that the settling tubes were collecting flocs that had not settled in the sedimentation zone below, however the settling velocity of these flocs was not known. It was also observed that that a section of the settling tubes had very high rates of floc carry-over. It is possible that hydraulic conditions are not ideal in the sedimentation zone. Even though the process model did not confirm that the ballasted flocculation process was working within typical design parameters, this is largely due to lack of information availability. The process model will be useful for further research.

Modelling of particle suspension would be advantageous to evaluating the performance of a full-scale ballasted flocculation process and would assist with understanding possible ballasting agent concentration gradient with depth observed in section 4.3.

Further work is recommended to include:

- Investigation of design parameters for settling tubes/lamellar plates in a ballasted flocculation process, particularly with regards to very high surface loading rates.
- Investigation of suspension of ballasting agent particles and ballasted flocs in a ballasted flocculation process, particularly with regard to developing suitable inputs to use the Zweitering correlation (or similar).

4.5. Jar testing

Jar testing was undertaken to investigate the impact which changing the particle size distribution could be expected to have on the sedimentation of ballasted flocculation. This was undertaken in a laboratory setting with standard jar testing equipment, with the exception of the jar test machine impellers being modified to better represent the impeller used in the full-scale process as described in the methodology.

The raw water quality parameters during these tests are recorded in Table 4-13.

Table 4-13: raw water quality - jar tests

Raw water quality parameter (28/8/2022)	**Value**
Colour (true) PtCo	177
Total Organic Carbon (mg/L)	22
Turbidity (NTU)	36.5
Alkalinity as $CaCO_3$ (mg/L)	20
Temperature	16.1

It is noteworthy that raw water has elevated concentrations of Total Organic Carbon (TOC), high colour and low alkalinity. The high TOC requires a high dose rate of Aluminium Chlorohydrate and this in turns requires the dosing of chemicals to increase the alkalinity. Hydrated lime and carbon dioxide are used to increase alkalinity and control pH in the full-scale process, however this added to the complexity of the experiment. Sodium Bicarbonate was used in the jar test experiments as it increases alkalinity without large changes to pH. The chemical dose rates used for all experiments is recorded in Table 4-14.

Table 4-14: chemical dose rates - jar tests

Chemical	Dose rate
Sodium bicarbonate (NaHCO3)	100 mg/L
Aluminium Chlorohydrate (Al2(OH)5Cl)	100 ppm (v/v)
Polymer (AN905PWG)	1.25 mg/L

4.5.1. Test 1 – control (no ballasting agent)

A jar test experiment was conducted with no ballasting agent. While this scenario is not expected in the full-scale process, it provides guidance on the performance expected should the ballasted flocculation process not be operating under optimal conditions.

The settled water turbidity results are shown in Figure 4-13.

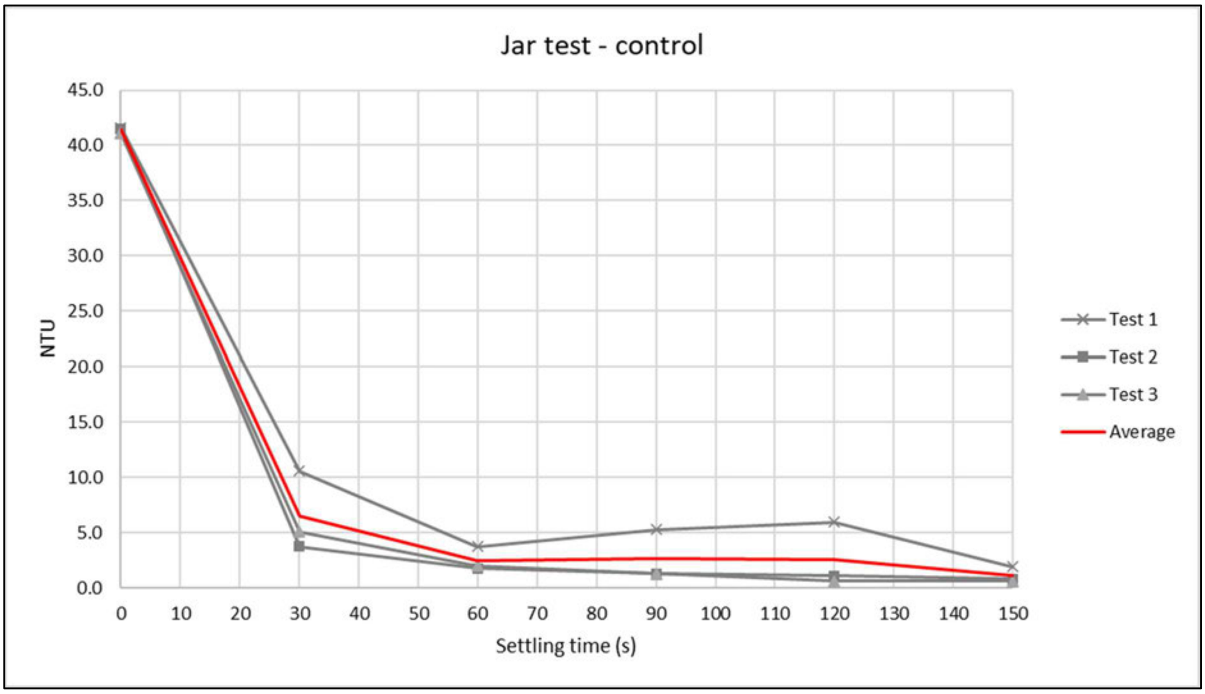

Figure 4-13: settled water turbidity - control

4.5.2. Test 2 – performance as designed

To ascertain an understanding of what performance could be expected from the ballasted flocculation under design conditions, an approximation of the design ballasting agent was used. This was achieved by using ballasting agent between 0.075mm and 0.150mm in diameter, recovered though a sieving exercise of the stock ballasting agent used onsite. The dose rate used was 6 g/L, which was chosen as this is stated as the upper typical dose rate in the Operation and Maintenance Manual.

The settled water turbidity results are shown in Figure 4-14.

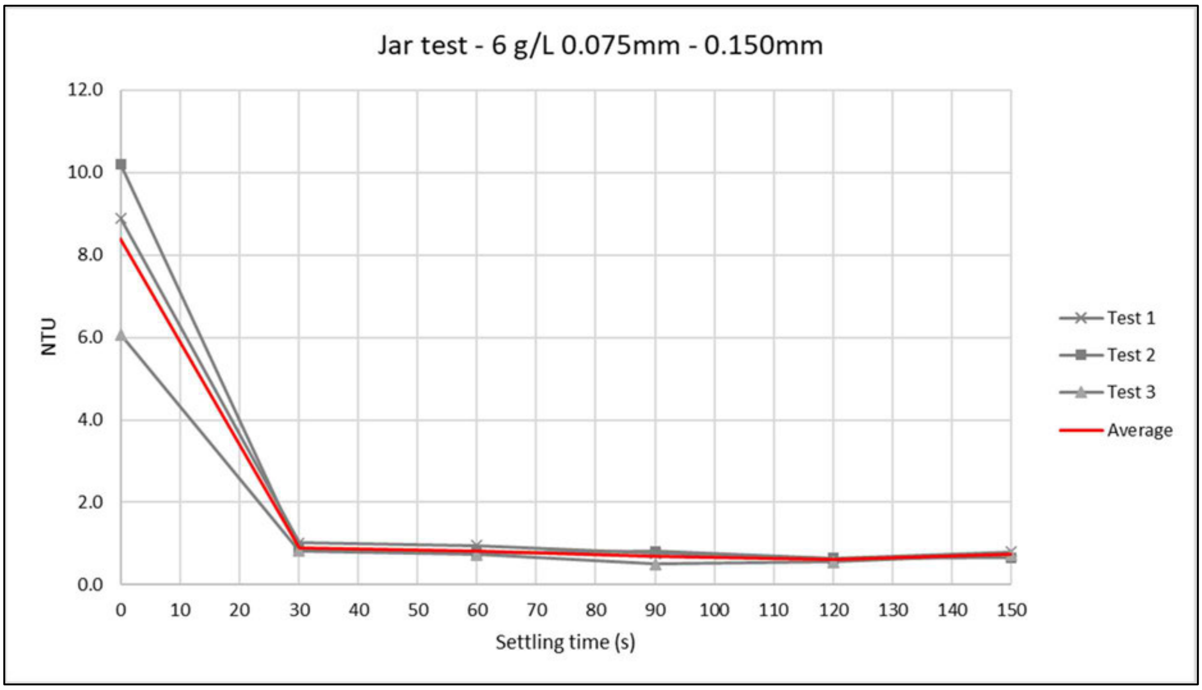

Figure 4-14: Settled water turbidity 6g/L 0.075 - 0.150 mm

A comparison of the average results of the control jar test and the design scenario with 6g/L of ballasting agent in the range of 0.075mm – 0.150mm in diameter is shown in Figure 4-15.

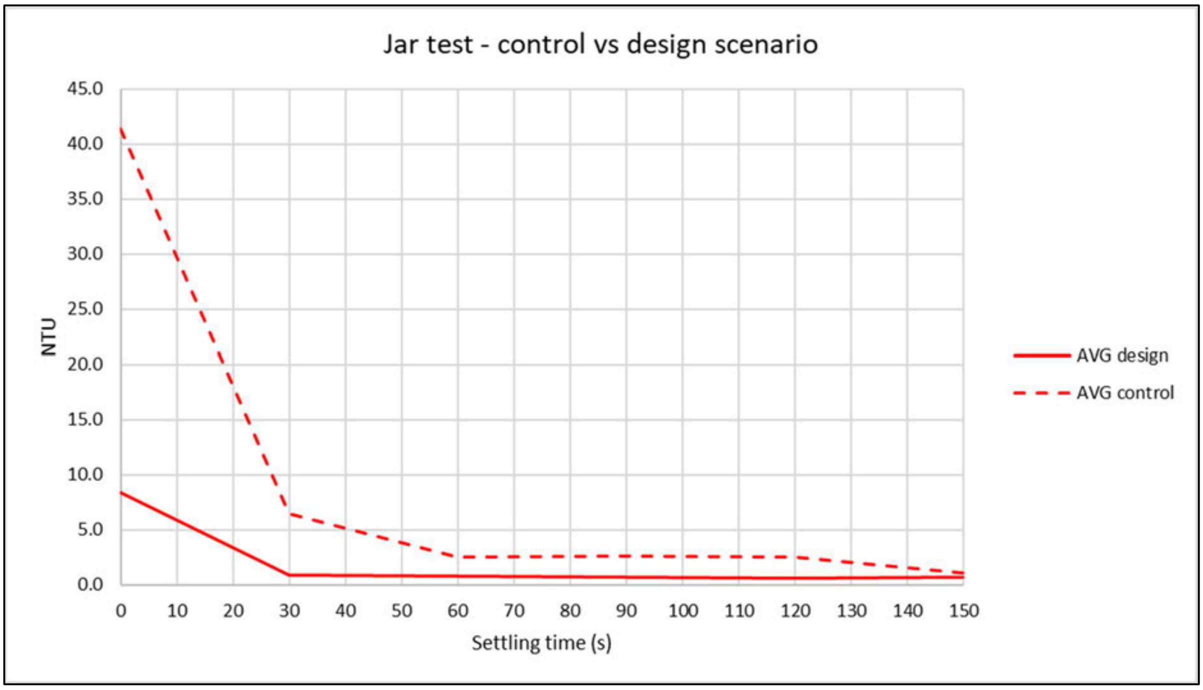

Figure 4-15: control vs ballasted flocculation comparison

4.5.3. Test 3 – increase in particle size distribution, constant mass

Jar tests were conducted maintaining the ballasting agent concentration constant at 6 g/L, however the ballasting agent particle size distribution was varied from 0.075mm – 0.150mm to a particle size ranging between 0.150mm – 0.250mm. The settled water turbidity results are shown in Figure 4-16.

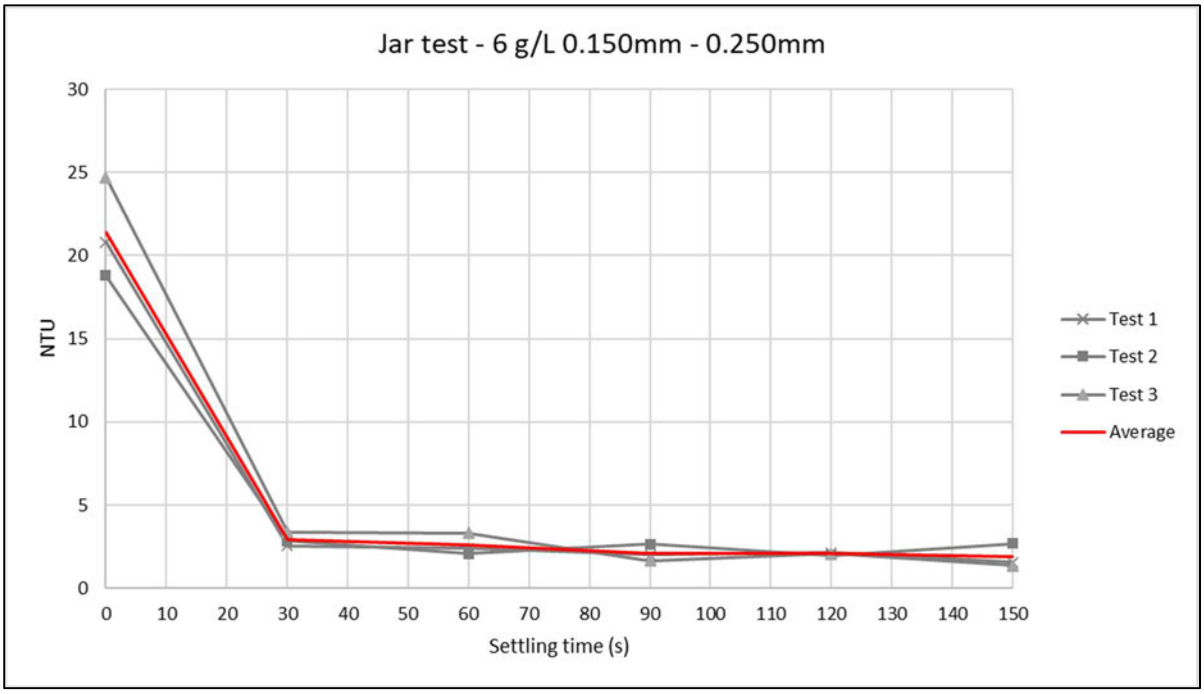

Figure 4-16: settled water turbidity 6g/L 0.15mm – 0.25mm

The comparison between of average settled water turbidity results for the two different size ballasting agents are shown in Figure 4-17.

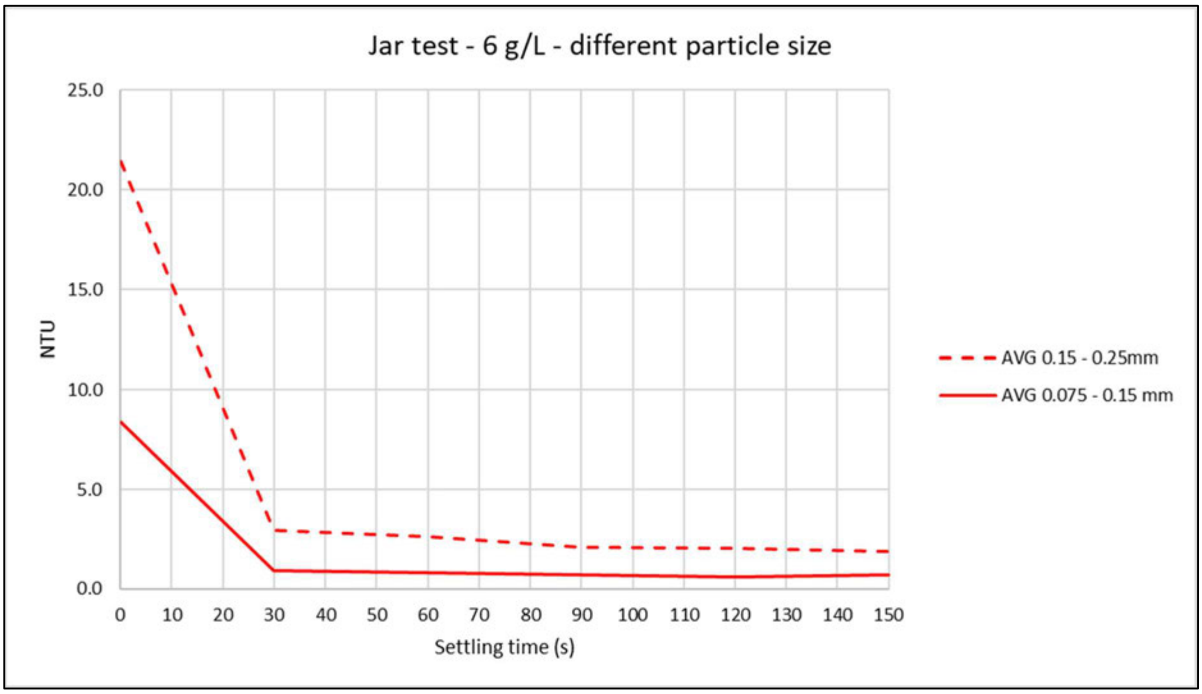

Figure 4-17: settled water turbidity - different particle size distributions

4.5.4. Test 4 – increase in particle size distribution, constant surface area

Jar tests were conducted using ballasting agent with a particle size ranging between 0.150mm – 0.250mm, however the dose rate was varied to match the surface area that would have existed with 6g/L of ballasting agent with particles in the range of 0.075mm – 0.150mm.

The methods of calculating surface area for ballasting agent have been described in section 3.2.7.

6 g/L of ballasting agent with particles in the range between 0.075mm – 0.150mm has a surface area of 0.12 m^2.

To attain the same surface are of 0.12 m^2 with a ballasting agent with particles in the range between 0.150mm – 0.250mm, a mass of 10.7g is required.

Therefore jar tests were conducted with 10.7g/L of ballasting agent with particles in the range between 0.150mm – 0.250mm.

The settled water turbidity results are shown in Figure 4-18.

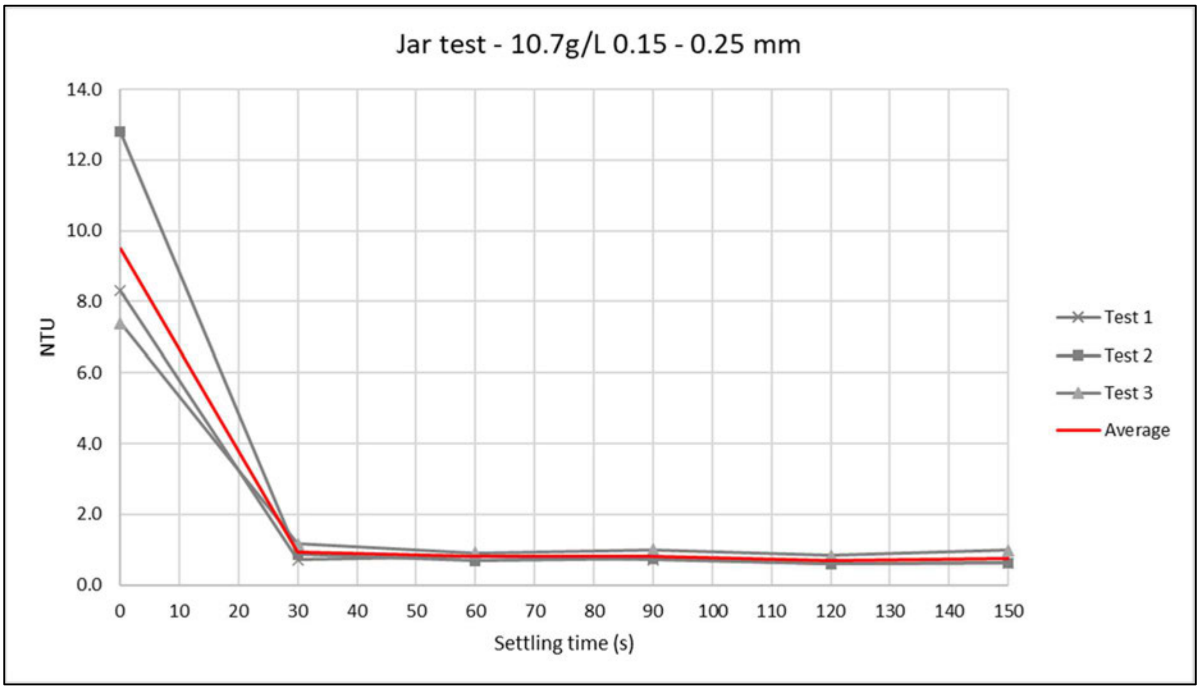

Figure 4-18: Settled water turbidity - 10.7g 0.15 - 0.25 mm

The comparison of settled water turbidity when varying the ballasting agent concentration to attain the same surface area for different particle size distributions is shown in Figure 4-19.

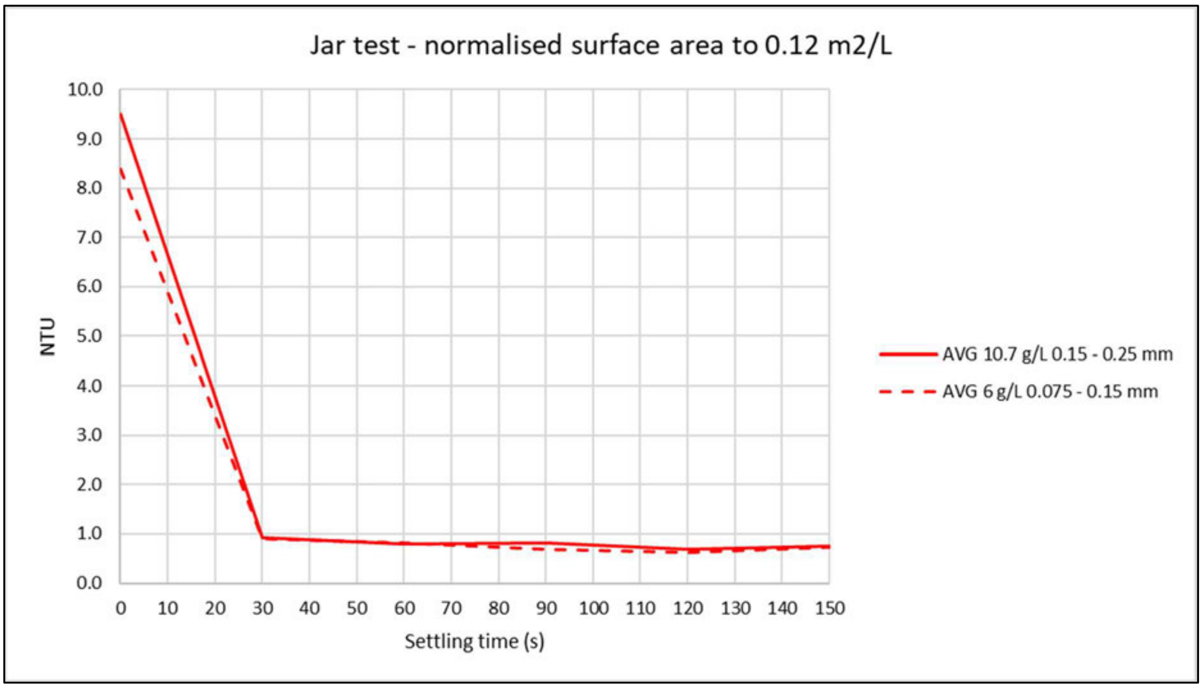

Figure 4-19: settled water turbidity - normalised surface area of ballasting agent

4.5.5. Discussion

The jar test experiments showed that settled water turbidity was improved when adding a ballasting agent, in terms of both the speed for turbidity reduction and overall lower turbidity.

It was seen that maintaining a constant concentration of ballasting agent, while increasing the particle size, resulted in a deleterious impact to settled water quality.

It was also seen that varying ballasting agent concentrations of different particle sizes to attain the same surface area per volume, that very similar performance occurs.

These observations aligned with experiments that have been described in previous research, although applied in a way representative of the particular site and process conditions being studied for this research. In particular, work by Lapointe (2018) documented laboratory experiments that compared various ballasting agents of different particle sizes, densities and concentrations by mass. The work found that similar performance could be expected form ballasting agents of different size, density and concentration if the surface area concentration was made constant.

This concept is proposed to have a tangible impact on the full-scale process being studied. It has been seen in section 4.2 that the in-process ballasting agent particle size distribution is different to the stock material and it also changes in response to flow rates through the process.

Using jar tests methods to predict performance of the full-scale process is problematic in this instance due to the significant differences between the particle size distributions of the stock and in-process ballasting agents. The specific surface area of the stock ballasting agent analysed through this research (5 samples) ranged between 0.016 – 0.017 m^2/g. The in-process ballasting agent also analysed (17 samples) in comparison ranged between 0.008 – 0.011 m^2/g.

Applying jar test conditions using stock ballasting agent to the full-scale process would require that the concentration of in-process ballasting agent would need to be multiplied by a factor in the order of 150% - 200%. The impact of this is 6g/L in the jar test would require an in-process ballasting agent concentration of up to 12g/L.

The impact of changes to the in-process ballasting agent as a response to operational changes observed through the period of this research are less profound. With the surface area concentrations ranging between 0.008 – 0.011 m^2/g across all of the scenarios, equating to a 37.5% change. This could result in poor performance if the in-process ballasting agent concentration was low and a change to larger particle sizes resulted in the surface area concentration falling below a threshold for effective operation.

CHAPTER 5 - CONCLUSIONS

The findings and observations made following evaluation of the results obtained through this research and further work identified to advance the literature on Ballasted Flocculation are summarised in this section.

5.1. Conclusions

Analysis of particle size distribution of the stock material being added to the full-scale process and the ballasting agent sampled directly from the full-scale process demonstrated that these were different. Results showed that the ballasting agent particles in the full-scale process subject to continuous recovery and recycling are larger than the stock material. During the control period of operation during the research period, the stock ballasting agent had a d10 value of 0.09mm and d60 value of 0.15mm whereas the in-process ballasting agent had a d10 values ranging between 0.13mm and 0.16mm and d60 values ranging between 0.27mm – 0.28mm.

Particle size distribution of ballasting agent was also seen to be sensitive to flow rate though the full-scale ballasted flocculation process. An increase in flow rate of 13.6% was seen to further increase the size of ballasting agent, where the stock ballasting agent had the same values as for the control period, the in-process ballasting agent had d10 values ranging between 0.15mm – 0.17mm and d60 values ranging between 0.32mm and 0.33mm.

The research indicates that for this full-scale ballasted flocculation process, the ballasting agent particle size distribution increases due to ballasting agent particles less than 0.2mm not being effectively recovered and recycled. The most likely cause of this is proposed to be that ballasting agent particles in this size range are being lost through carry over of poorly or partly ballasted flocs, although this was not directly measured or verified in this research.

Ballasting agent particle size was also seen to increase with greater mixing energy in the flocculation chamber, however it has been proposed in this research that the increase in mixing energy suspended larger particles that were not previously suspended and may have been retained on the flocculation chamber floor.

Measurement of ballasting agent concentrations in the full-scale process demonstrated that this parameter can be variable in temporal patterns. It was observed that ballasting agent concentration in the hydrocyclone underflow varies in the timeframe of less than 1 minute and has a relationship to the clarifier sludge scraper position, although this was not measured at this timescale. The ballasting agent concentration within the flocculation chamber was also seen to vary over a range of hours, when both calculated using the hydrocyclone underflow and directly measured from within the flocculation chamber. The methodologies provided substantially different results however, with the method using the hydrocyclone underflow returning values in the range of 7.2 g/L – 10.1 g/L and the direct measurement method returning values in the range of 3.0 g/L and 5.3 g/L.

Using the direct measurement method, data demonstrated that the ballasting agent concentration also varied spatially within the flocculation chamber vertically. In the full-scale process investigated, the data suggests ballasting agent concentration increases with depth.

Constraints with this data include the experiments not being replicated or the methods being applied simultaneously. Whilst variations in ballasting agent concentrations were measured, conclusions cannot be made with regards to the best methodology to measure this parameter of the cause for these variations.

The research proved that it is possible to model a full-scale ballasted flocculation system for coagulation, flocculation and settling processes. The evaluation of results is currently difficult for flocculation and settling as the literature provides only limited guidance for design values. This research showed that velocity gradient in the full scale process was far lower than the design value quoted by a single source but appears to be adequate. Due to the extremely high surface loading rates in the full-scale process there were no suitable design values covered in the literature for settling tubes/lamellar plates.

Modelling the suspension of flocs with ballasting agent in the flocculation process proved difficult as there are limitations with the approaches to modelling this process in the current literature. Methods such as the Zweitering correlation require many empirically derived inputs and factors which are not readily available for the impellers , tank geometry or particles of the full-scale process investigated. This has not just been a constraint on this research but would be a constraint for future work to model suspension of ballasting agent and ballasted flocs in a ballasted flocculation process.

Modelling of discrete ballasting agent particle settling in the sedimentation process was able to be achieved. The results demonstrated that for the full-scale ballasted flocculation process used in this research, that loss of ballasting agent as discrete particles would not be expected, with the minimum particle size retained calculated as 0.002mm, being may times smaller than the d10 value of the in-process ballasting agent of 0.13mm - 0.16mm. This information was used to assist in reaching the conclusion that any ballasting agent loss is through poorly or partly ballasted flocs that may have poor settling characteristics.

Jar testing demonstrated that the ballasted flocculation process is sensitive to ballasting agent changes observed in the full-scale ballasted flocculation process. Based on settled water turbidity data it was seen that increasing the ballasting agent size and maintaining the same concertation by mass resulted in a decrease in performance. It was also demonstrated that performance can be maintained with larger ballasting agent if the surface area concentration is kept constant which requires a higher concentration by mass. These results aligned well with the existing literature.

Considering information in this section and in relation to the full-scale ballasted flocculation process used in this research, it can be concluded that:

a) The ballasting agent particles in the full-scale process following continuous recycling are larger compared with the ballasting agent stock material.

b) The cause of ballasting agent particle size increase is most likely through loss of the smallest particles changing the particle size distribution.
c) The loss of the smaller ballasting agent particles will have a negative impact on settled water turbidity if the mass concentration is not adjusted to maintain the same surface area concentration of ballasting agent in the design or jar test results.
d) The ballasting agent mass concentration is variable within a full-scale process.
e) Jar testing to predict performance of a full-scale process needs to be modified to account for differences between stock and in-process ballasting agent particle size distributions.
f) Modelling and evaluation of ballasted flocculation processes is currently limited by insufficient design criteria available in the literature.

5.2. Summary of further work

Through undertaking this research a number of uncertainties and opportunities have been identified that if investigated could further advance the literature in ballasted flocculation operated at full-scale. The suggested further works are:

a) Undertake a ballasting agent mass balance, measuring the particle size distribution and concentration in-process, in the hydrocyclone overflow and in the clarified water.
b) Investigate if ballasting agent loss in clarified water is through floc carry over or as discrete particles.
c) Trial ballasting agents in the full-scale process with an effective size of 0.15mm and greater with a low Coefficient of Uniformity to determine if ballasting agent loss is reduced.
d) Develop a process model to investigate mixing energy and particle suspension in the flocculation process.
e) Undertake more rigorous sampling of ballasting agent concentrations to gather more data with respect to changes throughout the day.
f) Design a methodology to capture a more representative sample of ballasting agent returned in the hydrocyclone underflow and directly from the flocculation chamber and compare these methodologies.
g) Investigate ballasting agent concentration gradient in flocculation chamber in greater detail.
h) Investigate ways to reduce variability of ballasting agent in hydrocyclone underflow, including use of a balance tank.
i) Further work is recommended to include investigation of design parameters for settling tubes/lamellar plates in a ballasted flocculation process, particularly with regards to very high surface loading rates.
j) Investigation of suspension of ballasting agent particles and ballasted flocs in a ballasted flocculation process, particularly with regard to developing suitable inputs to use the Zweitering correlation (or similar).

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> (*Name and details withheld so as not to disclose manufacturer/supplier of full-scale equipment used in this research).*

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APPENDIX A – PROJECT SPECIFICATION

ENG4111/4112 Research Project
Project Specification

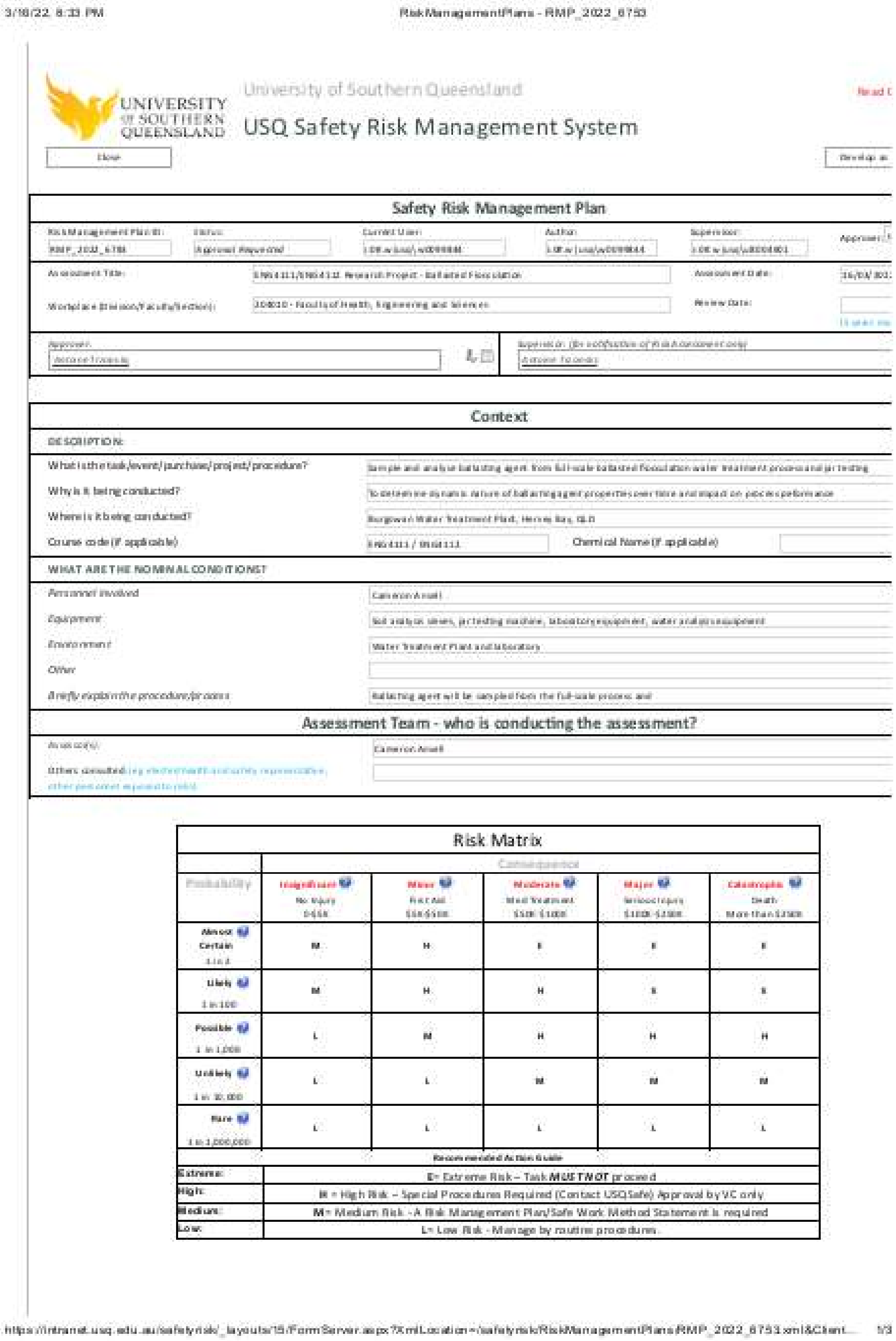
For:	Cameron Ansell
Title:	Understanding ballasting agent dynamics when recycled in a ballasted flocculation process and impact on performance.
Major:	Environmental engineering
Supervisor:	Dr Antoine Trzcinski
Enrolment:	ENG4111 – ONL S1 2022 ENG4112 – ONL S2 2022
Project Aim:	The aim of this research is to prove or disprove that ballasting agent properties are dynamic when the ballasting agent is continually recovered and recycled in a full-scale ballasted flocculation process and to apply the known principles of ballasted flocculation to explain impacts on process performance
Programme:	Version 1 6 March 2022

1. Revisit the literature review undertaken on ballasted flocculation in ENG4110 Research Methodology.
2. Design a methodology and undertake programme of sampling and measurement of ballasting agent properties (particle size distribution, mass per volume unit (g/L) dosed, surface area) in a full-scale ballasted flocculation process.
3. Develop a process model (Microsoft Excel) of the full-scale ballasted flocculation process to inform jar testing parameters and evaluation of data
4. Design a methodology and undertake programme of jar testing to compare flocculation and settling performance between the control ballasting agent and the ‘operating’ ballasting agent
5. Evaluate the performance of the full-scale process for the time period where ballasting agent properties were studied, using ballasting agent property data, the process model and using process setting and water quality data captured through operational monitoring by the owner.

If time and resources permit

6. If ballasting agent dynamics are found to impact process performance, identify and evaluate solutions to manage ballasting agent dynamics in a full-scale ballasted flocculation process.

APPENDIX B – PROJECT RISK ASSESSMENT



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Safety Risk Management Plan

Risk Management Plan ID:	Status:	Current User:	Author:	Supervisor:	Approver:
RMP_2022_6753	Approval Requested	[illegible]	[illegible]	[illegible]	

Assessment Title: ENG4111/ENG4112 Research Project - Ballasted Flocculation

Assessment Date: 16/03/202

Workplace (Division/Faculty/Section): [illegible] - Faculty of Health, Engineering and Sciences

Review Date:

Approver: Antoine Trzcinski

Supervisor: (for notification of Risk Assessment only) Antoine Trzcinski

Context

DESCRIPTION:

What is the task/event/purchase/project/procedure?	Sample and analyse ballasting agent from full-scale ballasted flocculation water treatment process and jar testing
Why is it being conducted?	To determine dynamic nature of ballasting agent properties over time and impact on process performance
Where is it being conducted?	Burgowan Water Treatment Plant, Hervey Bay, QLD
Course code (if applicable)	ENG4111 / ENG4112
Chemical Name (if applicable)	

WHAT ARE THE NOMINAL CONDITIONS?

Personnel involved	Cameron Ansell
Equipment	Soil analysis sieves, jar testing machine, laboratory equipment, water analysis equipment
Environment	Water Treatment Plant and laboratory
Other	
Briefly explain the procedure/process	Ballasting agent will be sampled from the full-scale process and

Assessment Team - who is conducting the assessment?

Assessor(s):	Cameron Ansell
Others consulted: (eg elected health and safety representative, other personnel exposed to risk)	

Risk Matrix

	Consequence				
Probability	Insignificant No Injury 0-$5K	Minor First Aid $5K-$50K	Moderate Med Treatment $50K-$100K	Major Serious Injury $100K-$250K	Catastrophic Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1,000	L	M	H	H	H
Unlikely 1 in 10,000	L	L	M	M	M
Rare 1 in 1,000,000	L	L	L	L	L

Recommended Action Guide	
Extreme:	E= Extreme Risk – Task ***MUST NOT*** proceed
High:	H = High Risk – Special Procedures Required (Contact USQSafe) Approval by VC only
Medium:	M= Medium Risk - A Risk Management Plan/Safe Work Method Statement is required
Low:	L= Low Risk - Manage by routine procedures.

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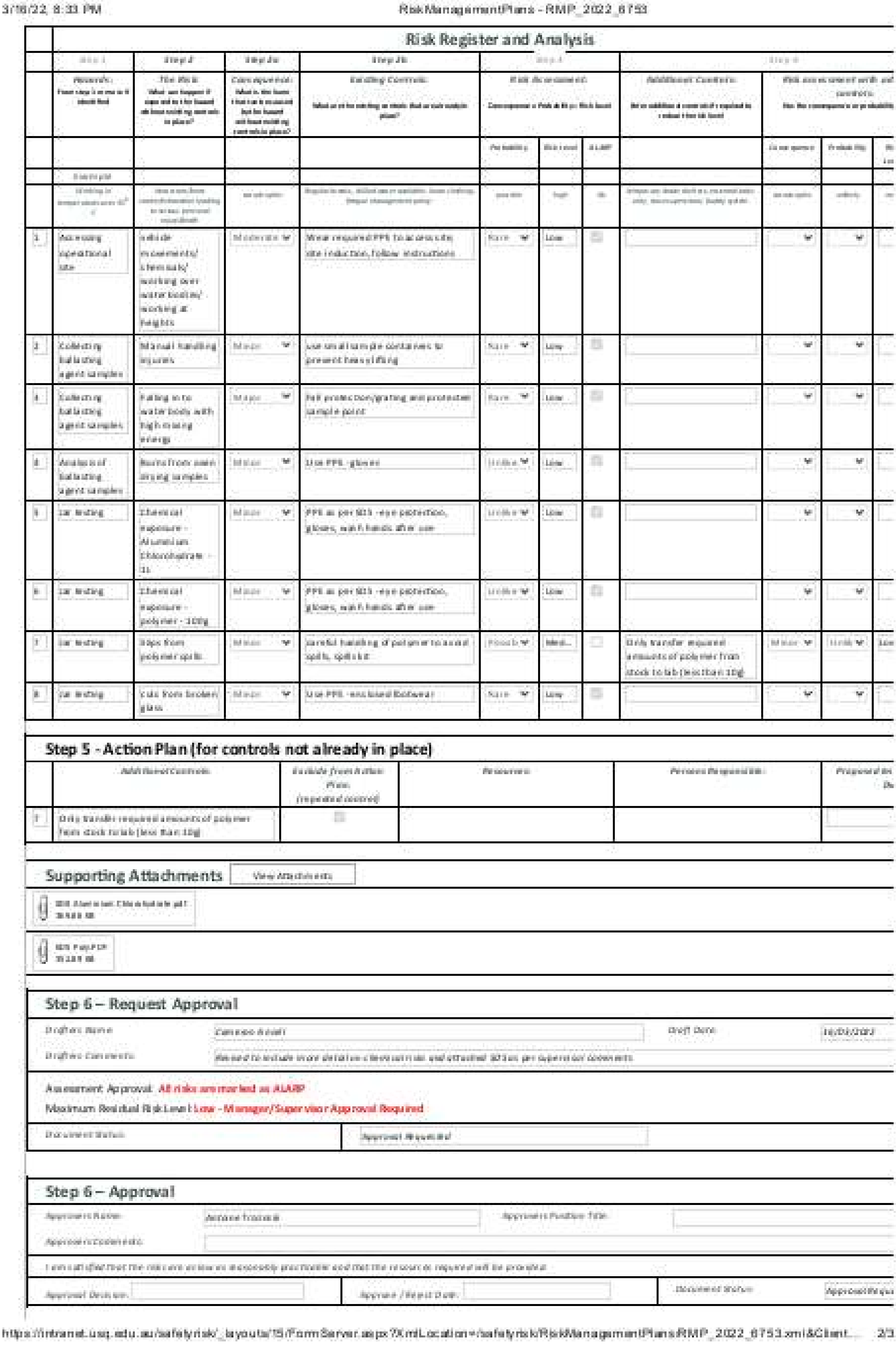

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Risk Register and Analysis

	Step 1	Step 2	Step 2a	Step 2b	Step 3			Step 4			
	Hazards: From step 1 or more if identified	The Risk: What can happen if exposed to the hazard without existing controls in place?	Consequence: What is the harm that can be caused by the hazard without existing controls in place?	Existing Controls: What are the existing controls that are already in place?	Risk Assessment: Consequence x Probability = Risk Level			Additional Controls: Enter additional controls if required to reduce the risk level	Risk assessment with additional controls: Has the consequence or probability		
					Probability	Risk Level	ALARP		Consequence	Probability	Ri
	Example										
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1	Accessing operational site	vehicle movements/ chemicals/ working over water bodies/ working at heights	Moderate	Wear required PPE to access site, site induction, follow instructions	Rare	Low	☐				
2	Collecting ballasting agent samples	Manual handling injuries	Minor	use small sample containers to prevent heavy lifting	Rare	Low	☐				
3	Collecting ballasting agent samples	Falling into water body with high mixing energy	Major	Fall protection/grating and protected sample point	Rare	Low	☐				
4	Analysis of ballasting agent samples	Burns from oven drying samples	Minor	Use PPE - gloves	Unlike	Low	☐				
5	Jar testing	Chemical exposure - Aluminium Chlorohydrate - 1L	Minor	PPE as per SDS - eye protection, gloves, wash hands after use	Unlike	Low	☐				
6	Jar testing	Chemical exposure - polymer - 100g	Minor	PPE as per SDS - eye protection, gloves, wash hands after use	Unlike	Low	☐				
7	Jar testing	Slips from polymer spills	Minor	careful handling of polymer to avoid spills, spill kit	Possib	Medi...	☐	Only transfer required amounts of polymer from stock to lab (less than 10g)	Minor	Unlik	Low
8	Jar testing	Cuts from broken glass	Minor	Use PPE - enclosed footwear	Rare	Low	☐				

Step 5 - Action Plan (for controls not already in place)

	Additional Controls:	Exclude from Action Plan: (repeated control)	Resources:	Persons Responsible:	Proposed Im Da
7	Only transfer required amounts of polymer from stock to lab (less than 10g)	☐			

Supporting Attachments

View Attachments

SDS Aluminium Chlorohydrate.pdf [illegible] KB

SDS Poly.PDF [illegible] KB

Step 6 – Request Approval

Drafter's Name: [illegible]

Draft Date: 16/03/2022

Drafter's Comments: Revised to include more detail on chemical risks and attached SDS as per supervisor comments

Assessment Approval: All risks are marked as ALARP

Maximum Residual Risk Level: Low - Manager/Supervisor Approval Required

Document Status: Approval Requested

Step 6 – Approval

Approver's Name: Antoine Trzcinski

Approver's Position Title:

Approver's Comments:

I am satisfied that the risks are as low as reasonably practicable and that the resources required will be provided.

Approval Decision:

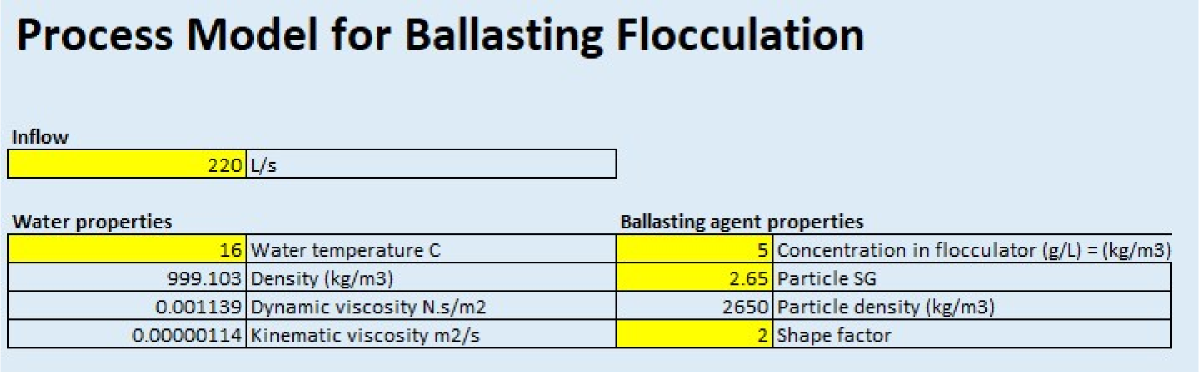
Approve / Reject Date:

Document Status: Approval Requ

https://intranet.usq.edu.au/safetyrisk/_layouts/15/FormServer.aspx?XmlLocation=/safetyrisk/RiskManagementPlans/RMP_2022_6753.xml&Client... 2/3

APPENDIX C – PROCESS MODEL OVERVIEW

General information input area of model - example



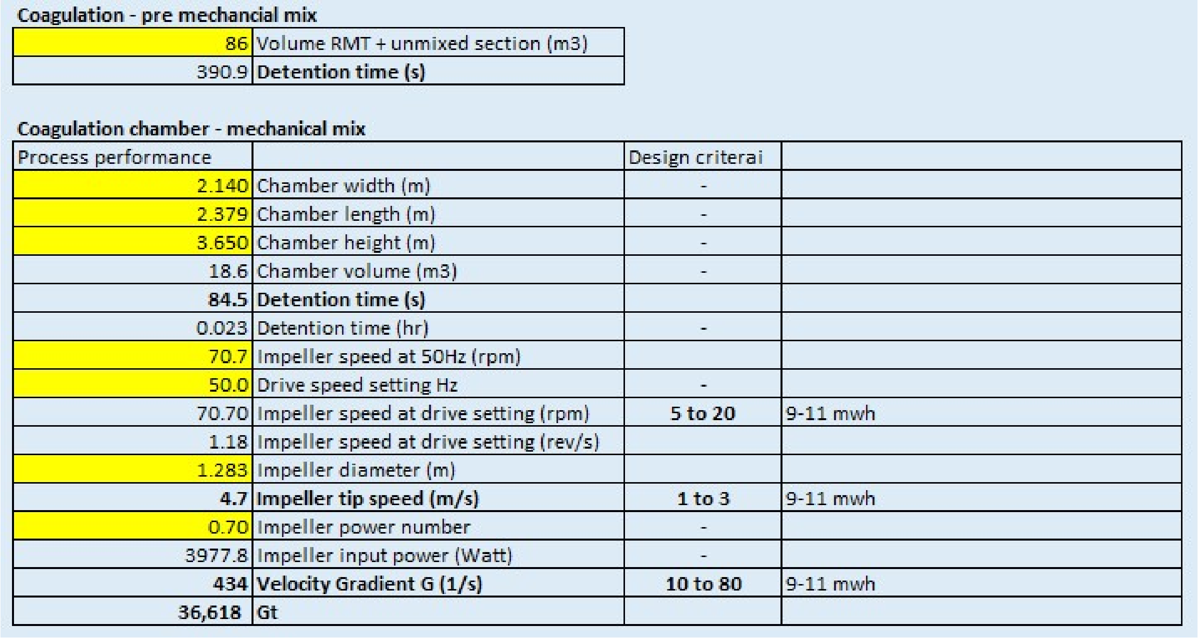
Process Model for Ballasting Flocculation

Inflow

220	L/s

Water properties		**Ballasting agent properties**	
16	Water temperature C	5	Concentration in flocculator (g/L) = (kg/m3)
999.103	Density (kg/m3)	2.65	Particle SG
0.001139	Dynamic viscosity N.s/m2	2650	Particle density (kg/m3)
0.00000114	Kinematic viscosity m2/s	2	Shape factor

Coagulation computational area of model - example



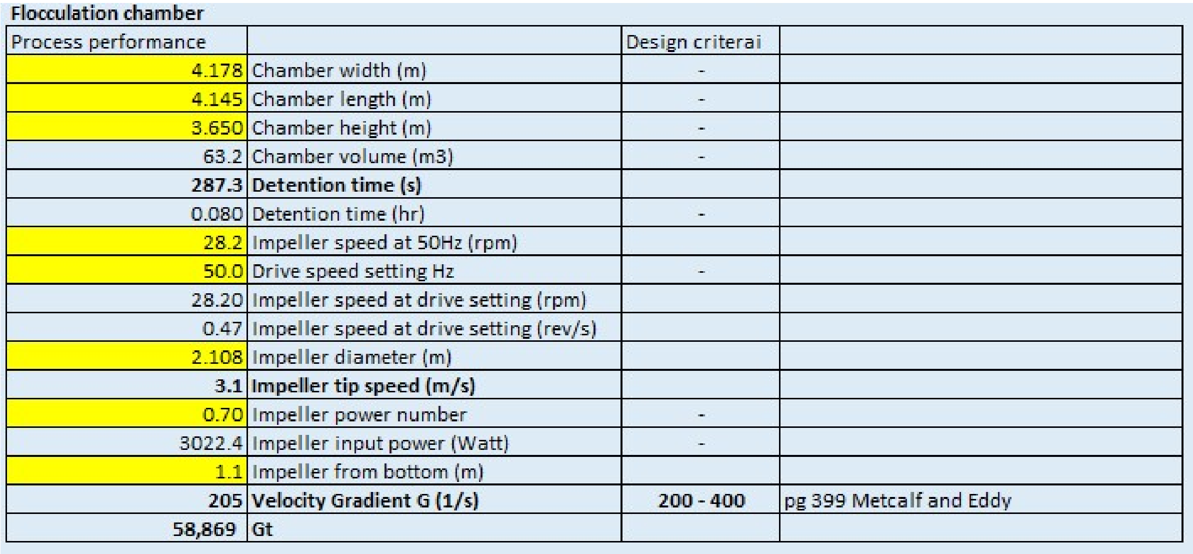
Coagulation - pre mechancial mix

86	Volume RMT + unmixed section (m3)
390.9	**Detention time (s)**

Coagulation chamber - mechanical mix

Process performance		Design criterai	
2.140	Chamber width (m)	-	
2.379	Chamber length (m)	-	
3.650	Chamber height (m)	-	
18.6	Chamber volume (m3)	-	
84.5	**Detention time (s)**		
0.023	Detention time (hr)	-	
70.7	Impeller speed at 50Hz (rpm)		
50.0	Drive speed setting Hz	-	
70.70	Impeller speed at drive setting (rpm)	**5 to 20**	9-11 mwh
1.18	Impeller speed at drive setting (rev/s)		
1.283	Impeller diameter (m)		
4.7	**Impeller tip speed (m/s)**	**1 to 3**	9-11 mwh
0.70	Impeller power number	-	
3977.8	Impeller input power (Watt)	-	
434	**Velocity Gradient G (1/s)**	**10 to 80**	9-11 mwh
36,618	**Gt**		

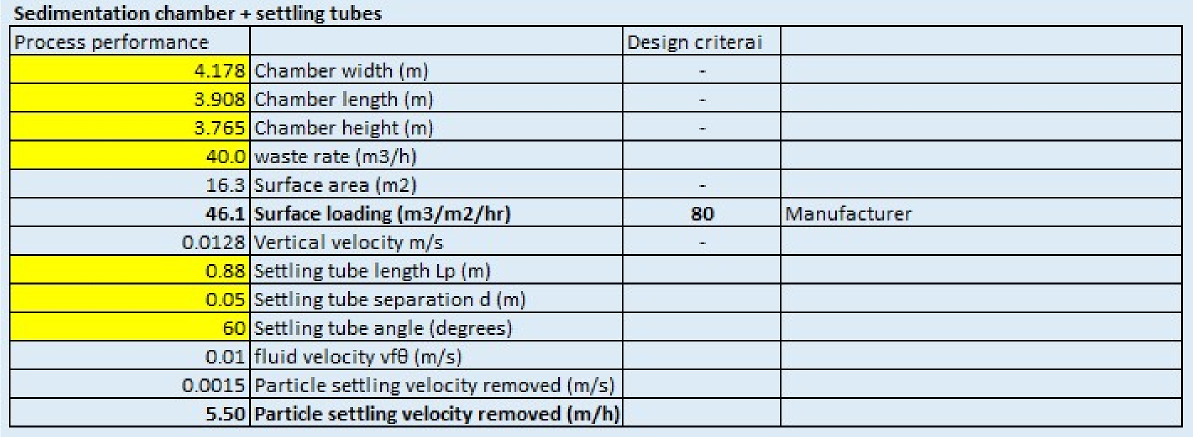
Flocculation computational area of model - example



Flocculation chamber

Process performance		Design criterai	
4.178	Chamber width (m)	-	
4.145	Chamber length (m)	-	
3.650	Chamber height (m)	-	
63.2	Chamber volume (m3)	-	
287.3	**Detention time (s)**		
0.080	Detention time (hr)	-	
28.2	Impeller speed at 50Hz (rpm)		
50.0	Drive speed setting Hz	-	
28.20	Impeller speed at drive setting (rpm)		
0.47	Impeller speed at drive setting (rev/s)		
2.108	Impeller diameter (m)		
3.1	**Impeller tip speed (m/s)**		
0.70	Impeller power number	-	
3022.4	Impeller input power (Watt)	-	
1.1	Impeller from bottom (m)		
205	**Velocity Gradient G (1/s)**	**200 - 400**	pg 399 Metcalf and Eddy
58,869	**Gt**		

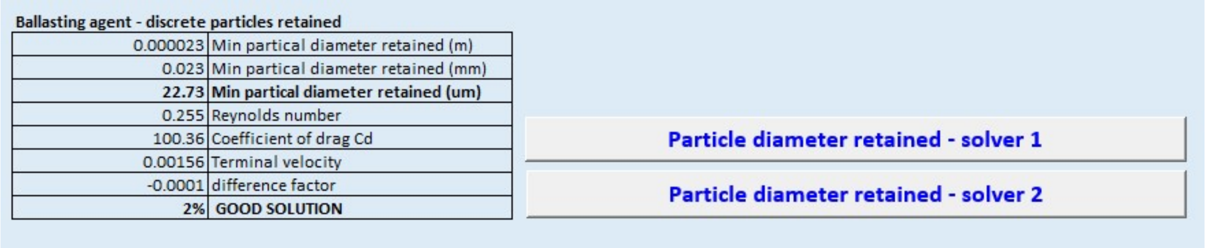
Sedimentation computational area of model - example



Sedimentation chamber + settling tubes

Process performance		Design criterai	
4.178	Chamber width (m)	-	
3.908	Chamber length (m)	-	
3.765	Chamber height (m)	-	
40.0	waste rate (m3/h)		
16.3	Surface area (m2)	-	
46.1	**Surface loading (m3/m2/hr)**	**80**	Manufacturer
0.0128	Vertical velocity m/s	-	
0.88	Settling tube length Lp (m)		
0.05	Settling tube separation d (m)		
60	Settling tube angle (degrees)		
0.01	fluid velocity vfθ (m/s)		
0.0015	Particle settling velocity removed (m/s)		
5.50	**Particle settling velocity removed (m/h)**		

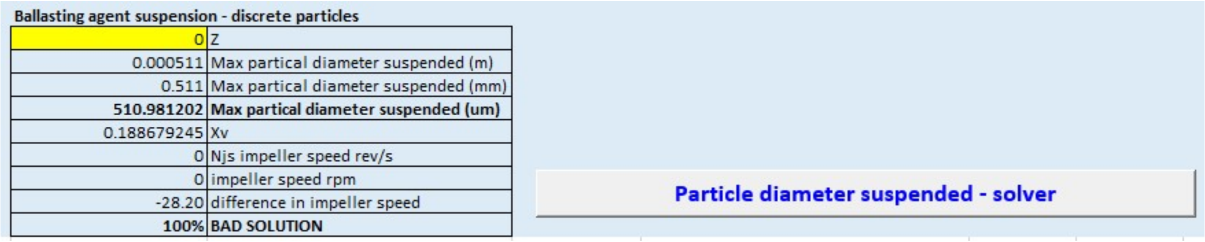
Discrete particle settling computational area of model - example



Ballasting agent - discrete particles retained

0.000023	Min partical diameter retained (m)
0.023	Min partical diameter retained (mm)
22.73	**Min partical diameter retained (um)**
0.255	Reynolds number
100.36	Coefficient of drag Cd
0.00156	Terminal velocity
-0.0001	difference factor
2%	**GOOD SOLUTION**

Discrete particle suspension computational area of model NOT USED



Ballasting agent suspension - discrete particles

0	Z
0.000511	Max partical diameter suspended (m)
0.511	Max partical diameter suspended (mm)
510.981202	**Max partical diameter suspended (um)**
0.188679245	Xv
0	Njs impeller speed rev/s
0	impeller speed rpm
-28.20	difference in impeller speed
100%	**BAD SOLUTION**

APPENDIX D – BA PARTICLE SIZE DISTRIBUTION DATA

Sieve analysis – accumulated mass on sieves results

			Accumulated mass (g)										
Source	Date	Time collected	sample weight (g)	0.85 mm	0.5 mm	0.425 mm	0.3 mm	0.25 mm	0.15 mm	0.075 mm	0.045 mm	0 mm	check
Process	30/04/22	8:45am	104.5	0	2	4.3	34.5	56.5	96.9	104.2	104 2	104.2	99.7%
Process	30/04/22	3:50pm	84.5	0	0.9	2.2	22.8	40.9	75.8	84.3	84.3	84.3	99.8%
Process	01/05/22	8:15am	86.1	0	0.9	2.1	24.3	43.3	79.2	85.8	85.8	85.8	99.7%
Process	02/05/22	2:50pm	95.9	0	1.8	3.6	30.7	50.3	85	95.9	95.9	95.9	100.0%
Process	07/05/22	9:00pm	91.8	0	1.2	2.7	26.8	46.5	81.5	91.5	91.5	91.5	99.7%
Process	07/05/22	4:45pm	88.9	0	1.7	3.6	29.3	48.3	80.8	88.4	88.4	88.4	99.4%
Process	08/05/22	8:40am	91.4	0	1	2.3	24.5	43.9	78.2	91	91	91	99.6%
Process	08/05/22	5:15pm	88.5	0	1.5	3.1	28.7	48.1	79.9	88.2	88.3	88.3	99.8%
Process	04/06/22	11:00am	96.8	0	2.4	5.6	43.1	65.4	86.8	95.6	95.6	95.6	98.8%
Process	04/06/22	1:30pm	97.2	0	3.1	6.6	47.8	70.8	90.8	97	97	97	99.8%
Process	04/06/22	5:00pm	96.4	0	2.5	5.3	45.6	69.3	90.1	96.3	96.3	96.3	99.9%
Process	05/06/22	10:00am	88.8	0	3.2	6.7	45.2	64.7	83.1	88.5	88.6	88.6	99.8%
Process	05/06/22	12:00pm	92.8	0	3.4	7.2	49.8	70.8	89.2	92.5	92.5	92.5	99.7%
Process	05/06/22	2:00pm	95	0	3.3	6.9	49.7	71.6	91.2	94.5	94.6	94.6	99.6%
Process	16/07/22	10:30am	92.9	0	2.3	5.1	38.3	51	79.7	92.4	92.5	92.5	99.6%
Process	16/07/22	1:00pm	92.7	0	1.5	3.7	30.3	41.5	73.3	92	92.1	92.1	99.4%
Process	16/07/22	5:30pm	92.2	0	1.5	3.5	30.8	42.5	75	91.7	91.7	91.7	99.5%
stock	30/04/22		96.3	0	0.4	0.9	6.7	10.6	42.7	96	96.2	96.2	99.9%
stock	01/05/22		89.4	0	0.4	0.8	6 3	9.7	37.5	88.9	89.1	89.1	99.7%
stock	07/05/22		94.9	0	0.1	0.3	3 3	5.8	34.7	93.6	94.2	94.2	99.3%
stock	04/06/22		90	0	0.3	0.5	4 9	8	36.4	89.1	89.3	89.3	99.2%
stock	16/07/22		87.1	0	0	0	0	0	35.4	86.3	86.5	86.6	99.4%

Sieve analysis - % finer than sieve results

			% passing / finer								
Source	Date	Time collected	0.85 mm	0.5 mm	0.425 mm	0.3 mm	0.25 mm	0.15 mm	0.075 mm	0.045 mm	0 mm
Process	30/04/22	8:45am	100%	98%	96%	67%	46%	7%	0%	0%	0%
Process	30/04/22	3:50pm	100%	99%	97%	73%	51%	10%	0%	0%	0%
Process	01/05/22	8:15am	100%	99%	98%	72%	50%	8%	0%	0%	0%
Process	02/05/22	2:50pm	100%	98%	96%	68%	48%	11%	0%	0%	0%
Process	07/05/22	9:00pm	100%	99%	97%	71%	49%	11%	0%	0%	0%
Process	07/05/22	4:45pm	100%	98%	96%	67%	45%	9%	0%	0%	0%
Process	08/05/22	8:40am	100%	99%	97%	73%	52%	14%	0%	0%	0%
Process	08/05/22	5:15pm	100%	98%	96%	67%	46%	10%	0%	0%	0%
Process	04/06/22	11:00am	100%	97%	94%	55%	32%	9%	0%	0%	0%
Process	04/06/22	1:30pm	100%	97%	93%	51%	27%	6%	0%	0%	0%
Process	04/06/22	5:00pm	100%	97%	94%	53%	28%	6%	0%	0%	0%
Process	05/06/22	10:00am	100%	96%	92%	49%	27%	6%	0%	0%	0%
Process	05/06/22	12:00pm	100%	96%	92%	46%	23%	4%	0%	0%	0%
Process	05/06/22	2:00pm	100%	97%	93%	47%	24%	4%	0%	0%	0%
Process	16/07/22	10:30am	100%	98%	94%	59%	45%	14%	0%	0%	0%
Process	16/07/22	1:00pm	100%	98%	96%	67%	55%	20%	0%	0%	0%
Process	16/07/22	5:30pm	100%	98%	96%	66%	54%	18%	0%	0%	0%
stock	30/04/22		100%	100%	99%	93%	89%	56%	0%	0%	0%
stock	01/05/22		100%	100%	99%	93%	89%	58%	0%	0%	0%
stock	07/05/22		100%	100%	100%	96%	94%	63%	1%	0%	0%
stock	04/06/22		100%	100%	99%	95%	91%	59%	0%	0%	0%
stock	16/07/22		100%				100%	59%	0%	0%	0%

Sieve analysis - % accumulated on sieve results

			%accumulated								
Source	Date	Time collected	0.85 mm	0.5 mm	0.425 mm	0.3 mm	0.25 mm	0.15 mm	0.075 mm	0.045 mm	0 mm
Process	30/04/22	8:45am	0%	2%	2%	29%	21%	39%	7%	0%	0%
Process	30/04/22	3:50pm	0%	1%	2%	24%	21%	41%	10%	0%	0%
Process	01/05/22	8:15am	0%	1%	1%	26%	22%	42%	8%	0%	0%
Process	02/05/22	2:50pm	0%	2%	2%	28%	20%	36%	11%	0%	0%
Process	07/05/22	9:00pm	0%	1%	2%	26%	22%	38%	11%	0%	0%
Process	07/05/22	4:45pm	0%	2%	2%	29%	21%	37%	9%	0%	0%
Process	08/05/22	8:40am	0%	1%	1%	24%	21%	38%	14%	0%	0%
Process	08/05/22	5:15pm	0%	2%	2%	29%	22%	36%	9%	0%	0%
Process	04/06/22	11:00am	0%	3%	3%	39%	23%	22%	9%	0%	0%
Process	04/06/22	1:30pm	0%	3%	4%	42%	24%	21%	6%	0%	0%
Process	04/06/22	5:00pm	0%	3%	3%	42%	25%	22%	6%	0%	0%
Process	05/06/22	10:00am	0%	4%	4%	43%	22%	21%	6%	0%	0%
Process	05/06/22	12:00pm	0%	4%	4%	46%	23%	20%	4%	0%	0%
Process	05/06/22	2:00pm	0%	3%	4%	45%	23%	21%	3%	0%	0%
Process	16/07/22	10:30am	0%	2%	3%	36%	14%	31%	14%	0%	0%
Process	16/07/22	1:00pm	0%	2%	2%	29%	12%	35%	20%	0%	0%
Process	16/07/22	5:30pm	0%	2%	2%	30%	13%	35%	18%	0%	0%
stock	30/04/22		0%	0%	1%	6%	4%	33%	55%	0%	0%
stock	01/05/22		0%	0%	0%	6%	4%	31%	58%	0%	0%
stock	07/05/22		0%	0%	0%	3%	3%	31%	63%	1%	0%
stock	04/06/22		0%	0%	0%	5%	3%	32%	59%	0%	0%
stock	16/07/22		0%	0%	0%	0%	0%	41%	59%	0%	0%

Sieve analysis – surface area and indices results

Source	Date	Time collected	Specific surface area m2/g	d10	d60	d50	CU
Process	30/04/22	8:45am	0.0095	0.1577	0.2837	0.26	1.7986
Process	30/04/22	3:50pm	0.0101	0.1494	0.2698	0.2464	1.8063
Process	01/05/22	8:15am	0.0098	0.1555	0.2736	0.2511	1.7595
Process	02/05/22	2:50pm	0.01	0.141	0.2805	0.256	1.9893
Process	07/05/22	9:00pm	0.0101	0.1436	0.2751	0.2519	1.9156
Process	07/05/22	4:45pm	0.0097	0.1538	0.2841	0.2608	1.8467
Process	08/05/22	8:40am	0.0105	0.1283	0.2693	0.2453	2.0989
Process	08/05/22	5:15pm	0.0098	0.1514	0.2829	0.2602	1.8694
Process	04/06/22	11:00am	0.009	0.1536	0.3162	0.2895	2.0592
Process	04/06/22	1:30pm	0.0086	0.1675	0.3273	0.2985	1.9541
Process	04/06/22	5:00pm	0.0087	0.1665	0.322	0.2946	1.9338
Process	05/06/22	10:00am	0.0085	0.1683	0.3317	0.3029	1.9713
Process	05/06/22	12:00pm	0.0081	0.1823	0.3376	0.3104	1.8513
Process	05/06/22	2:00pm	0.0082	0.1809	0.3346	0.307	1.8497
Process	16/07/22	10:30am	0.01	0.129	0.3049	0.2687	2.3629
Process	16/07/22	1:00pm	0.011	0.1115	0.2708	0.2357	2.4279
Process	16/07/22	5:30pm	0.0108	0.1162	0.2749	0.2397	2.3659
stock	30/04/22		0.0158	0.0883	0.1631	0.1424	1.8486
stock	01/05/22		0.016	0.0877	0.1567	0.1397	1.7865
stock	07/05/22		0.0167	0.0862	0.1462	0.1342	1.6955
stock	04/06/22		0.0162	0.0874	0.1524	0.1383	1.7432
stock	16/07/22		0.0167	0.0873	0.1521	0.1384	1.7424

APPENDIX E – BA CONCENTRATION DATA

Methodology 1 results

Tub dimensions		sand density (bulk) g/mL	1.7
width (m)	0.412		
length (m)	0.412	WTP inflow (L/s)	250
height (m)	0.55		
v (m3)	0.093359		

Date	**time**	**time to fill (s)**	**water level from top (m)**	**sand level from top (m)**	**sand mass kg**	**sand dose rate g/s**	**Sand dose rate g/L**	**Comments**
01/10/22	10:09	27.52	0.08	0.344	59.44435	2160.042	8.6	random timing
01/10/22	10:44	27.1	0.058	0.345	59.15578	2182.87	8.7	random timing
01/10/22	11:34	28.16	0.065	0.367	52.80736	1875.261	7.5	random timing
01/10/22	12:39	27.12	0.078	0.38	49.05602	1808.85	7.2	random timing
01/10/22	13:13	27.06	0.075	0.349	58.00152	2143.441	8.6	concentrated stage
01/10/22	13:25	29.12	0.044	0.34	60.59861	2080.996	8.3	concentrated stage
01/10/22	14:16	25.36	0.11	0.362	54.25018	2139.203	8.6	concentrated stage
01/10/22	15:38	26.13	0.086	0.33	63.48426	2429.554	9.7	concentrated stage
01/10/22	16:20	23.52	0.13	0.345	59.15578	2515.127	10.1	concentrated stage
01/10/22	16:38	25.12	0.11	0.371	51.6531	2056.254	8.2	avoided concentrated stage
01/10/22	17:21	24.25	0.115	0.344	59.44435	2451.313	9.8	concentrated stage
01/10/22	17:43	26.76	0.087	0.347	58.57865	2189.038	8.8	concentrated stage

Methodology 2 results

Date	**Time collected**	**Sample volume (L)**	**Ballast agent weight (g)**	**Ballast agent concentration (g/L)**
17/07/22	9:24	1.08	4.50	4.2
17/07/22	10:28	1.16	5.10	4.4
17/07/22	11:24	0.90	3.40	3.8
17/07/22	12:35	0.91	4.10	4.5
17/07/22	13:30	0.90	3.50	3.9
17/07/22	14:40	1.04	3.70	3.6
17/07/22	15:40	1.03	3.10	3.0
17/07/22	16:30	0.89	4.20	4.7
17/07/22	17:30	0.90	4.80	5.3

APPENDIX F – JAR TEST DATA

TEST:	**CONTROL - no sand**				
Date:	**28/08/2022**				
Raw water quality		Dose rate			
Colour true PtCo	177	NaHCO3 mg/L	100		
Turbidity NTU	36.5	ACH ppmv	100		
Alkalinity mg/L CaCO3	20	Polymer mg/L	1.25		
Jar test results					
		Test 1	Test 2	Test 3	AVG
Settling time (s)	**Sample depth (mm)**	**Turbidity (NTU)**	**Turbidity (NTU)**	**Turbidity (NTU)**	**Turbidity (NTU)**
0	50	41.6	41.5	41.1	41.4
30	50	10.6	3.8	5.1	6.5
60	50	3.7	1.8	2.0	2.5
90	50	5.3	1.3	1.3	2.6
120	50	6.0	1.1	0.6	2.6
150	50	1.9	0.8	0.6	1.1

TEST:	**6g/L 0.075 - 0.150 mm sand**				
Date:	**28/08/2022**				
Raw water quality		Dose rate			
Colour true PtCo	177	NaHCO3 mg/L	100		
Turbidity NTU	36.5	ACH ppmv	100		
Alkalinity mg/L CaCO3	20	Polymer mg/L	1.25		
Jar test results					
		Test 1	Test 2	Test 3	AVG
Settling time (s)	Sample depth (mm)	Turbidity (NTU)	Turbidity (NTU)	Turbidity (NTU)	Turbidity (NTU)
0	50	8.9	10.2	6.1	8.4
30	50	1.0	0.9	0.8	0.9
60	50	1.0	0.8	0.7	0.8
90	50	0.8	0.8	0.5	0.7
120	50	0.6	0.7	0.6	0.6
150	50	0.8	0.7	0.7	0.7

TEST:	**6g/L 0.150 - .0.250 mm**				
Date:	**28/08/2022**				
Raw water quality		Dose rate			
Colour true PtCo	177	NaHCO3 mg/L	100		
Turbidity NTU	36.5	ACH ppmv	100		
Alkalinity mg/L CaCO3	20	Polymer mg/L	1.25		
Jar test results					
		Test 1	Test 2	Test 3	AVG
Settling time (s)	Sample depth (mm)	Turbidity (NTU)	Turbidity (NTU)	Turbidity (NTU)	Turbidity (NTU)
0	50	21	19	25	21.4
30	50	3	3	3	2.9
60	50	2	2	3	2.6
90	50	2	3	2	2.1
120	50	2	2	2	2.1
150	50	2	3	1	1.9

TEST:	**10.7g/L 0.150 - .0.250 mm**				
Date:	**28/08/2022**				
Raw water quality		Dose rate			
Colour true PtCo	177	NaHCO3 mg/L	100		
Turbidity NTU	36.5	ACH ppmv	100		
Alkalinity mg/L CaCO3	20	Polymer mg/L	1.25		
Jar test results					
		Test 1	Test 2	Test 3	AVG
Settling time (s)	Sample depth (mm)	Turbidity (NTU)	Turbidity (NTU)	Turbidity (NTU)	Turbidity (NTU)
0	50	8.3	12.8	7.4	9.5
30	50	0.7	0.9	1.2	0.9
60	50	0.8	0.7	0.9	0.8
90	50	0.7	0.7	1.0	0.8
120	50	0.6	0.6	0.8	0.7
150	50	0.6	0.6	1.0	0.7