



**THE UNIVERSITY
OF QUEENSLAND**
A U S T R A L I A

Bachelor of Engineering Thesis

Improving the testing of sedimentation processes

Development of a large column and observations of solid
concentration using turbidity measurements

Student Name: Johnny GIAN

Student Number: 42379993

Course Code: CIVL4580

Supervisor: Dr.-Ing habil. Alexander Scheuermann

Submission date: 28 October 2016

A thesis submitted in partial fulfilment of the requirements of the
Bachelor of Engineering degree in Civil & Geotechnical Engineering

School of Civil Engineering
Faculty of Engineering, Architecture and Information Technology

Johnny Gian
34 Wana St
Sunnybank
QLD, 4109

28 October 2016

Dr. Jose L. Torero
Head
School of Civil Engineering
The University of Queensland
Queensland 4072

Dear Sir,

I hereby submit my thesis titled "*Improving the testing of sedimentation processes – Development of a large column test and observations of solid concentration using turbidity measurements*" for consideration as partial fulfilment of the Bachelor of Engineering degree.

All the work contained within this thesis is my original work except where otherwise acknowledged.

I understand that this thesis may be made publicly available and reproduced by The University of Queensland unless a limited term embargo on publication has been negotiated with a sponsor.

Yours sincerely

Johnny Gian

Student ID: 42379993

ABSTRACT

Sedimentation is an important natural process with widespread applications in water treatment and dredging. Existing methods used to characterise sedimentation processes are often limited by wall effects of the apparatus or the influence of sampling on settling dynamics. In addition, these methods and apparatuses do not allow for post-sedimentation testing, valuable for determining important geotechnical parameters. This research project adopts a novel approach towards sedimentation testing, investigating correlations of turbidity and dielectric measurements to mixture concentration and their use in characterising settling processes without disturbance. A modular large column apparatus was designed to accommodate a suite of instrumentation along its length. This consisted of two different configurations, with specialised base designs, accommodating compatibility with the slurry consolidometer equipment and allowing for post-sedimentation density profiling and hydraulic conductivity tests. In total, six components of this design were developed, with detailed design drawings produced. To determine the relationship between turbidity measurements and the concentration of a suspension, calibration tests were undertaken using TSD-10 turbidity sensors. Inverse function relationships between these parameters were obtained for four different mixture types. The model column tests were designed to investigate the complementary use of dielectric and turbidity correlations in characterising settling processes as a proof-of-concept for the large column design. Findings from these tests indicate that correlating the two sets of measurements provide an improved resolution of concentration data. Additionally, turbidity measurements at low initial mixture concentrations successfully show evidence of hindered settling processes occurring. To continue developing this approach towards sedimentation testing, further design development of the large column is required, followed by fabrication, calibration and experimental testing. Furthermore, additional calibration tests may lead to a better defined relationship between turbidity measurements and concentration, while model column tests using a wider range of initial concentrations and different mixture types should be pursued.

CONTRIBUTIONS BY OTHERS

While this report has been completed individually, some calculations have been undertaken and data collected in partnership with Yucheng (Sophia) Jiang, with the generous assistance of Dr. Thierry Bore. The data loggers essential for undertaking the turbidity measurements were kindly provided by Dr. Alistair Grinham.

ACKNOWLEDGEMENTS

Firstly, I would like to thank Alex, my thesis supervisor, for his kindness, patience and encouragement in the undertaking of this project. It would not have been possible if it were not for his clear guidance and timely support.

Secondly, I would also like to thank Al for his guidance and advice throughout this project and for providing the data loggers that I desperately needed. I would also like to thank Thierry and Sophia for their work in investigating dielectric correlations and in organising the fabrication of the model column.

Thirdly, many thanks go to Sebastian, Jenny and Shayne for their laboratory and workshop assistance. Without their help within apologetically short timeframes, this project would not have been possible.

Last but not least, I would like to thank my family and Elaine for supporting me in my studies and in particular, this project. Their support, encouragement and reminders to backup my work were instrumental towards this project's success.

TABLE OF CONTENTS

Abstract.....	i
Contributions by Others	ii
Acknowledgements.....	iii
Table of Contents	iv
List of Figures	vii
List of Tables	ix
Notation	x
1.0 General Introduction	1
2.0 Literature Review	2
2.1 Sedimentation types	2
2.2 Factors influencing settling behaviour	4
2.3 Existing sedimentation testing methods	5
2.4 Summer research project	10
2.5 Research gaps	13
3.0 Project Scope	14
3.1 Research objective	14
3.2 Research methodology.....	14
3.3 Key project outcomes	14
3.4 Contents of thesis.....	15
4.0 Large Column Design	16
4.1 Design objectives	16
4.2 Design considerations	17
4.2.1 General considerations	17
4.2.2 Consolidometer arrangement.....	20
4.2.3 Density testing arrangement	24

4.3 Design outcomes	25
4.4 Design documentation	26
5.0 Experimental Testing	27
5.1 Calibration Tests	27
5.1.1 Aim	27
5.1.2 Mixtures	27
5.1.3 Equipment	27
5.1.4 Variables.....	29
5.1.5 Methodology	29
5.1.6 Results and discussion.....	34
5.2 Model Column Tests	39
5.2.1 Aim	39
5.2.2 Column design.....	39
5.2.3 Mixtures	41
5.2.4 Equipment	41
5.2.5 Methodology	42
5.2.6 Results and discussion.....	44
6.0 Conclusion and Evaluation	54
6.1 Calibration tests	54
6.2 Model column tests	55
6.3 Large column design.....	57
References	58
Appendices.....	62
Appendix A: USACE settling test methodology	62
Appendix B: Summer research project details	65
Appendix C: USACE sedimentation column plans.....	69
Appendix D: Large column design drawings, version 1 (23 rd May 2016)	71

Appendix E: Large column design drawings, version 2 (13 th August 2016).....	73
Appendix F: Preliminary calibration tests	75
Appendix G: Example of calibration test data processing	81
Appendix H: Turbidity calibration test results.....	86
Appendix I: Comparisons of output from different sensors.....	156
Appendix J: TableCurve 2D outputs.....	158
Appendix K: As-built drawing of the model column	163
Appendix L: Example of model column turbidity test data processing.....	165
Appendix M: Model column turbidity test results	169

LIST OF FIGURES

Figure 1: Sedimentation process.....	1
Figure 2: Settling characteristics of discrete and flocculant particles.....	3
Figure 3: Settling velocity vs. concentration	4
Figure 4: Batch analysis	5
Figure 5: Relationship between initial concentration and settling curves.....	6
Figure 6: Conceptual plot of interface height against time.....	6
Figure 7: Settling column for analysing type I settling	7
Figure 8: Settling column for analysing type II settling	7
Figure 9: Example of isoremoval lines from type II settling column test	8
Figure 10: Schematic of the USACE settling test apparatus	9
Figure 11: Outline drawing of assembled Owen Tube.....	9
Figure 12: Sketches of density-stratified fluids stirred by oscillating grids	10
Figure 13: Observations from summer research project	12
Figure 14: Column arrangements.....	16
Figure 15: Plans for USACE sedimentation column	17
Figure 16: Elevation of 30cm module	18
Figure 17: Horizontal section through 30cm module	18
Figure 18: Vertical section through 40cm top unit	19
Figure 19: Flange detail.....	19
Figure 20: Consolidometer arrangement for post-sedimentation testing	20
Figure 21: Slurry consolidometer apparatus.....	20
Figure 22: Initial design approach for consolidometer arrangement base	21
Figure 23: Section through consolidometer arrangement tube unit	22
Figure 24: Section through flange unit.....	23
Figure 25: Assembly of consolidometer arrangement base	23
Figure 26: Arrangement for post-sedimentation density profiles and hydraulic conductivity testing	24
Figure 27: Perspective of 10cm column unit	24
Figure 28: Section through density base unit	25
Figure 29: Experimental setup during mixing	28
Figure 30: Preparation of the 'beakers'	30

Figure 31: Collated calibration test data for kaolin in tap water, organised by sensor	34
Figure 32: Collated calibration test data, organised by mixture type	35
Figure 33: Leakage of mixture into sensor and reapplied silicone	38
Figure 34: Build-up of material at base of 'beaker'	38
Figure 35: Arrangement of sensors on model column	39
Figure 36: Fabricated model column	40
Figure 37: Experimental setup during settling	42
Figure 38: Plot of concentration over duration of Test i	44
Figure 39: Concentration data from Test i over the first hour	45
Figure 40: Camera images of the interface passing each sensor	45
Figure 41: Concentration data from Test iv over the first hour	46
Figure 42: Concentration data from Test i after the first hour	47
Figure 43: Observed changes in supernatant turbidity	48
Figure 44: Changes in lighting conditions observed in column reflection	48
Figure 45: Plot of concentration over duration of Test iii from turbidity data	49
Figure 46: Concentration over time for Test iii at sensor 3 using turbidity and dielectric data	50
Figure 47: Concentration over time for Test iii at sensor 4 using turbidity and dielectric data	50
Figure 48: Concentration over the first four hours of Test iii at sensor 4, turbidity and dielectric data	51
Figure 49: Observed build-up of material on dielectric sensors	52
Figure 50: Bubbles observed inside the sedimentation column	53
Figure 51: Settled material observed on top of turbidity sensors during the model column tests	53

LIST OF TABLES

Table 1: Limitations of tests from summer research project with associated observations	11
Table 2: Designations of tests undertaken with various combinations of sensor and material	27
Table 3: Mixing volumes for calibration tests.....	32
Table 4: Mixing volumes for additional calibration tests	33
Table 5: Curve fitting constants for negative exponential curves fitted to calibration test data	36
Table 6: Curve fitting constants for inverse function curves fitted to calibration test data	36
Table 7: Relationships between turbidity in ‘bits’ and mixture concentration for the four mixtures.....	37
Table 8: Overview of data quality and correlation quality for each model column test	44
Table 9: Limitations identified in the calibration tests	54
Table 10: Limitations identified in the model column tests	56

NOTATION

AEB	Advanced Engineering Building
GEC	Geotechnical Engineering Centre
NTU	Nephelometric Turbidity Unit
PSD	Particle size distribution
UQ	The University of Queensland
USACE	United States Army Corps of Engineers

1.0 GENERAL INTRODUCTION

Settling or sedimentation is the process by which solid particles settle through a liquid, either to produce a concentrated slurry from a dilute suspension or to clarify a liquid containing solid particles (Law & Rennie, 2015). This results in a layer of the settled material with an overlying supernatant liquid. This process is illustrated in Figure 1.

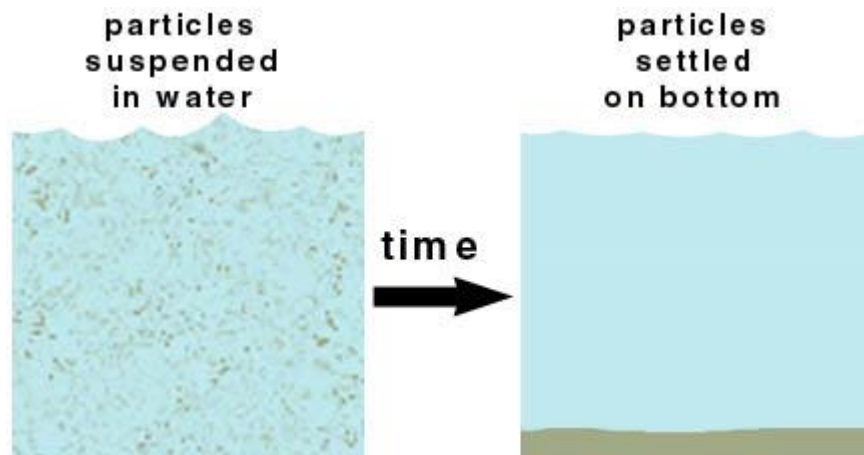


Figure 1: Sedimentation process (Casiday, et al., 2008)

In practice, sedimentation is often used as a method to remove suspended solids from a suspension. Conventional water treatment methods commonly utilise sedimentation following coagulation and flocculation processes as part of the treatment process (Crittenden, et al., 2012). Additionally, it is often used in wastewater treatment to mechanically remove suspended solids (The World Bank Group, 2016).

Sedimentation is also an important consideration in the construction and maintenance of ports and navigable waterways. While this process causes the deposition of eroded material and results in necessary dredging works, sedimentation is also a key factor in the disposal of the dredged material (Montgomery, 1980).

With its relevance in various important applications, it is important to develop procedures to better understand and characterise sedimentation processes.

2.0 LITERATURE REVIEW

A review of existing literature and sedimentation testing methods was first undertaken.

2.1 Sedimentation types

There are four key classifications of sedimentation processes, each characterised by different settling behaviour. Bose (2009) describes these as:

- Type I: Discrete particle settling – particles settle individually without interaction with neighbouring particles.
- Type II: Flocculant settling – flocculation causes the particles to increase in mass and settle at a faster rate.
- Type III: Hindered or Zone settling – a mass of particles tends to settle as a unit with individual particles remaining in fixed positions with respect to each other.
- Type IV: Compression settling – the concentration of particles is so high that sedimentation can only occur through compaction of the structure.

Discrete particle settling occurs in dilute mixtures where there is no particle interaction, with discrete particles being defined as particles whose size, shape and specific gravity do not change with time (Peavy, et al., 1985). The settling velocity of a single spherical particle undergoing discrete settling under laminar conditions can be described by Stokes' law (Chapuis, et al., 2015):

$$v_s = \frac{g(\rho_s - \rho_f)D^2}{18\eta_f}$$

where:

v_s = settling velocity [m/s]

g = gravitational acceleration [m/s^2]

ρ_s = particle density [kg/m^3]

ρ_f = fluid density [kg/m^3]

D = particle diameter [m]

η_f = fluid viscosity [$kg/m/s$]

Flocculant settling describes the behaviour of flocculating particles in a dilute suspension, where the process of flocculation causes these particles to coalesce with other particles during settling. This effectively increases the overall size and shape of the flocs and results in an increased settling velocity (Kocamemi, n.d.). As these particles collide and agglomerate continually during settling, changes to the floc size, shape and specific gravity will also occur continually. With many factors affecting the flocculation process, it is not possible to develop a general formula to determine settling velocities for flocculant suspensions (Peavy, et al., 1985). Nonetheless, the difference in its settling behaviour compared to Type I settling is indicated in Figure 2.

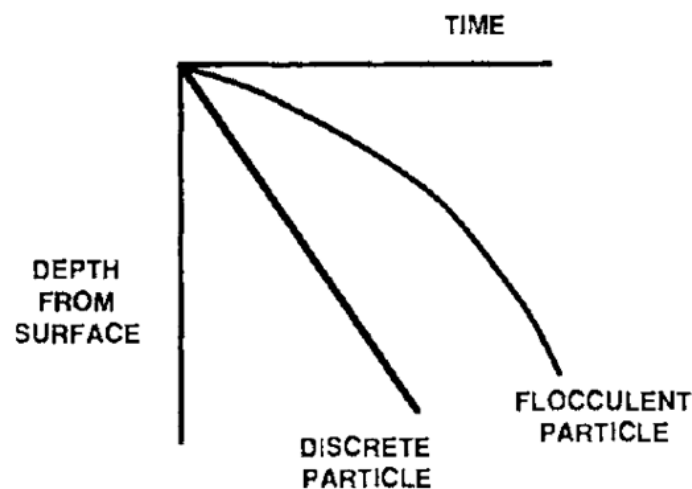


Figure 2: Settling characteristics of discrete and flocculant particles (Bhosale, 2015)

Hindered settling occurs in concentrated solutions whereby particles are closely packed to the degree where movement is restricted. In this type of sedimentation, the particles settle as a whole due to their packing arrangement, more so than as individual particles (Alemayehu, 2010). Interference by fluids results in a reduction in the settling velocity, with flow being limited by the hydraulic conductivity through the particle groups. The characterisation of hindered settling has been attempted, with many models being based on the solid flux theory, while a number of empirical relations, such as Vesilinds formula, have been used to describe settling parameters (Carlsson, 1998).

Compression settling occurs in highly concentrated solutions or sludges, where particles are in contact and settle under compression at a low velocity. This results in a reduction of the material's porosity as it consolidates under the weight of material above it, squeezing water out of the void spaces and increasing in concentration (Xu, et al., 2012).

2.2 Factors influencing settling behaviour

There are many factors that affect the settling behaviour of a suspension. Schroeffer (1933) described a range of factors that influence sewage sedimentation processes. Those relating to the properties of the solid and fluid are detailed below:

- Fluid specific gravity: The higher this parameter, the slower the settling.
- Fluid viscosity: More viscous fluids result in slower particle settling.
- Particle size: The larger the particle, the faster it will settle.
- Particle shape: More spherical particles will have less surface area per unit weight, minimising skin friction and hence, will settle faster.
- Solid specific gravity: The heavier the particle, the faster it will settle.
- Solid concentration: The concentration of particles in a mixture will affect its settling behaviour.
- Flocculation: Flocculation behaviour of the particles will form larger aggregates, settling at a higher rate.

The effect of solids concentration of the suspension has been explored in a number of studies, with Figure 3 describing the dependence of settling velocity of a kaolinite suspension on its concentration (Wolanski, et al., 1992).

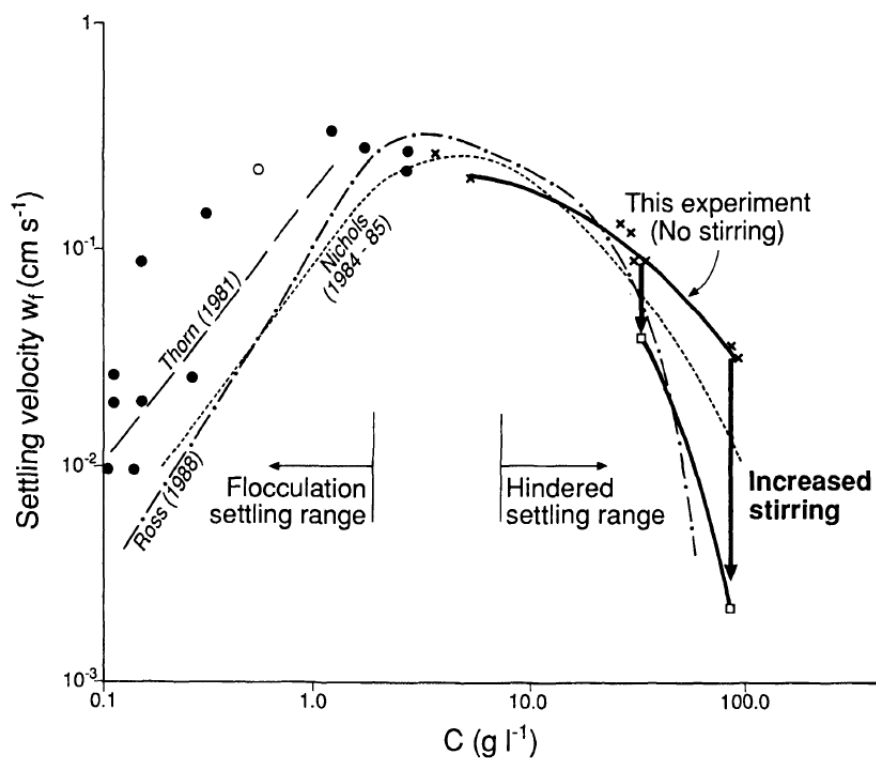


Figure 3: Settling velocity vs. concentration (Wolanski, et al., 1992)

Fluid temperature has also been described to have an effect on the sedimentation rate, with the rate of settling decreasing with lower temperatures (Sarmiento & Urlherr, 1979). Another factor is the electrical charge present on the particles, as all particles tend to have a slight charge and those charged similarly will be kept from congregating into flocs (Minnesota Rural Water Association, 2009). The salinity of the fluid also appears to be another factor that may affect settling, with the presence of salt acting as a coagulant for fine-grained dredged material (USACE, 1987).

2.3 Existing sedimentation testing methods

From literature, it was found that there are many different apparatuses and methods used for undertaking sedimentation testing. A number of these are based on batch analyses of a suspension. This involves the filling of a column with a suspension that is allowed to settle without disturbance and is described in Figure 4.

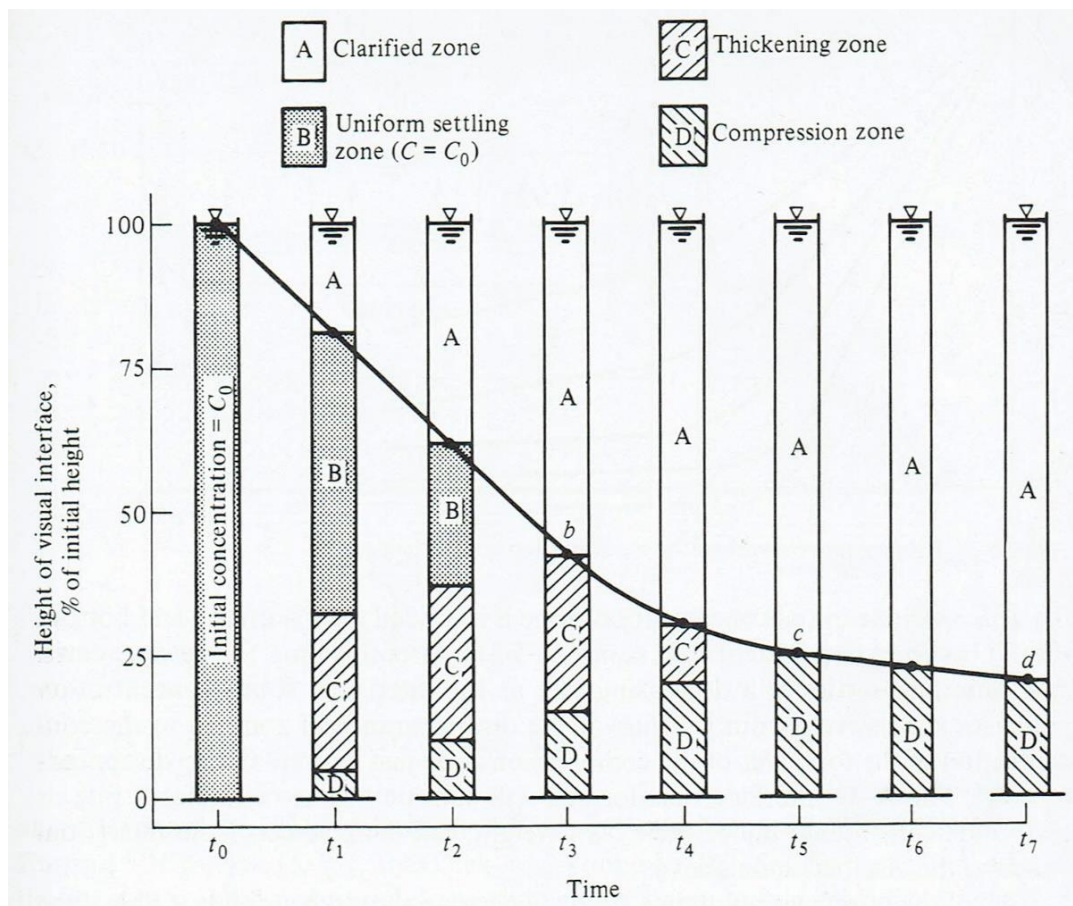


Figure 4: Batch analysis (Peavy, et al., 1985)

The interface height defining the clarified zone is measured over time and can be plotted over the duration of the test. Figure 5 illustrates this, with relationships for different initial concentrations also shown.

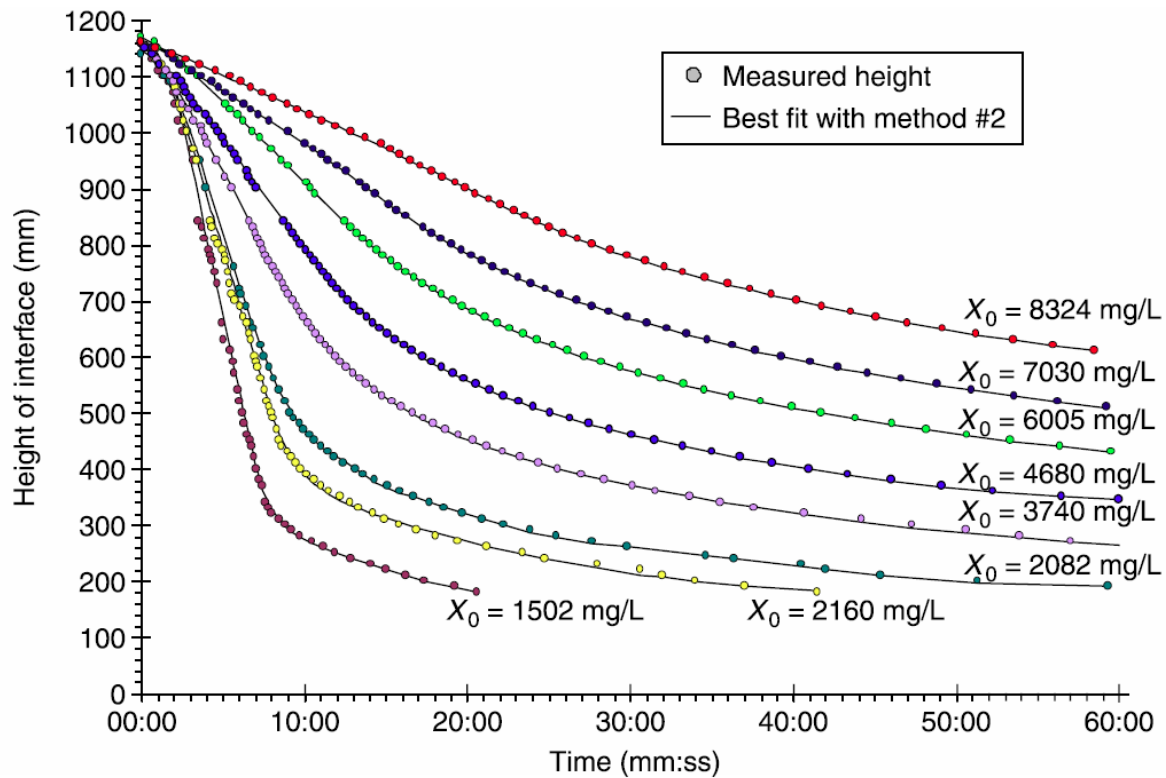


Figure 5: Relationship between initial concentration and settling curves (Stricker, et al., 2007)

Interpretation of these graphs can be used to determine sedimentation behaviour of the mixture, with the settling velocity being interpreted as the slope of the plotted graph. This is shown in Figure 6, along with annotations indicating the different settling processes that occur during one of these tests.

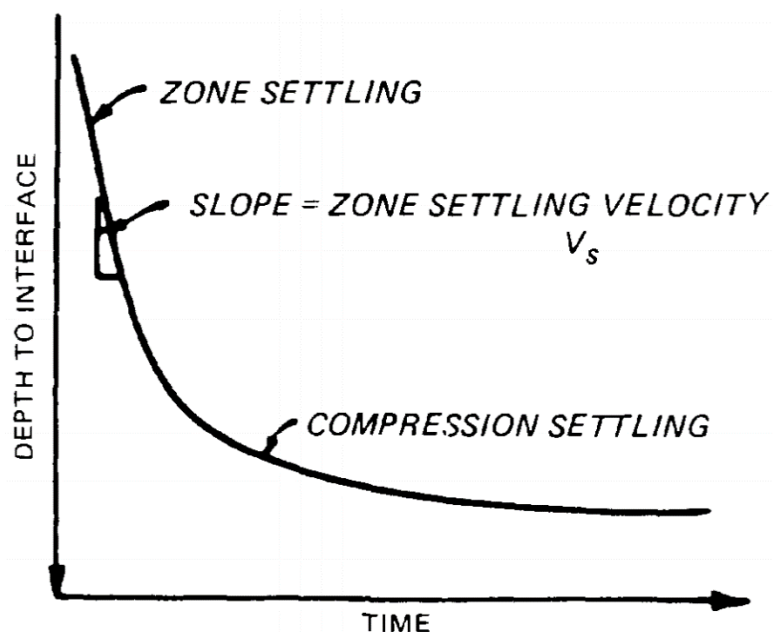


Figure 6: Conceptual plot of interface height against time (USACE, 1987)

There are a range of different apparatuses used in the batch analysis of suspensions, with the most simple being a basic settling column with a sampling port located near its base, as seen in Figure 7. This column is used to observe the time required for a particle to settle the length of the column, with settling velocity calculated based on these parameters.

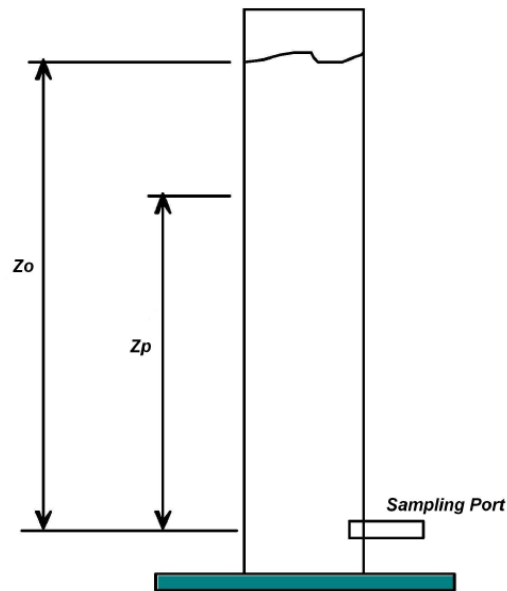


Figure 7: Settling column for analysing type I settling (Samdani & Kapoor, n.d.)

Similar to this settling column, there are other columns designed with a number of sampling ports along the length of them used for Type II sedimentation testing, as seen in Figure 8.

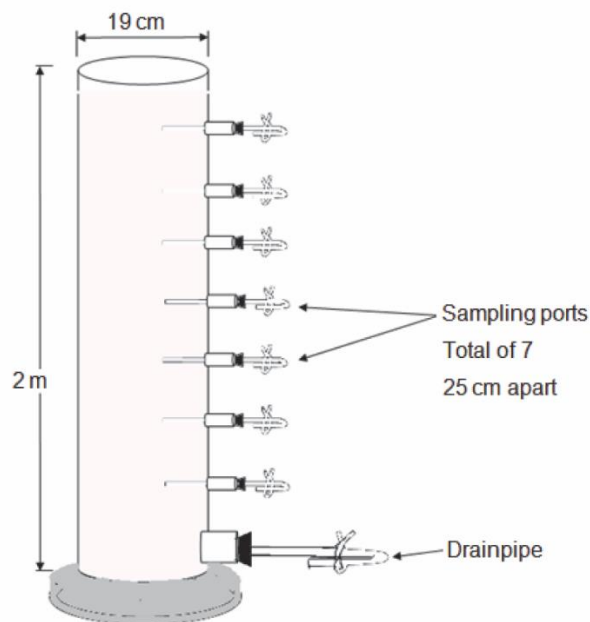


Figure 8: Settling column for analysing type II settling (Sithebe, et al., 2014)

A settling test undertaken using this type of column requires the removal of samples from the sampling ports at several time intervals. The concentration of these samples is determined and, using these results, mass fractions can be calculated and sets of isoremoval lines are drawn, as seen in Figure 9. The slope at any point along these lines is the instantaneous velocity of the fraction of particles represented by that line (Peavy, et al., 1985).

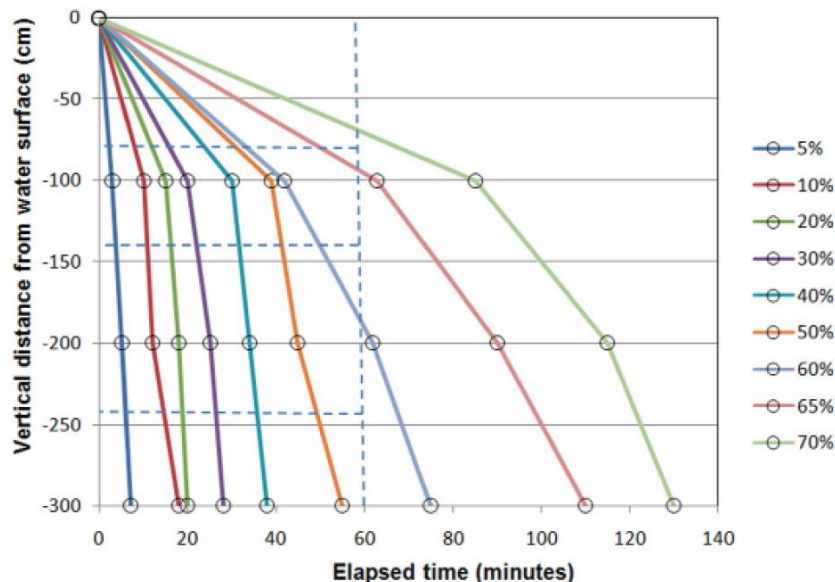


Figure 9: Example of isoremoval lines from type II settling column test (Templeton & Butler, 2011)

Another method of interpreting the data collected from this type of column has been proposed, based on a modified average method and using turbidity measurements. This process removes the subjective nature of drawing the isoremoval lines and has been found to give similar results by Pise & Halkude (2011).

The United States Army Corps of Engineers (USACE) have also developed a comprehensive method to define the settling properties of dredged materials. This involves an initial pilot test, followed by the loading of an 8 in. diameter column, as depicted in Figure 10. The loading of the column once is, in most cases, sufficient to undertake the three settling tests specified by this methodology, including a compression settling test, a flocculant settling test and a zone settling test (USACE, 2015). Flowcharts describing these tests are included in Appendix A of this report.

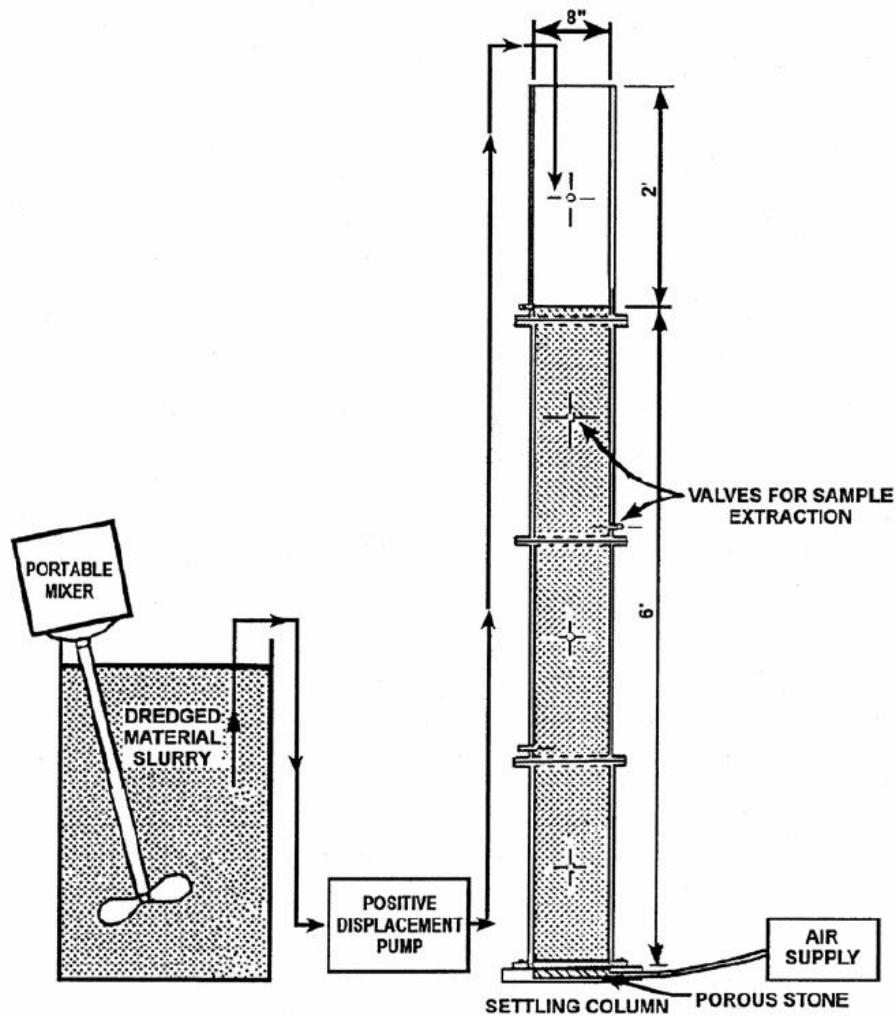


Figure 10: Schematic of the USACE settling test apparatus (USACE, 2015)

In addition to these conventional column tests, some other testing apparatuses were also found during the literature review. A report by Owen (1976) describes various settling velocity tests undertaken using a tube shaped testing apparatus, referred to as an 'Owen Tube'. This is illustrated in Figure 11.

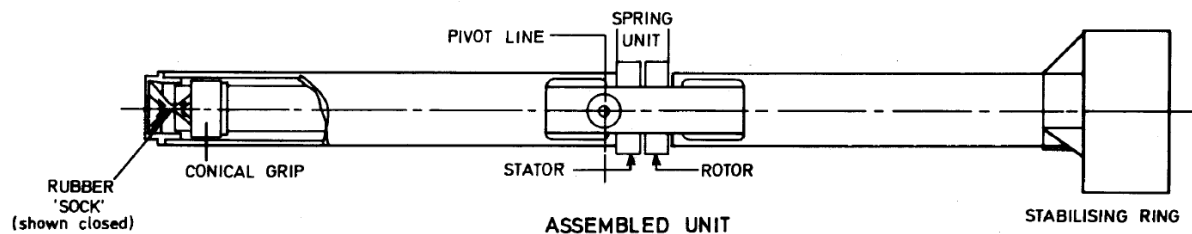


Figure 11: Outline drawing of assembled Owen Tube (Owen, 1976)

However, studies by Dearnaley (1991) and Whitehouse et al. (2000) indicate that, when compared with video image processing, the results from an Owen Tube analysis appear to significantly overestimate the settling velocity of a suspension.

One other apparatus used for testing sedimentation processes has been described by Wolanski et al. (1992), constructed of Plexiglas and with turbulence generated using oscillating rings. This is described in greater detail in a previous study by Wolanski et al. (1989), alongside the sketches shown in Figure 12.

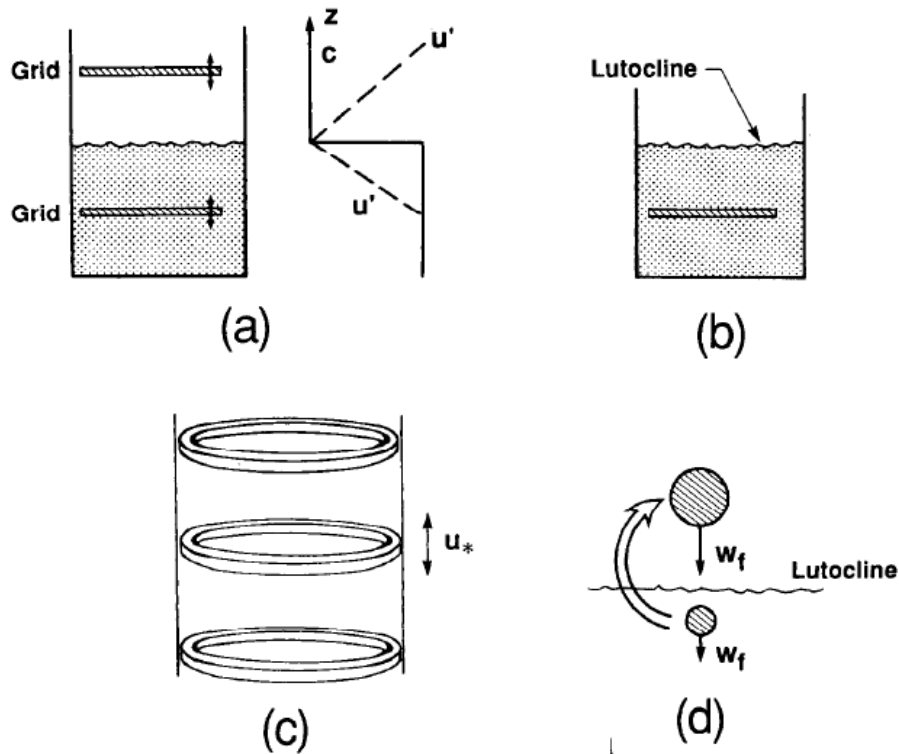


Figure 12: Sketches of density-stratified fluids stirred by oscillating grids (Wolanski, et al., 1989)

As drawings of the apparatus and details regarding the experimental method were not documented in these papers, the methodology for using this apparatus to test sedimentation could not be determined.

2.4 Summer research project

From November 2015 through to February 2016, a research project was undertaken, seeking to observe the sedimentation behaviour and settling velocities of a variety of mixtures at varying concentrations. The methodology employed was a modified form of the column sedimentation test outlined in AS1289.3.6.3 (Standards Australia, 2003) and is described by Scheuermann (2015) in an internal report. Further details regarding the testing methodology and the results are presented in Appendix B.

Based on this experience, there were a range of limitations that impacted upon the quality of the data collected and the validity of the conclusions reached. These are collated in Table 1, with some associated photographs presented in Figure 13.

Table 1: Limitations of tests from summer research project with associated observations

Limitation	Observation
Assumption that concentration of settled material is constant	Methodology implemented assumes a constant concentration of particles in the settled slurry, while some qualitative observations indicated otherwise (see Figure 13a).
Unable to collect data once interface passed 100mL mark	No gradations on measuring cylinder below 100mL resulted in an inability to collect data past this point (see Figure 13b).
Differential settling within column	Some non-uniform settling was observed, with uneven interfaces observed in of some experiments (see Figure 13c).
Wall friction affected interface height readings	With frictional effects occurring between the settling material and the internal walls of the column, visible concavity of the interface was observed (see Figure 13d), resulting in errors in the recorded interface height based on the column gradations.
Unable to distinguish silica interface levels	Interface between turbid supernatant and clear supernatant was difficult to define for settling tests of silica mixtures and several interfaces were observed at times (see Figure 13e). Subjective interpretation of this interface height was required for raw data collection.
Unable to make measurements regarding the supernatant	Based on the experimental method for this project, changes in the supernatant could not be measured or parameterised.
Poor resolution of volume data	Resolution of raw data measurements of interface height were limited by the density of gradations on the cylinders.
Poor resolution of time data	With the methodology adopted, some of the changes in the interface height may not have been captured due to the time gap between observation points. This results in a poor definition of the sedimentation curve.
Disturbance of settling process from laboratory setting	Interfaces were, at times, observed to increase in height during a test, presumed to have resulted from minor disturbances of the column during the settling process. This behaviour was only observed in tests of silica mixtures.
Material loss prior to oven drying	Loss of material prior to oven drying due to particles present in the decanted supernatant. Additional losses due to residue remaining on the column lid and walls once emptied.
Small diameter column may affect sedimentation process	Wall friction may have an impact on the sedimentation process, given the small diameter of the column. Kocamemi (n.d.) suggests using a minimum diameter of about 150mm to 200mm to minimise sidewall effects.

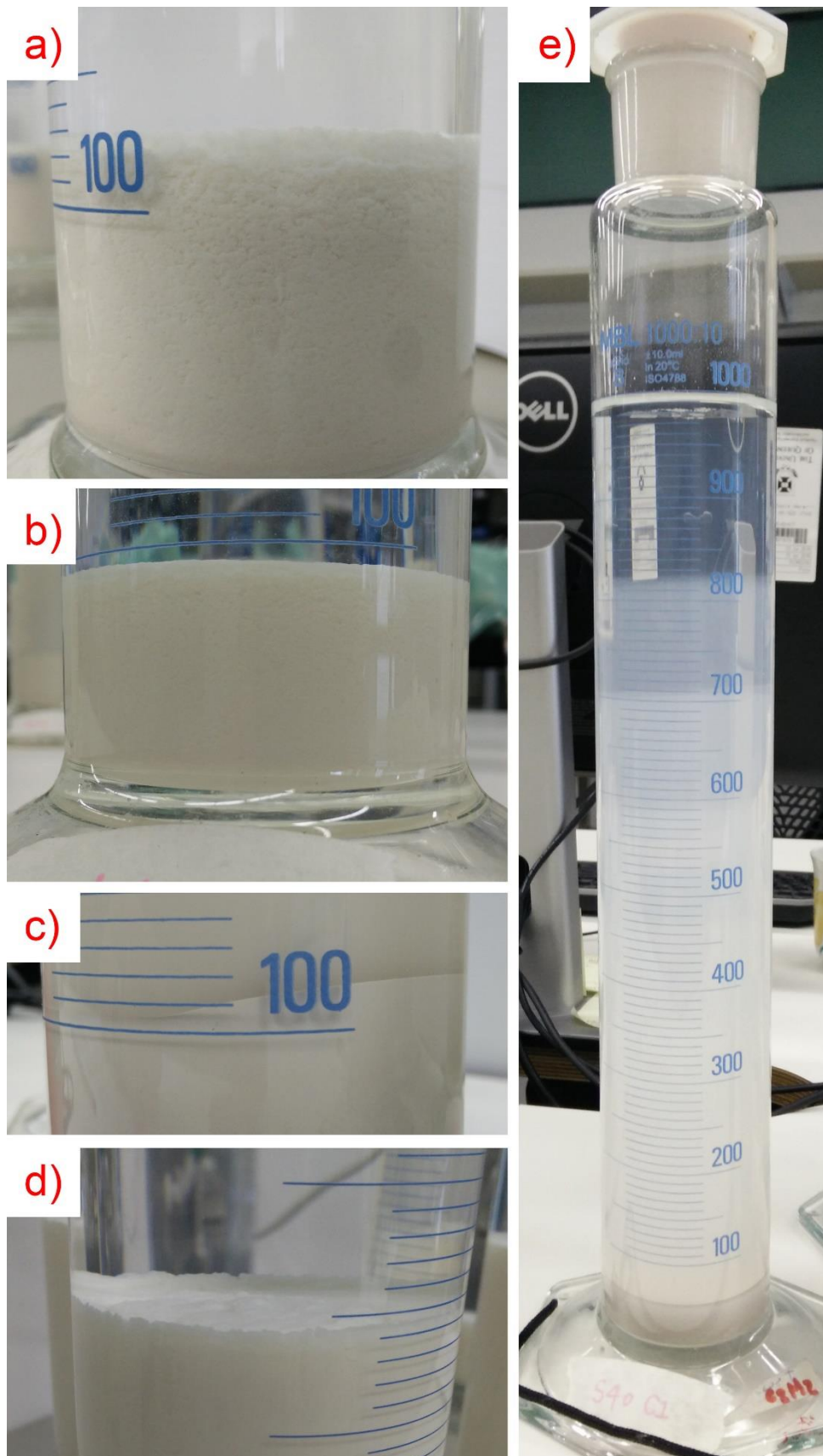


Figure 13: Observations from summer research project. (a) depicts variations in concentration of settled material; (b) depicts issues where the interface has passed the bottommost gradation; (c) depicts an uneven interface; (d) depicts wall friction effects on the interface and its recorded height; and (e) depicts issues with identifying an interface with the silica tests.

From this project, it was clear that further exploration of sedimentation testing methods should attempt to address some of the limitations listed in Table 1.

2.5 Research gaps

Existing methods for characterising sedimentation processes often involve a number of limitations. From existing studies, the methodologies of sedimentation tests have been found to involve either the visual identification of a settling front or the extraction of samples from the column during sedimentation. As seen in Section 2.4, the accuracy of visual measurement of the interface is hindered by various factors such as wall effects and, in the case of mixtures of fine-grained silica, a poor definition of the interface itself. Meanwhile, it is evident that sampling from a column during sedimentation will result in localised changes in the settling dynamics, leading to potential non-uniformity in the settling of the material. In turn, these limitations will affect the accuracy and validity of the experiment. As such, there is an opportunity to develop an experimental methodology that will address these limitations.

In addition to this, existing sedimentation testing processes have not been found to have any interaction with geotechnical testing once sedimentation has been completed. There are valuable opportunities to undertake post-sedimentation testing of the settled material to determine parameters of the slurry, such as its hydraulic conductivity and consolidation parameters. Given the range of testing equipment available at the Geotechnical Engineering Centre (GEC) at The University of Queensland (UQ), consideration of this opportunity should be explored.

3.0 PROJECT SCOPE

3.1 Research objective

The objective of this thesis project is to improve the methods used in the testing of sedimentation processes in response to the research gaps identified in Section 2.5.

3.2 Research methodology

To achieve this objective, a novel approach towards measuring sedimentation processes has been adopted. It has been proposed that measurements of parameters such as turbidity and dielectric permittivity can be correlated with the solid concentration of the suspension during sedimentation. Using these correlations and a specially designed large sedimentation column, sedimentation processes can then be characterised along the length of the column.

In particular, correlations between solid concentration and turbidity and dielectric permittivity were of interest. This report considers the turbidity correlations, while a separate report by Yucheng (Sophia) Jiang has explored the dielectric permittivity approach.

The design of the large sedimentation column should also seek to allow for post-sedimentation geotechnical testing using equipment currently in use at the GEC.

3.3 Key project outcomes

Using this approach, a number of key outcomes were identified for the project:

- Develop the design of a modular large sedimentation column, allowing for a suite of instrumentation to be attached along the length of the column. The design shall accommodate existing apparatus of the GEC and be suitable for various post-sedimentation tests.
- Experimentally establish a relationship between turbidity measurements and the solid concentration of a suspension.
- Develop the design of a model column as a proof of concept for the large sedimentation column design, focussing on dielectric and turbidity measurements. Experimentally determine its effectiveness in characterising sedimentation processes.

3.4 Contents of thesis

This thesis report is organised into six main sections:

- Section 1.0 (General Introduction) provides a contextual basis for sedimentation processes.
- Section 2.0 (Literature Review) describes sedimentation processes and outlines existing methods that have been used for sedimentation testing.
- Section 3.0 (Project Scope) defines the objective of the thesis project, the methodology adopted and its intended outcomes.
- Section 4.0 (Large Column Design) presents the design development of the large sedimentation column.
- Section 5.0 (Experimental Testing) presents the laboratory testing that was undertaken as part of the project.
 - Section 5.1 (Calibration Tests) focusses on the testing used to determine a relationship between turbidity measurements and mixture concentration.
 - Section 5.2 (Model Column Tests) describes the model column design and discusses the subsequent experimental test results.
- Section 6.0 (Conclusion and Evaluation) concludes the report and discusses further research pathways that may be explored in the future.

4.0 LARGE COLUMN DESIGN

4.1 Design objectives

The design development of the large column was focussed towards achieving a number of key design objectives and requirements. These are listed below:

- Minimum two metre tall modular sedimentation column.
- Column to be made of Acrylic / Plexiglas / clear plastic for observations.
- Two column arrangements for post-sedimentation testing (see Figure 14):
 - Consolidometer arrangement: interface with slurry consolidometer for consolidation testing,
 - Density arrangement: small segments at lower end for obtaining density profiles and undertaking hydraulic conductivity testing.
- Allow for various instrumentation to be installed along the column, including:
 - Dielectric sensors,
 - Turbidity sensors,
 - pH sensors,
 - Pressure transducers,
 - Sampling valves.

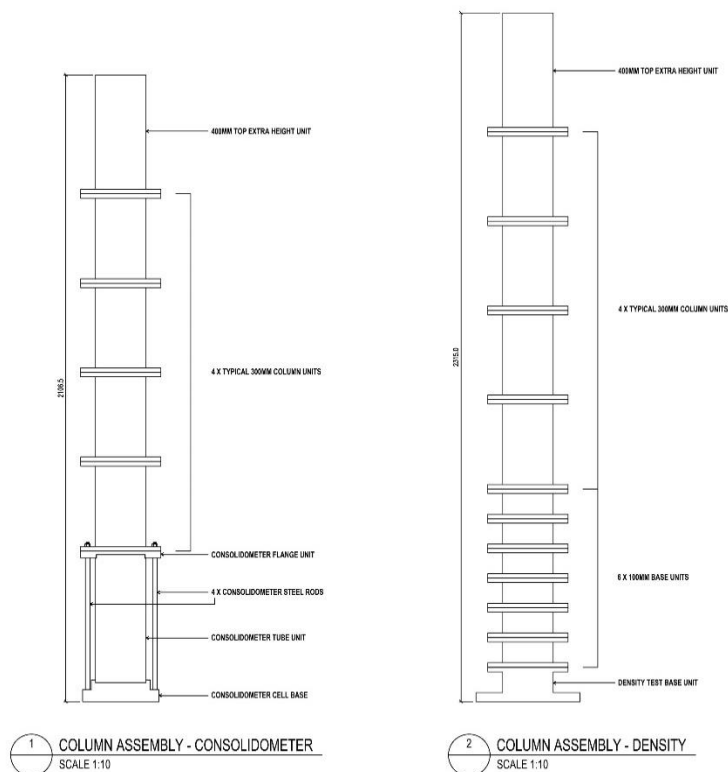


Figure 14: Column arrangements

4.2 Design considerations

4.2.1 General considerations

Initially, the sedimentation column used by the USACE was adopted as a starting point the design of this column. This is partly shown in Figure 15, with the USACE design drawings provided in Appendix C. Key design details include its construction from separable components, its placement of ports along the length of the column and its height of about 2m.

To meet the design objectives of this project, as identified in Section 4.1, a number of modifications to the USACE design were proposed:

- Six ports at each level to accommodate instrumentation, with one spare for any future additions. As there are to be multiple instruments per level, ports will be aligned vertically down the column with no rotational offset.
- Increased height to suit room height of geomechanics research laboratory in the Advanced Engineering Building (AEB) at UQ.
- Modified flange design to minimise impact on attachment of instrumentation.
- Column to be comprised of an increased number of smaller modules.

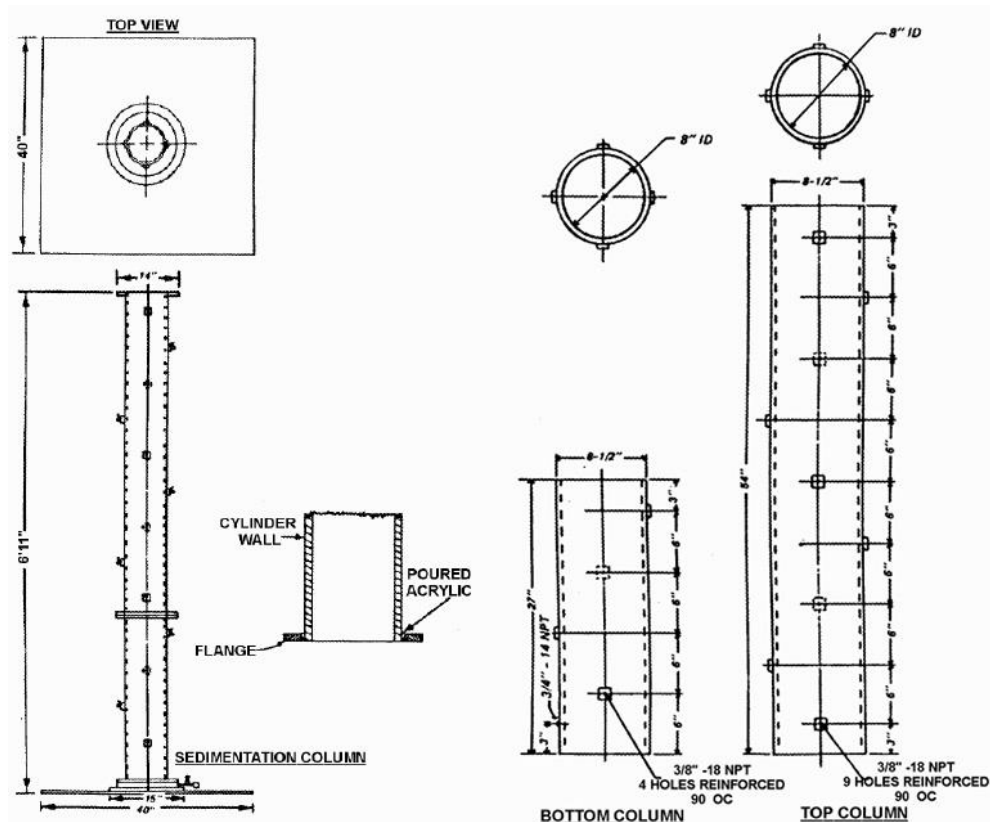


Figure 15: Plans for USACE sedimentation column (USACE, 2015)

The spacing of instrumentation along the column was one factor considered during the initial design stages. This was considered alongside the objective for the column to be comprised of smaller common modules. In response to these aspects, it was decided that the majority of the column was to consist of 30cm tall modules, with two levels of instrumentation per module. It is noted that this contrasts with the USACE design, being composed of two components only. The centres of the instrumentation ports shall be located 7.5cm from each end of the module, such that a consistent 15cm spacing will be achieved between each level of instrumentation along the length of the column. Figure 16 shows this design.

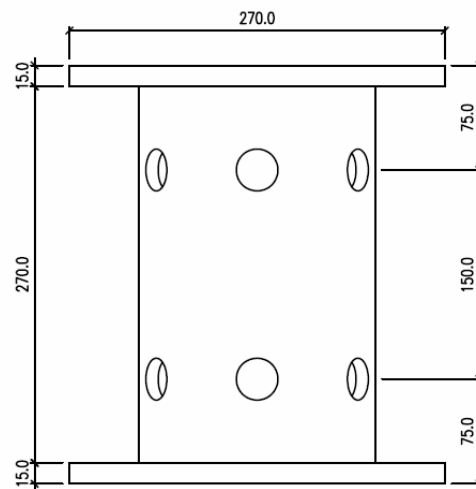


Figure 16: Elevation of 30cm module

To incorporate the six instrumentation ports into the column, each level of instrumentation consisted of six ports equally spaced around the circumference. This is depicted in Figure 17. It should be noted that while these ports have currently been oversized to accommodate the turbidity sensors, these dimensions shall be updated prior to fabrication once the diameters of the various sensors are confirmed.

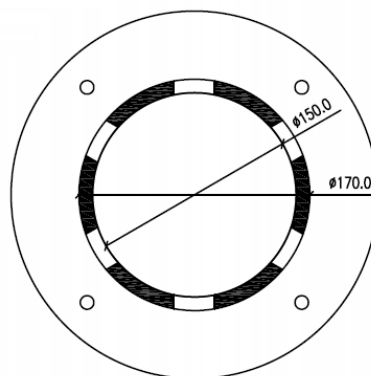


Figure 17: Horizontal section through 30cm module

While the original USACE sedimentation column design specifies a height of about 2.1m, it was found that the clear height available in the AEB geomechanics research laboratory was about 2.6m. As such, the two proposed column arrangements were designed to suit a total height of about 2.3m, with some spare headroom provided for column filling purposes and general manoeuvrability. Notably, the topmost unit adopted for both arrangements is primarily intended to allow for agitation of the sample prior to sedimentation without spilling over into the laboratory. This 40cm unit has no instrumentation ports and can be seen in Figure 18.

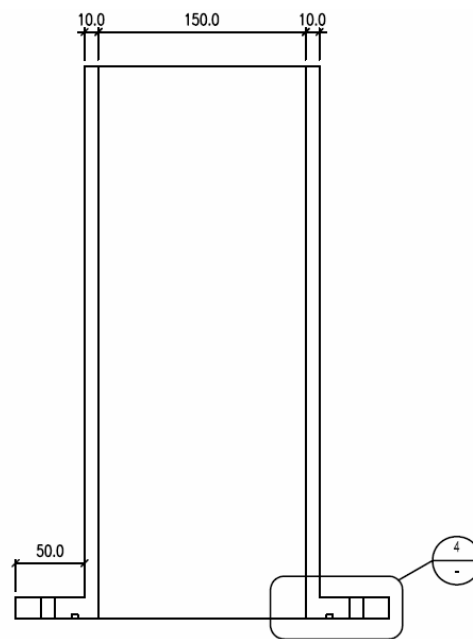


Figure 18: Vertical section through 40cm top unit

A different flange design to the USACE column was also developed, with four holes adopted instead of the 8 holes specified in the USACE design. These holes are to be through holes to minimise wear and sized to accommodate a standard nut and bolt. Meanwhile, to hydraulically seal the column, a groove has been added to the flanges to accommodate a 3.5mm diameter O-ring. This is shown in Figure 19.

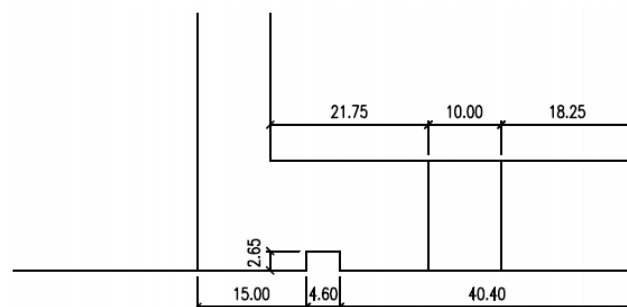


Figure 19: Flange detail

4.2.2 Consolidometer arrangement

As noted in Section 4.1, one of the key objectives of this column design is to interface with the existing slurry consolidometer owned by the GEC. The overall concept for this interface is summarised in Figure 20, while Figure 21 depicts the components of the consolidometer and its loading cell.

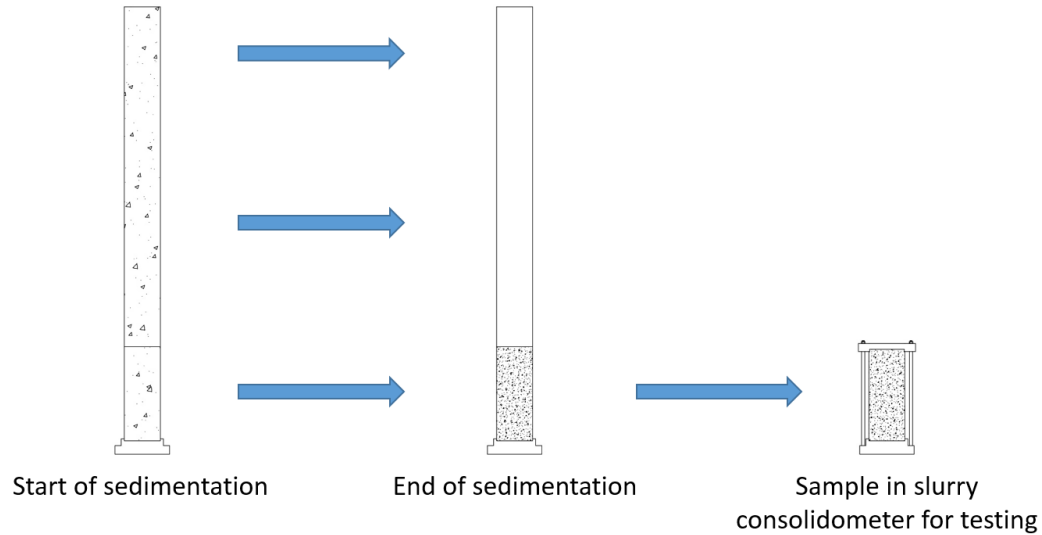


Figure 20: Consolidometer arrangement for post-sedimentation testing



Figure 21: Slurry consolidometer apparatus

To begin, the inner diameter of the entire sedimentation column was adapted to match the consolidometer equipment. After undertaking some measurements, a 15cm inner diameter was selected for all of the components of the sedimentation column.

To design the consolidometer arrangement, an approach was adopted that sought to replace all components of the consolidometer from the piston down. This required the design of a base support unit, filter unit and tube unit.

While this design approach fulfilled the requirements for sedimentation and the post-sedimentation consolidation testing, difficulties arose when waterproofing was considered. This was due to the contrasting needs of the assembly to both maintain the sealed column during sedimentation but also be able to move once consolidation testing was to be undertaken. A complicated system involving screws, O-rings and a supported filter unit was designed before being abandoned in favour of a simpler approach. Documentation of this initial approach can be found in Appendix D, with a drawing of the base assembly shown in Figure 22.

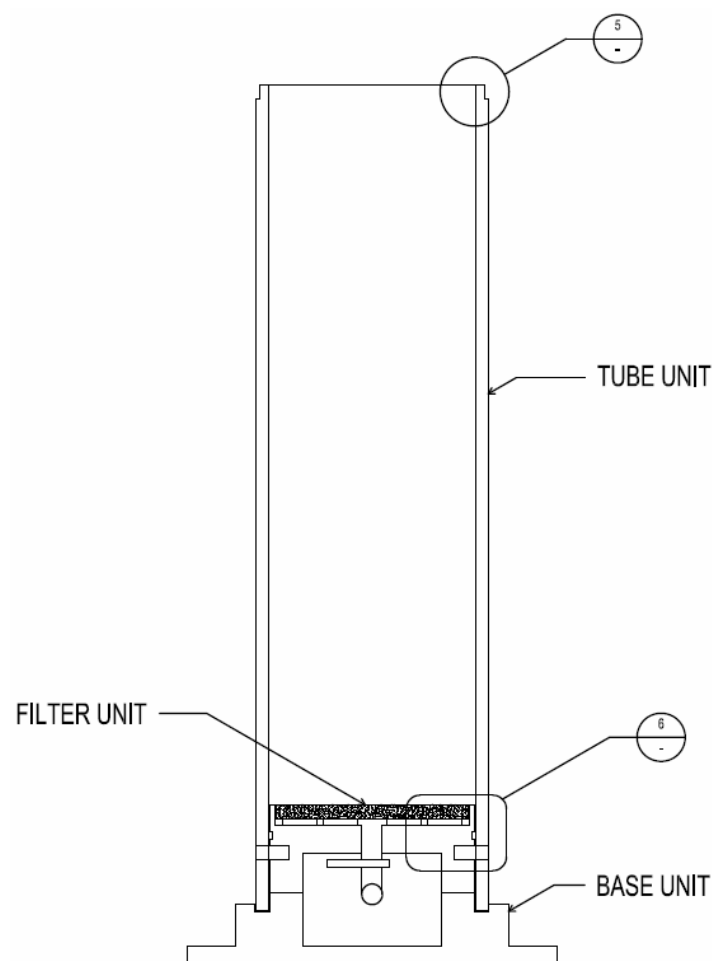


Figure 22: Initial design approach for consolidometer arrangement base

The simpler approach towards this design issue involved incorporating the existing consolidometer base unit (see Figure 21d) as the base of the arrangement. As such, a design for the tube and a flange unit was required to interface this solution with both the existing equipment and the 30cm modules of the sedimentation column.

Designing a tube unit to take the place of the steel slurry consolidometer tube involved consideration of a number of factors, such as the position of the steel support rods, detailing at the ends of the tube and the location of sensors along its length. From discussions with Dr. Thierry Bore, the addition of instrumentation ports for dielectric sensors along the length of this unit was made. These sensors were to be located in a vertical line along the length of the tube, while ports to accommodate the existing pressure transducers of the consolidometer were staggered for geometric reasons. A section through this unit can be seen in Figure 23, with further details provided in the design drawings attached in Appendix E.

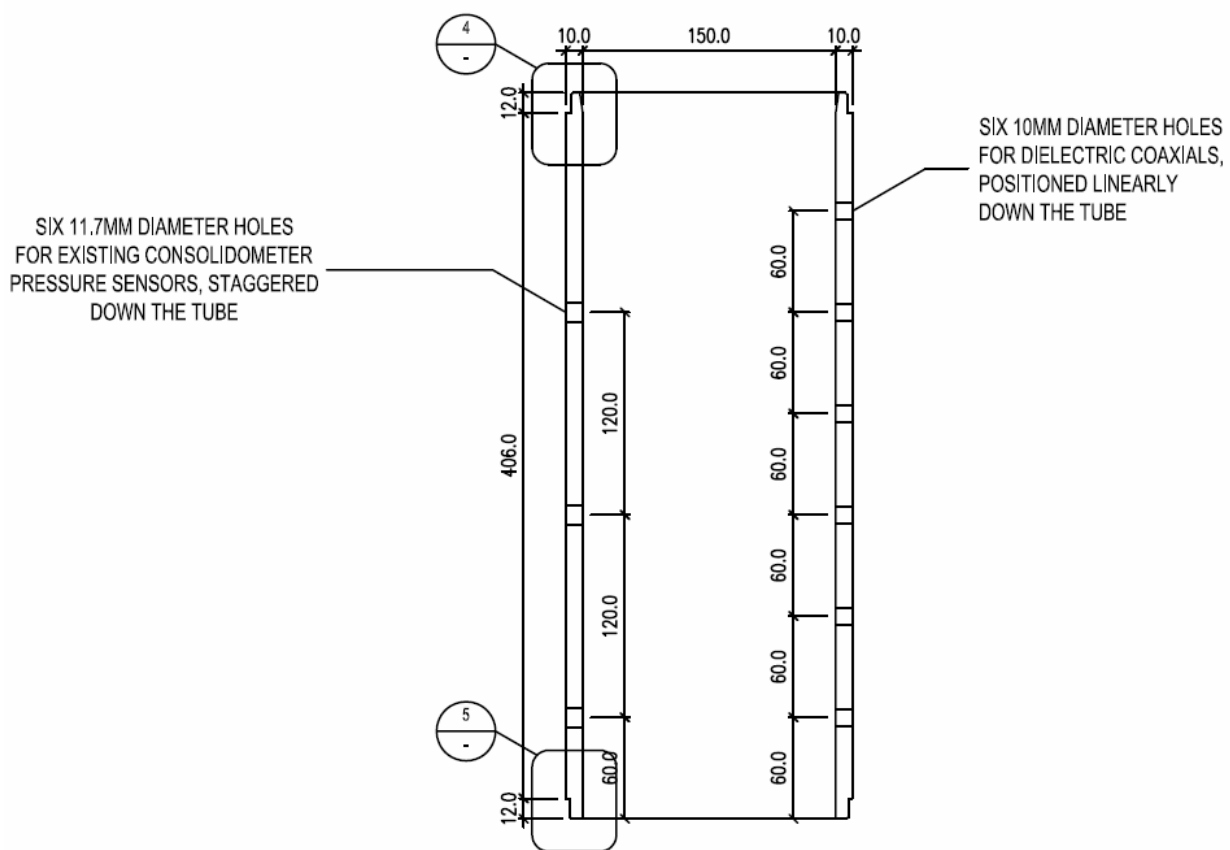


Figure 23: Section through consolidometer arrangement tube unit

Importantly, this tube unit is to be made of Plexiglas to allow for visual observation of the consolidation process during the post-sedimentation testing.

Design of the flange unit was necessary to accommodate the sedimentation process while also matching the geometry of the existing consolidometer base unit and support rods. As such, the existing consolidometer lid (see Figure 21b) was used as a basis for the design, but modified with a 15cm diameter central hole through it. A section through the designed unit is shown in Figure 24, with further details in Appendix E.

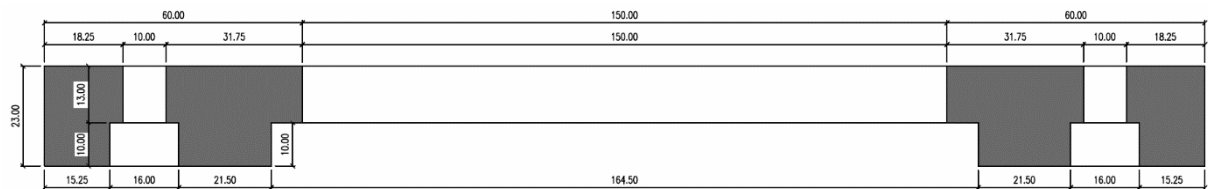


Figure 24: Section through flange unit

Another design aspect to consider was the position of the holes in its flange. These needed to be replicated in order to match the position of the steel support rods. As such, the position of these holes in the flange design of other components was updated to reflect this requirement.

Once assembled, the tube unit and flange unit for this consolidometer arrangement are to interface precisely with the existing equipment while allowing sedimentation to occur. The base assembly of this configuration is shown in Figure 25.

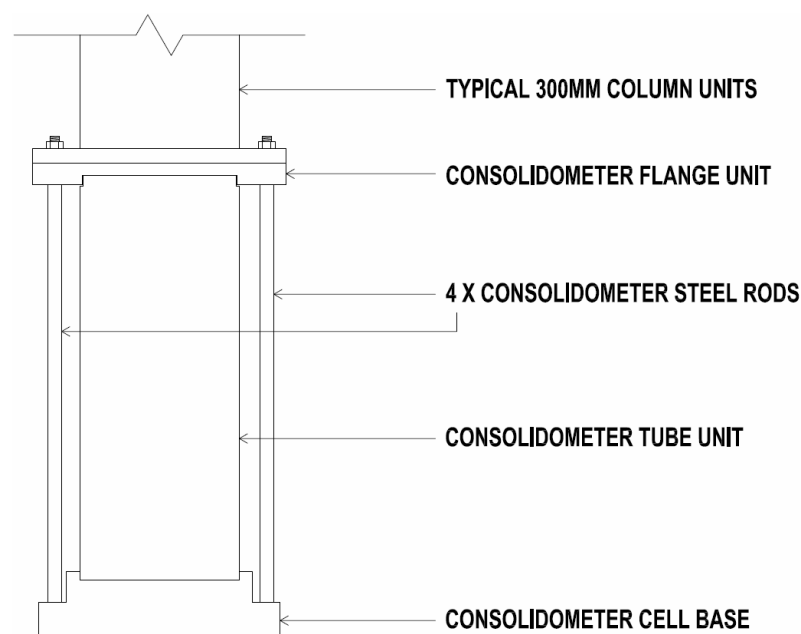


Figure 25: Assembly of consolidometer arrangement base

It should be noted that stability of the consolidometer column arrangement is to be provided by tying the column to a wall of the laboratory along its length.

4.2.3 Density testing arrangement

While this column configuration has been referred to as the ‘density’ arrangement, its design objective was focussed around the intent to both determine a density profile of the settled material, as well as subject this material to hydraulic conductivity testing. The overall concept of this arrangement is summarised in Figure 26.

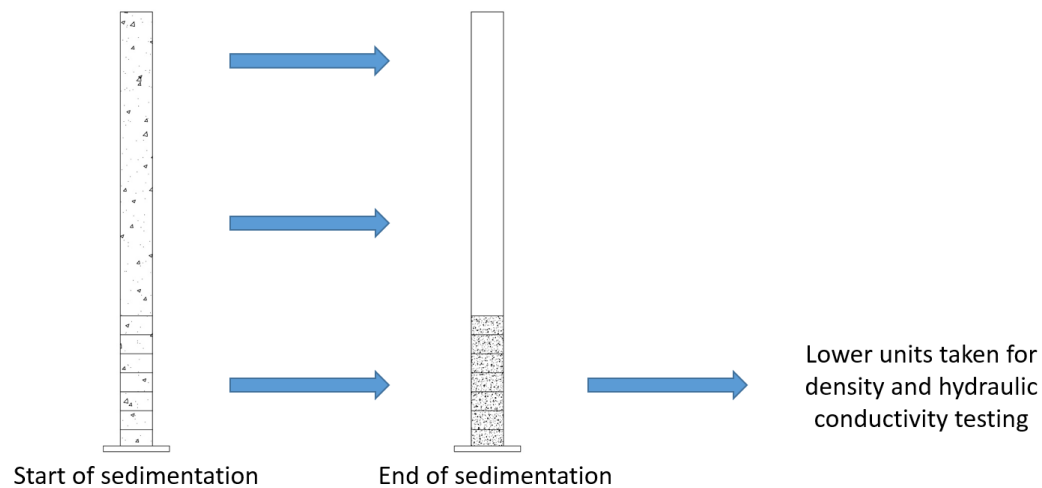


Figure 26: Arrangement for post-sedimentation density profiles and hydraulic conductivity testing

To obtain density profiles, smaller column units were designed for the base of this column arrangement. Through design discussions, it was determined that a 10cm tall unit would be an appropriate size for obtaining density profiles while maintaining useability. These units also accommodate the instrumentation intended for the typical 30cm units. Figure 27 presents a perspective drawing of one of these units.

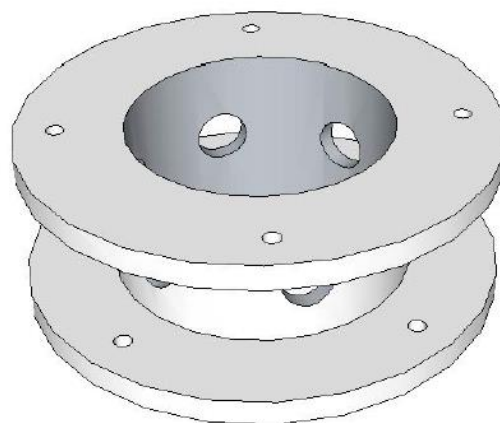


Figure 27: Perspective of 10cm column unit

It should be noted that the flange holes are offset in the design of this unit. This was implemented in response to the small space available between the flanges for both installing instrumentation and tightening nuts and bolts to connect column units.

In addition to these 10cm units, a base unit needed to be designed for this arrangement. Taking the existing consolidometer base as a starting point, the design of this density arrangement base unit was developed. This involved consideration for the sizing of the drainage channels, outlets for removing air from the drainage channels and the location of the filter stone. In addition to this, an air inlet was added to the side of the unit to allow for agitation of the suspension prior to sedimentation. A section through this base unit is shown in Figure 28.

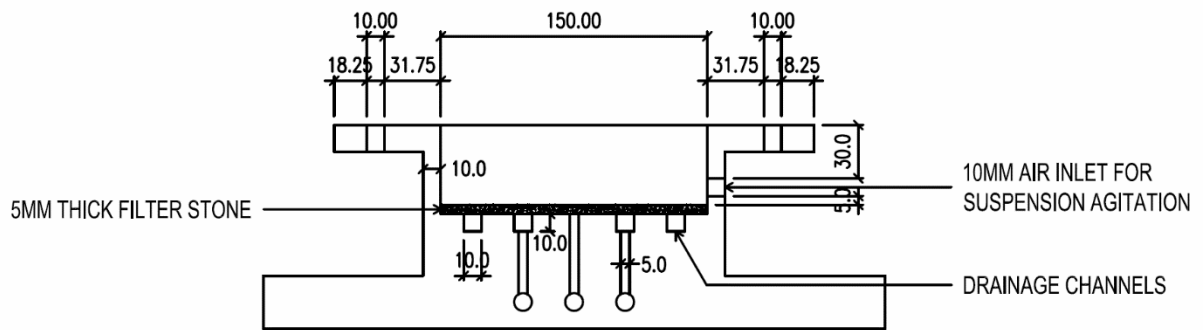


Figure 28: Section through density base unit

The air inlet has been located above the filter stone in order to prevent any disturbance of the filter stone and the possibility of it being dislodged. Furthermore, the bottom flange of this unit has been designed to be wider providing greater stability to the column arrangement. This column arrangement for density testing will also be tied to the wall of the laboratory along its length to ensure its stability.

4.3 Design outcomes

In summary, the design of the following components of the large sedimentation column have been developed, responding to the various design objectives outlined in Section 4.1:

- 30cm module
- 40cm top module
- Consolidometer tube unit
- Consolidometer flange unit
- 10cm density module
- Density base unit

Quantities required for the fabrication and assembling of these columns are detailed in DWG 1-0 of Appendix E.

4.4 Design documentation

Design drawings have been produced as part of this project in order to document the design process. Two versions of design drawings have been produced to date, with the first version being a preliminary concept design and the second version being a more substantially developed design. These can be found in Appendices D and E respectively.

5.0 EXPERIMENTAL TESTING

5.1 Calibration Tests

5.1.1 Aim

Calibration tests were undertaken to establish the relationship between the turbidity measurements from the sensors selected and the solid concentration of a mixture.

5.1.2 Mixtures

In preparation for the model column test, five sensors were tested under these calibration tests with four different mixtures. It should be noted that salt water mixtures contained a concentration of 5g/L of sodium chloride. Table 2 summarises the tests undertaken in these various combinations.

Table 2: Designations of tests undertaken with various combinations of sensor and material

		Material			
		Silica in tap water	Kaolin in tap water	Silica in salt water	Kaolin in salt water
Sensor	1	A, AX1	F, FX1, FX2	K, KX1	P, PX1, PX2
	2	B, BX1	G, GX1, GX2	L, LX1	Q, QX1, QX2, QX3
	3	C	H	M	R
	4	D	I	N, N2	S, S2, S3
	5	E	J	O	T

Note: Tests with an "X" in their designation are explained in greater detail in Section 5.1.5.

5.1.3 Equipment

Amphenol TSD-10 turbidity sensors were selected due to their ease of use when paired with the correct data logging system. These are optical sensors and measure the amount of emitted light from the light emitting port that is received by the light receiving port as the mixture passes in between these components (Amphenol Corporation, 2014). When turbidity and solid concentration of the mixture is increased, less transmitted light is received. The sensor therefore reads the amount of received light as its direct output in units of 'bits'. It should be noted that this has an inverse relationship to true turbidity, in units of NTU.

In consultation with Dr. Alistair Grinham, an Arduino Uno data logger was obtained, along with the relevant cables and a battery pack power supply. This system also features Arduino code designed for turbidity monitoring, as written by Fisher (2015). As such, these were used together to obtain the sensor output data.

The specific equipment used in these calibration tests are listed below:

- 5 x Amphenol TSD-10 turbidity sensors
- 5 x soft plastic containers (approx. capacity of 600mL), 'beakers'
- 1 x Arduino Uno data logger with battery pack and jumper leads
- 1 x 2GB microSD memory card
- 1 x IKA C-MAG MS 7 magnetic stirrer with stirrer bars
- 1 x A&D GX-2000 electronic balance
- 11 x small oven drying tins
- 11 x plastic oven drying containers
- 1 x 2L measuring jug
- 1 x 250mL measuring cylinder
- 1 x electronic stopwatch
- 4 x 20L buckets
- Syringes with 10mL, 25mL and 50mL capacities
- Electric drill with mixer attachment
- Silicone sealant (24hr curing time), caulk gun, utility knife
- Masking tape, permanent marker

A photograph of the experimental setup is shown in Figure 29.

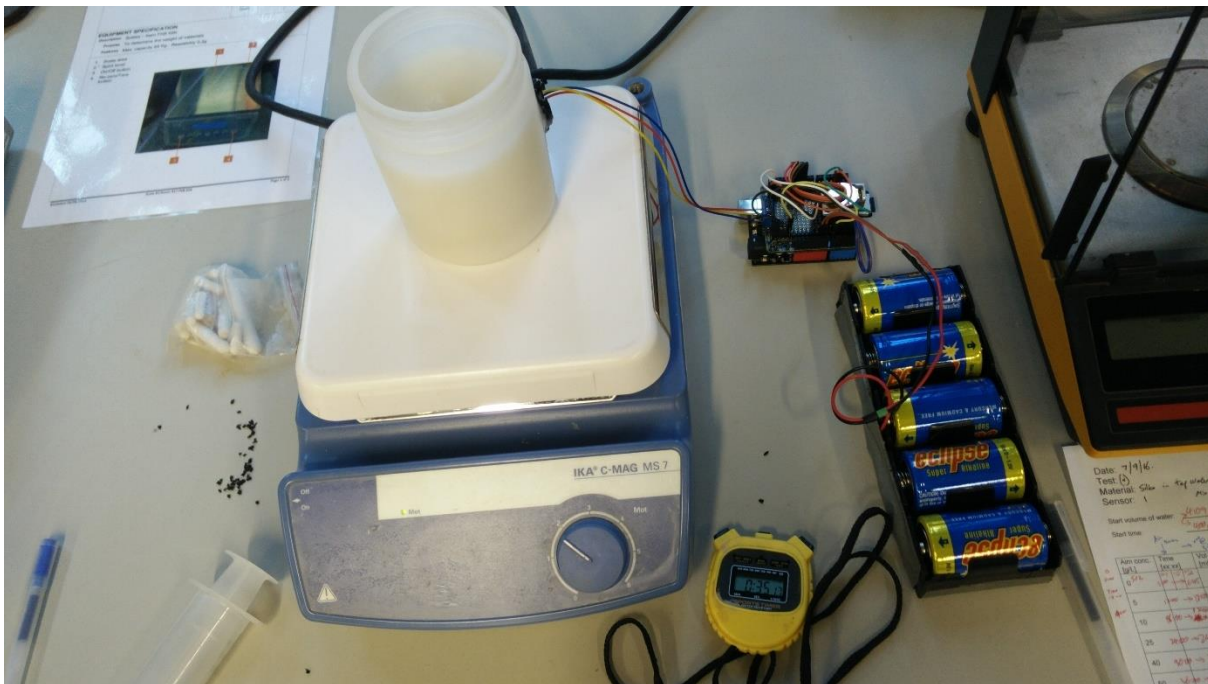


Figure 29: Experimental setup during mixing

5.1.4 Variables

To gain a clear understanding of the variables that may affect the results of these tests, a series of preliminary tests were conducted. The details and results of these tests are provided in Appendix F. From this, the independent, dependent and control variables were identified for these calibration tests and are detailed below:

- Independent Variables:
 - Sensors: Five TSD-10 sensors, labelled “1” through to “5”.
 - Mixtures: Four mixtures:
 - Silica mixed in tap water
 - Kaolin mixed in tap water
 - Silica mixed in 5g/L salt water
 - Kaolin mixed in 5g/L salt water
 - Concentrations: 11 target concentrations for each test, being 0g/L, 5g/L, 10g/L, 25g/L, 40g/L, 50g/L, 75g/L, 100g/L, 110g/L, 125g/L, 150g/L.
- Dependent Variable: Turbidity measurement output by TSD-10 turbidity sensor, taken at 10 second increments.
- Control Variables:
 - Same stirrer speed (2) and stirrer bar size (medium) to be used
 - Similar lighting conditions in laboratory
 - Same observer for all measurements and observations

5.1.5 Methodology

A number of different procedures were undertaken in order to conduct these calibration tests. The experimental method for each of these steps were designed for these calibration tests and are detailed separately below.

(A1) Apparatus preparation

1. Outline the profile of a TSD-10 sensor onto the outside of a ‘beaker’ using a marker (see Figure 30). Number the container to match the sensor.
 2. Using the utility knife, cut through the marked hole, ensuring the sensor will fit.
 3. Place the sensor into the hole, ensuring the slot in the sensor is aligned horizontally in the ‘beaker’. Using the silicone sealant and caulk gun, apply silicone around the hole to seal the sensor to the container (see Figure 30).
 4. Leave the modified ‘beaker’ for at least 24 hours to allow the silicone to set.
 5. Repeat steps 1 to 4 for the other four sensors and ‘beakers’.
-



Figure 30: Preparation of the 'beakers'

(A2) 150g/L mixture preparation

1. For a given mixture, oven dry the fine-grained material for 48 hours to remove any moisture from the powder.
2. Weigh 1.5kg of the dried powder using the electronic balance and place into a labelled 20L bucket.
3. Measure 9.42L of the solvent (tap water or salt water) and pour into the same 20L bucket to form the 150g/L solution. Mix thoroughly using the electric drill with mixer attachment.
4. Cover and leave the bucket for at least 24 hours to allow the particles to saturate.
5. Repeat steps 1 to 4 for the other three mixtures.

(B1) Equipment preparation

1. Select and label 11 oven drying tins or containers (use tins for tap water mixtures, while salt water mixtures require the plastic containers).
2. Weigh each tin or container three times using the electronic balance, recording the masses of the empty tins. Set aside.

(B2) Initial 150g/L test

1. For a particular test, agitate the prepared 150g/L mixture in its 20L bucket using the electric drill with mixer attachment.
2. Once sufficiently mixed, extract between 700mL to 900mL of solution from the bucket using the 2L measuring jug. Replace the cover of the bucket.
3. Place stirrer bar into 'beaker' and fill with about 400mL of the 150g/L mixture. Place filled 'beaker' onto magnetic stirrer and start the stirrer.
4. Connect the Arduino data logger with empty 2GB microSD memory card.
5. To start the test, connect the battery pack to the Arduino data logger and start the stopwatch at the same time. Leave for five minutes to gather data.
6. At the end of the five minutes, disconnect the battery pack and the data logger from the 'beaker'. Extract 20mL of the mixture from the 'beaker', approximately at the height of the TSD-10 sensor. Put 20mL sample into one of the labelled drying tins. Empty 'beaker' contents into measuring jug, clean 'beaker' and reset all equipment. Extract data from the memory card.

(B3) Mixing test of other concentrations

1. Place stirrer bar into 'beaker' and fill 'beaker' with 400mL of solvent (tap or salt water). Place filled 'beaker' onto magnetic stirrer and start the stirrer.
 2. Connect the Arduino data logger with empty 2GB microSD memory card.
 3. To start the test, connect the battery pack to the Arduino data logger and start the stopwatch at the same time.
 4. Leave for five minutes to gather data.
 - a. During this time, prepare a predetermined volume of solvent and 150g/L mixture. These predetermined volumes are described in columns C and D of Table 3 respectively.
 5. Once five minutes have passed, extract 20mL of the mixture from the 'beaker', approximately at the height of the TSD-10 sensor and put into one of the labelled drying tins. Continue extracting mixture from the 'beaker' until the predetermined removal volume has been removed (see column B of Table 3).
 6. Add both of the prepared volumes of solvent and 150g/L mixture. Note the time at which this is complete.
 7. Repeat steps 4 to 6 until all mixture concentrations have been tested.
 8. Finish test, place drying tins into 60°C oven and reset equipment.
-

Table 3: Mixing volumes for calibration tests

Column:	A	B	C	D	E
Mix:	Initial Volume [mL]	Volume to extract [mL]	Solvent to add [mL]	150g/L to add [mL]	Final Volume [mL]
1	400	50	40	20	410
2	410	50	30	10	400
3	400	50	10	40	400
4	400	50	0	50	400
5	400	50	10	40	400
6	400	100	0	100	400
7	400	130	0	130	400
8	400	100	0	100	400
9	400	150	0	150	400
10	400	50	-	-	-
11	400	50	-	-	-

Note: Mix 1 refers to the test with solvent only, while mix 11 refers to the 150g/L test.

(C) Oven drying

1. Check the drying tins regularly, weighing each one three times and recording the masses measured. Calculate the average mass of each tin with dried sample.
2. Repeat step 1 until the average mass for each tin does not vary greater than 0.01g (within the error margins of the equipment).
3. Once step 2 is complete, remove labels from drying tins, clean tins and allow to dry.

In addition to these calibration tests, a small number of additional tests were undertaken using leftover material collected from the tests above. These followed a similar methodology, but with some notable differences in the volumes mixed due to the varied concentrations of the leftover material. Tests undertaken using this method sought to test six different concentrations at concentrations less than 20g/L. These additional tests are labelled with an “X” in their test designation, as seen in Section 5.1.2.

(X) Additional mixing test for low concentrations

1. Select and label 6 oven drying tins or containers (use tins for tap water mixtures, while salt water mixtures require the plastic containers).
2. Weigh each tin or container three times using the electronic balance, recording the masses of the empty tins. Set aside.
3. Place stirrer bar into 'beaker' and fill 'beaker' with 400mL of solvent (tap or salt water, depending on the mixture). Place filled 'beaker' onto magnetic stirrer and start the stirrer.
4. Connect the Arduino data logger with empty 2GB microSD memory card.
5. To start the test, connect the battery pack to the Arduino data logger and start the stopwatch at the same time.
6. Leave for five minutes to gather data.
 - a. During this time, prepare a predetermined volume of solvent and leftover material from other tests. These predetermined volumes are described in columns C and D of Table 4 respectively.
7. Once five minutes have passed, extract 20mL of the mixture from the 'beaker', approximately at the height of the TSD-10 sensor and put into one of the labelled drying tins.
8. Add both of the prepared volumes of solvent and leftover material. Note the time at which this is complete.
9. Repeat steps 6 to 8 until all mixture concentrations have been tested.
10. Finish test, place drying tins into 60°C oven and reset equipment.

Table 4: Mixing volumes for additional calibration tests

Column:	A	B	C	D	E
Mix:	Initial Volume [mL]	Volume to extract [mL]	Solvent to add [mL]	Leftover mixture to add [mL]	Final Volume [mL]
1	400	20	10	10	400
2	400	20	10	10	400
3	400	20	10	10	400
4	400	20	10	10	400
5	400	20	10	10	400
6	400	20	-	-	-

Note: Mix 1 refers to the test with solvent only.

5.1.6 Results and discussion

By using the methodology outlined in Section 5.1.5, the full suite of calibration tests described in Section 5.1.2 was undertaken. An example of the data processing methods used is provided in Appendix G, while a summary of the experimental data obtained from each calibration test is presented in Appendix H.

It should be noted that, while the individual sensors were originally expected to have some deviation in their readings, this did not appear to be the case. This can be seen in Figure 31, which presents the data for mixtures of kaolin in tap water, organised by sensor number. Comparisons of sensor output for all of the mixture types can be found in Appendix I.

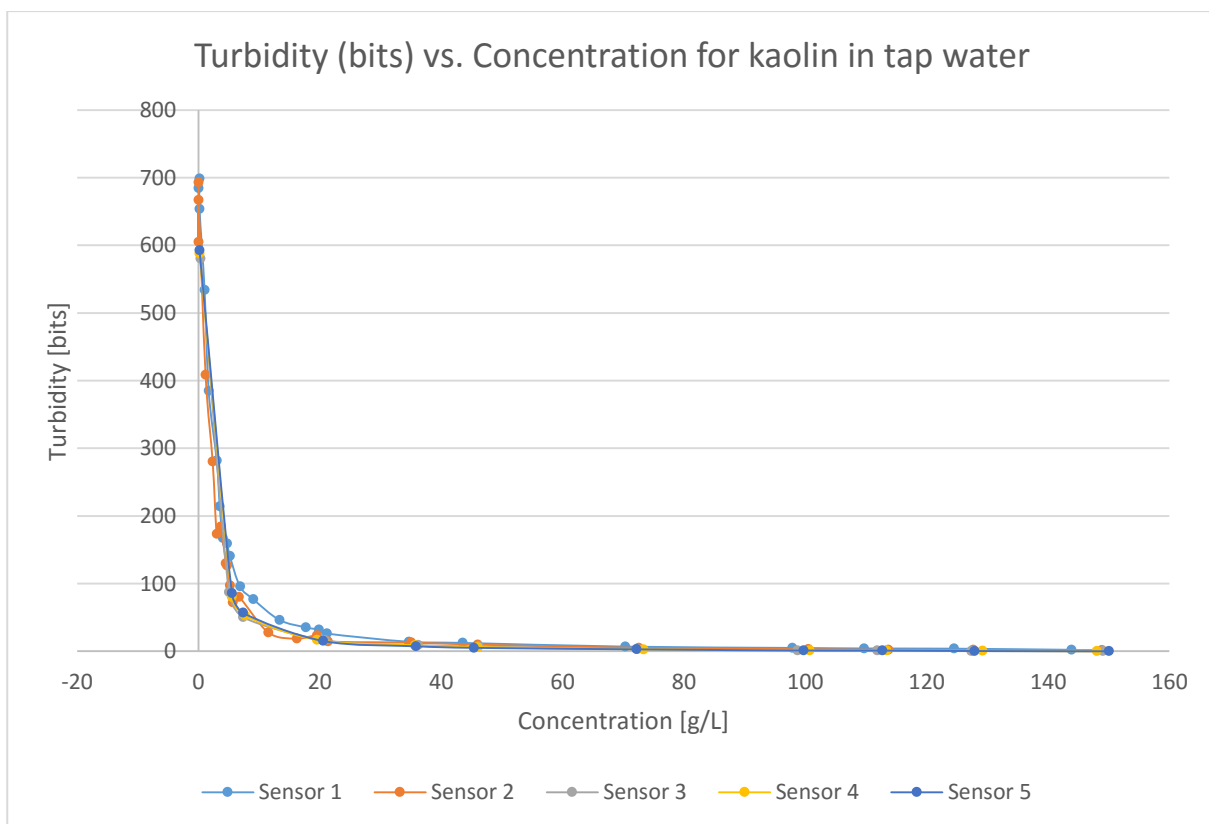


Figure 31: Collated calibration test data for kaolin in tap water, organised by sensor

From Figure 31, it is clear that the data points from the different sensors appear to follow the same relationship and hence, the data from these sensors can be collated.

Having collated the data by mixture type, variations in the relationship between the turbidity in 'bits' and the mixture concentration are apparent when comparing the data organised by mixture composition. Figure 32 presents this.

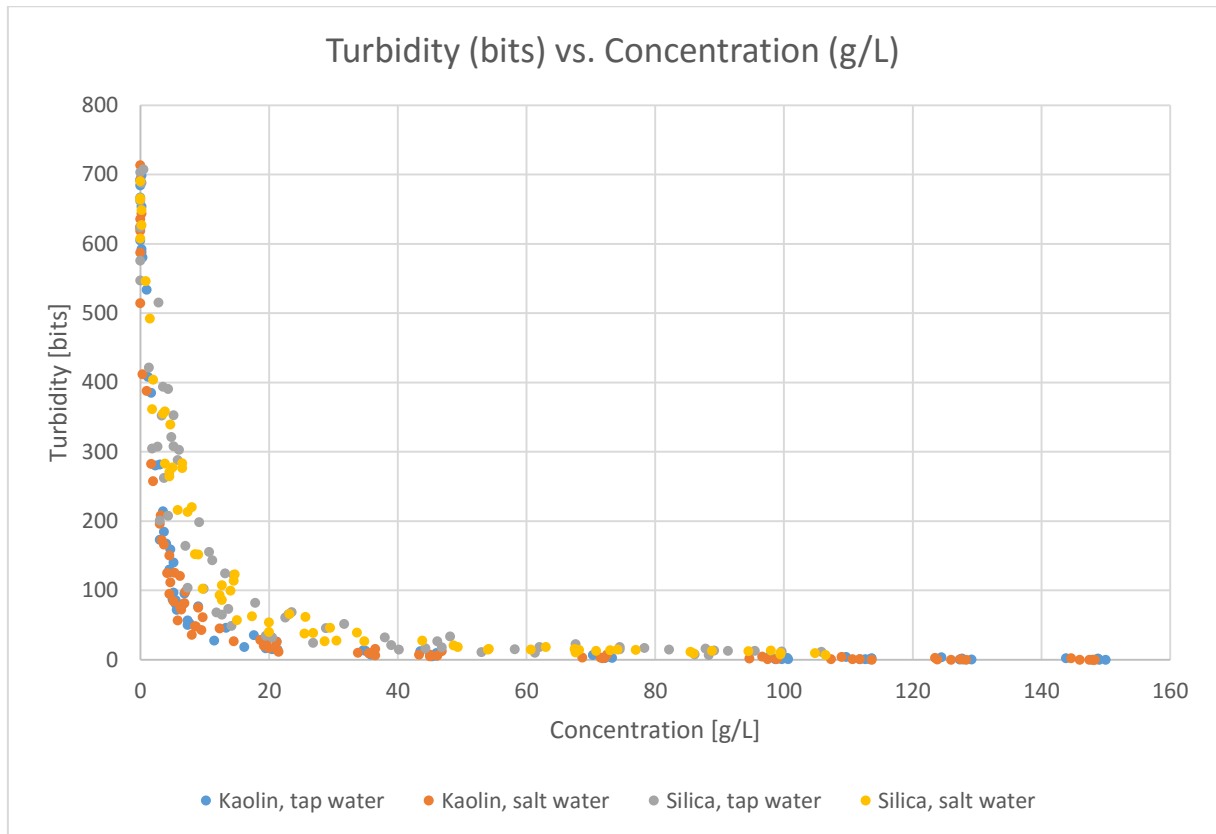


Figure 32: Collated calibration test data, organised by mixture type

Overall, the shape of the relationship between the turbidity readings and the concentration is consistent with initial expectations, with higher concentration mixtures permitting less light to transmit, leading to a lower reading from the sensor. It also appears that the effective range of concentrations that can be correlated using this data ranges from about 0g/L to 50g/L for silica mixtures and 0g/L to 20g/L for kaolin mixtures.

There appears to be more scattering of the data points for the mixtures containing silica, as opposed to kaolin. From discussions with Dr. Alistair Grinham, it is suspected that this may be due to effects resulting from differences in the particle size distribution (PSD) of the two materials. However, as these effects were not a key focus of this project, an investigation into these factors was not pursued.

Based on the overall shape of the graphs, it is expected that the relationship between concentration and turbidity in 'bits can be described by a negative exponential function or an inverse function. For fitting these curves, the general forms of these functions are shown below:

Negative exponential:

$$y = ae^{-\frac{x}{b}}$$

Inverse function:

$$y = \frac{1}{a + bx^{1.5}}$$

where:

$y = \text{turbidity measurement [bits]}$

$x = \text{mixture concentration [g/L]}$

$a, b = \text{curve fitting constants}$

TableCurve 2D is a software program that was used to determine functions in these forms that fit the collected data for each of the four mixture types. The direct outputs from this program can be found in Appendix J, with the key outputs summarised in Tables 5 and 6.

Table 5: Curve fitting constants for negative exponential curves fitted to calibration test data

Mixture:	a	b	R ² value
Silica in tap water	617.00903	6.3703639	0.92344958
Kaolin in tap water	665.82443	2.9068132	0.9883264
Silica in salt water	628.59395	6.4652278	0.97499047
Kaolin in salt water	612.07295	2.7817991	0.97557067

Table 6: Curve fitting constants for inverse function curves fitted to calibration test data

Mixture:	a	b	R ² value
Silica in tap water	0.00153333	0.00014116672	0.90010365
Kaolin in tap water	0.0015129384	0.00051759833	0.98812892
Silica in salt water	0.0015727941	0.00016184864	0.97490658
Kaolin in salt water	0.0015774501	0.0006336186	0.97581492

It can be seen that the fit of these curves suit the data rather well, with a relatively high coefficient of determination (R^2) value. Between the fit of the negative exponentials and inverse functions and based on the R^2 values, it would appear that the negative exponential curves fit the calibration test data better. However, upon visual inspection of the graphs in Appendix J, the inverse function relationships appear to provide a better overall fit to the data points. As such, inverse functions were adopted as the relationships between the TSD-10 turbidity readings and the mixture concentration for the different mixtures and are expressed in full in Table 7.

Table 7: Relationships between turbidity in 'bits' and mixture concentration for the four mixtures

Mixture:	Relationship
Silica in tap water	$y = \frac{1}{0.00153333 + 0.00014116672x^{1.5}}$
Kaolin in tap water	$y = \frac{1}{0.0015129384 + 0.00051759833x^{1.5}}$
Silica in salt water	$y = \frac{1}{0.0015727941 + 0.00016184864x^{1.5}}$
Kaolin in salt water	$y = \frac{1}{0.0015774501 + 0.0006336186x^{1.5}}$

Note: 'y' refers to the turbidity measurement [bits] and 'x' refers to the mixture concentration [g/L].

As the calibration tests sought to define the relationship between the turbidity readings in 'bits' and the mixture concentration, the selection of the inverse function relationships with the relevant curve fitting constants has effectively achieved this goal.

However, there were a number of experimental limitations and shortcomings that were observed during these tests. These are detailed below:

- Some leakage of material was observed from the 'beakers' early on in the calibration testing regime, where insufficient silicone was applied (see Figure 33a). This led to some of the material entering into the sensor, rendering them defunct. These 'beakers' were reconstructed with more silicone and required new sensors to be purchased (see Figure 33b).
- While attempts were made to keep the lighting conditions similar during and between tests, this could not be achieved due to weather variations affecting the intensity of natural light entering into the laboratory.
- The data logger did not always capture all of the data from a test, requiring the test to be restarted (see Appendix H, sections H14, H20, H21 and H34).

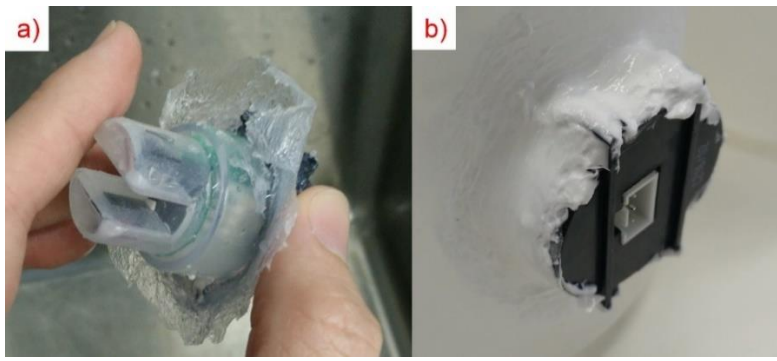


Figure 33: Leakage of mixture into sensor and reapplied silicone

- The occurrence or absence of settling within the 'beaker' during mixing could not be verified due to the turbidity of the mixture. Hence, it was uncertain whether or not the sensors were free from deposited material within the mixing environment.
- The 20mL sample extracted for oven drying from the 'beakers' was assumed to be representative of the mixture concentration being detected by the TSD-10 sensors. While this is a fair assumption (the syringe was inserted to extract the sample from the approximate height of the sensor), this could not be verified.
- Observations after emptying the 'beakers' noted the presence of settled material at the edges of the base of the 'beaker', indicating that some material had settled where the steady rotational flow was insufficient to keep the particles suspended (see Figure 34a). This may have also varied between tests as the precise position of the stirrer bar within the 'beaker' was not recorded. Also of note was the localised increase in the build-up near the sensor, indicating that the presence of the sensor interrupts the flow (see Figure 34b) and may lead to localised settling.

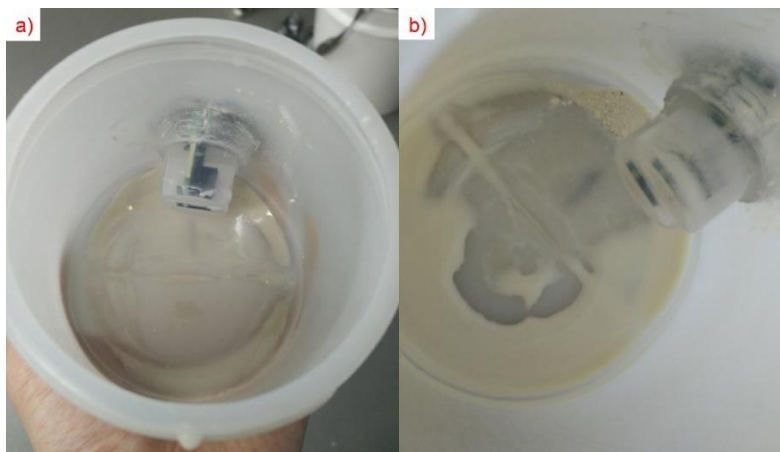


Figure 34: Build-up of material at base of 'beaker'

5.2 Model Column Tests

5.2.1 Aim

A model column was designed and tested as a proof-of-concept to demonstrate the methods by which the large column can be used in characterising sedimentation processes. In particular, this sought to align the findings from the dielectric correlation studies undertaken by Yucheng (Sophia) Jiang and the turbidity correlation studies detailed in Section 5.1.

5.2.2 Column design

To correlate the dielectric and turbidity measurements, the Plexiglas model column was designed to accommodate both the dielectric sensors and turbidity sensors. From the studies undertaken, it was determined that the dielectric sensors were better suited to measuring changes in concentration of the suspension at high concentrations, whereas the turbidity sensors were better suited to low concentrations. As such, the sensors were arranged along the column such that the turbidity sensors were placed towards the upper end, while the dielectric sensors were located more towards the lower end, as seen in Figure 35. All sensors were evenly spaced and the middle four locations were aligned such that both types of sensors were level.

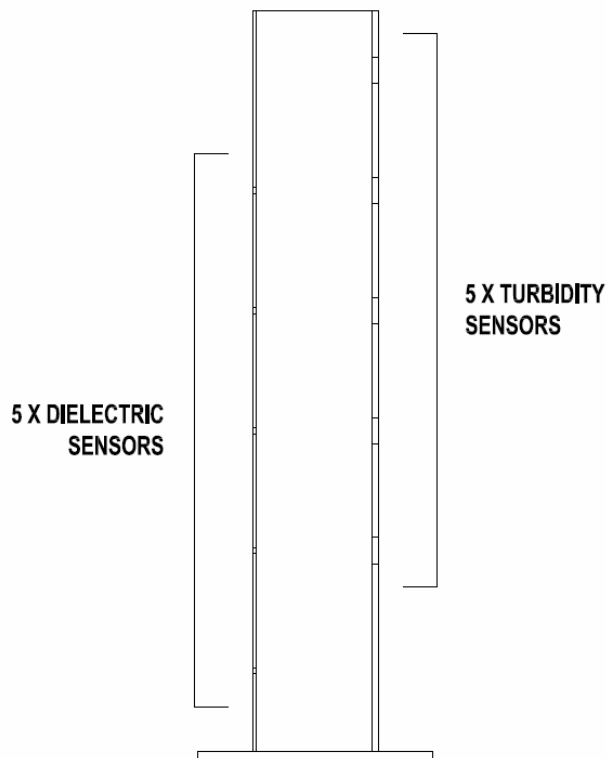


Figure 35: Arrangement of sensors on model column

To attach the sensors to the column, holes were cut into two flat Plexiglas sheets, sized to fit the sensors. As the dielectric sensors required a flat surface to attach to, the cylindrical column was cut and these two flat Plexiglas sheets were glued into place. Figure 36 shows a photograph of the completed column, with as-built drawings provided in Appendix K.

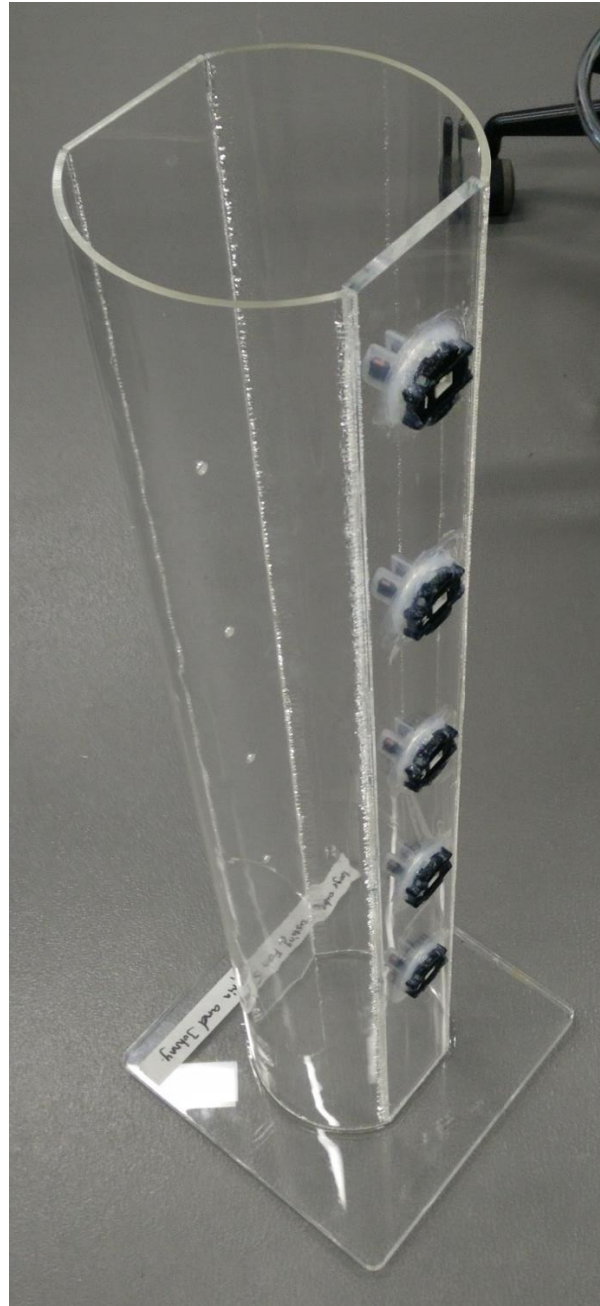


Figure 36: Fabricated model column

Following this process of fabrication, the need to efficiently empty the column was identified. As such, the column was elevated by two blocks glued to the base and a valve was installed, centred at the base of the column.

5.2.3 Mixtures

Based on the results of both the dielectric and turbidity calibration tests, kaolin mixtures in tap water were selected as the material to be tested in the model column. Three different initial concentrations were tested, being approximately 20g/L, 40g/L and 80g/L.

5.2.4 Equipment

Based on the calibration tests undertaken, the same TSD-10 sensors were used, with all five sensors installed. These were arranged such that sensor 1 was the uppermost sensor and sensor 5 was the bottommost sensor. Note that sensors 2 to 5 are located at the same height as the dielectric sensors.

The equipment used in the model column tests are listed below. Please note that this equipment list does not include components used for the dielectric measurements.

- 5 x Amphenol TSD-10 turbidity sensors
- 5 x Arduino Uno data loggers with battery packs and jumper leads
- 5 x 2GB microSD memory cards
- 1 x A&D GX-2000 electronic balance
- 3 x small oven drying tins
- 1 x 20mL syringe
- 1 x 20L bucket
- 1 x electronic stopwatch
- Electric drill with mixer attachment
- Digital camera with tripod
- Silicone sealant (24hr curing time) and caulk gun
- Cover for the column, boxes and containers for the data loggers

A photograph of the experimental setup during testing is shown in Figure 37.

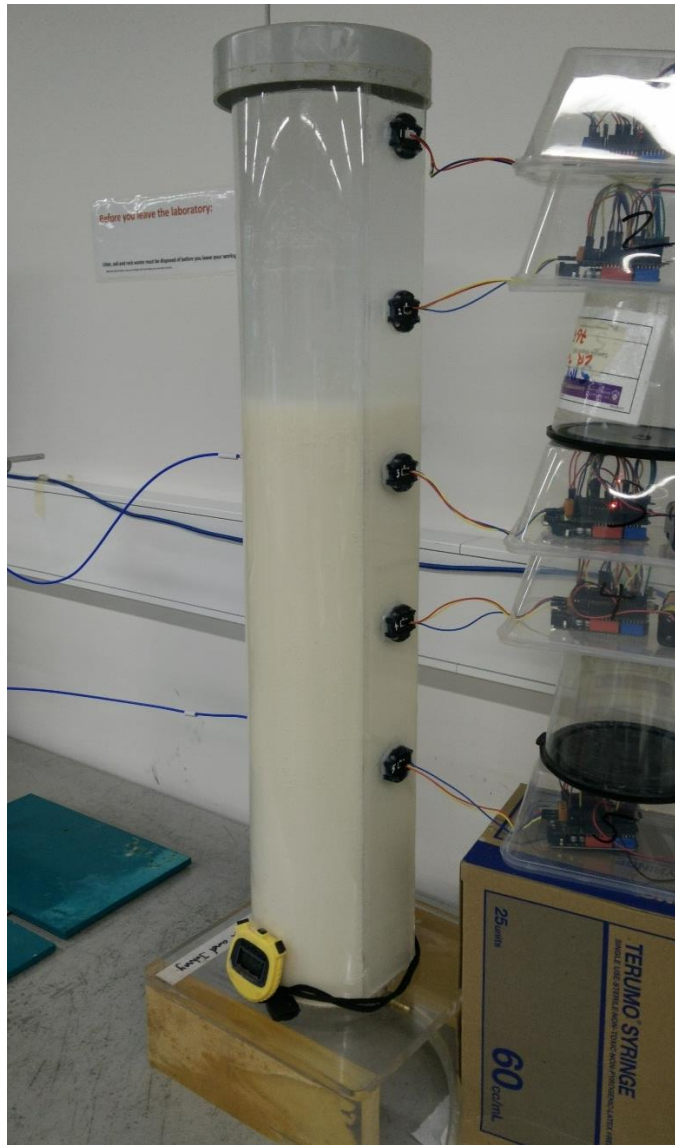


Figure 37: Experimental setup during settling

5.2.5 Methodology

A number of different procedures were undertaken in order to conduct the model column tests. The method for each of these steps are detailed separately below. Please note that the procedures outlined in detail do not include steps required for the dielectric measurements.

(A1) Apparatus preparation

1. Place sensor 5 into the bottommost hole, ensuring the slot in the sensor is aligned vertically. Using the silicone sealant and caulk gun, apply silicone around the hole to seal the sensor to the column (see Figure 34).
2. Leave the sensor for at least 24 hours to allow the silicone to set.
3. Repeat steps 1 and 2 for the other four sensors, going up the column.

(A2) Mixture preparation

1. For a given mixture, oven dry the fine-grained kaolin for 48 hours to remove any moisture from the powder.
2. Weigh the required amount of dried powder using the electronic balance and place into a labelled 20L bucket.
3. Measure the required of the tap water and pour into the same 20L bucket. Mix thoroughly using the electric drill with mixer attachment.
4. Cover and leave the bucket for at least 24 hours to allow the particles to saturate.

(B) Sedimentation test

1. Insert empty microSD memory cards into the Arduino data loggers. Connect battery packs to Arduino data loggers and connect data loggers to the turbidity sensors in the column using the jumper leads. Use the boxes and containers to ensure these are placed at an appropriate height.
2. Agitate the prepared mixture in its 20L bucket using the electric mixer. Ensure the valve at the base of the column is closed. Set the camera to 'interval shooting' mode at regular intervals. Adjust the tripod to position the camera to take photos of the column during sedimentation.
3. Once sufficiently mixed, start the test by pouring the mixture into the column, starting the stopwatch and starting the camera's 'interval shooting'.
4. Leave the column to settle at least until the interface has passed the bottommost sensor. Conclude the test when required.

(C) Oven drying

1. Label the three oven drying tins and weigh each tin three times using the electronic balance, recording the masses of the empty tins. Set aside
2. Re-agitate the mixture in the 20L bucket and extract 20mL of the mixture using the 20mL syringe. Place tins into 60°C oven.
3. Check the drying tins regularly, weighing each one three times and recording the measurements. Calculate the average mass of each tin with dried sample.
4. Repeat step 3 until the average mass for each tin does not vary greater than 0.01g (within the error margins of the equipment).
5. Once step 4 is complete, remove labels from tins, clean tins and allow to dry.

5.2.6 Results and discussion

Based on the methodology outlined in Section 5.2.5, four tests were undertaken using the model column. Unfortunately, issues were encountered with the data recording equipment during some of these tests, resulting in either poor quality dielectric or turbidity data captured or a poor correlation between them. Table 8 summarises this.

Table 8: Overview of data quality and correlation quality for each model column test

Test:	Concentration [g/L]	Turbidity data	Dielectric data	Correlation
i	28.28	Very Good	Poor	N/A
ii	39.56	Good	Poor	N/A
iii	80.56	Poor	Good	Fair
iv	22.94	Good	Poor	Poor

Note: Mixture concentration calculations are detailed in Appendix M.

From the tests undertaken, data from the turbidity sensors was obtained and processed. Appendix L details the procedure used in evaluating the raw data, while Appendix M presents a summary of the data obtained from each model column test.

Given the quality of the data obtained, this report will focus on the findings from these tests by referring to data most pertinent to particular observations. To begin, the concentration over time plot for Test i is presented in Figure 38.

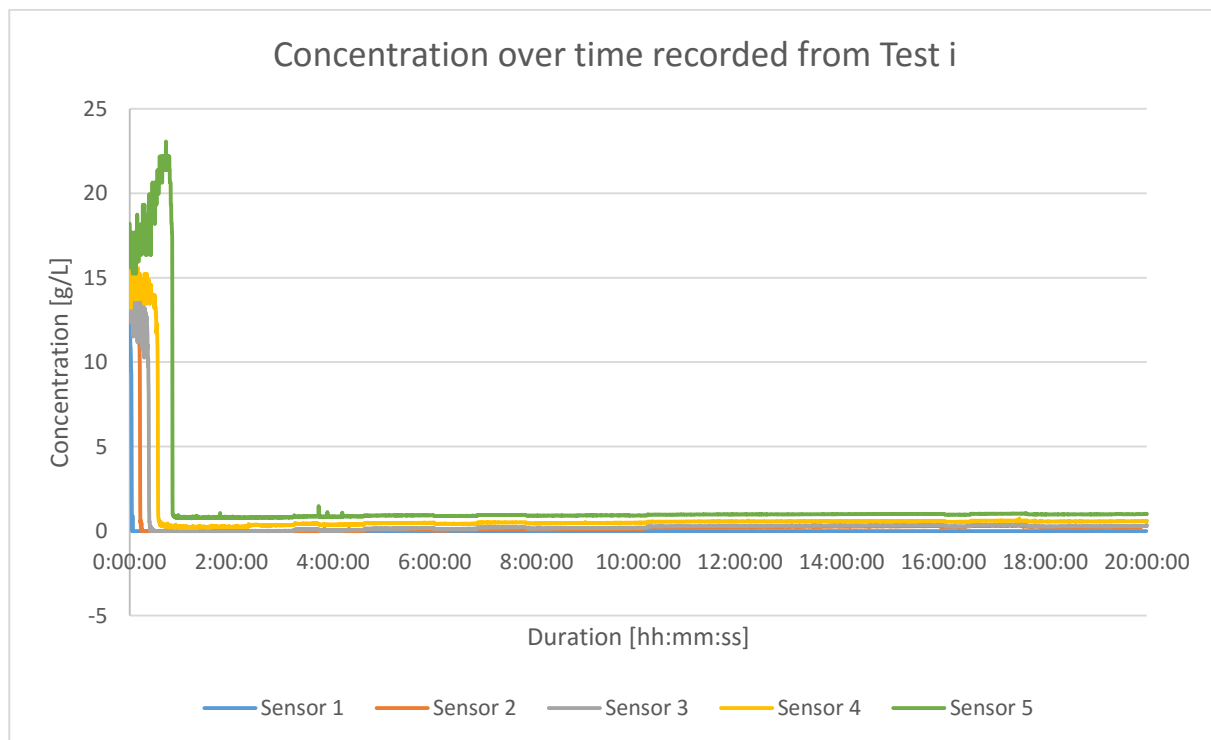


Figure 38: Plot of concentration over duration of Test i

Given the sedimentation processes occurring within the column, the overall shape of this graph matches the initial expectations, with sharp drops in the concentration detected as the settling front or interface passes the sensor. It was noted that this occurred within the first hour of Test i. Figure 39 shows the mixture concentrations over this period of time in greater detail, while Figure 40 shows the corresponding camera images taken as the interface passed each of the five sensors.

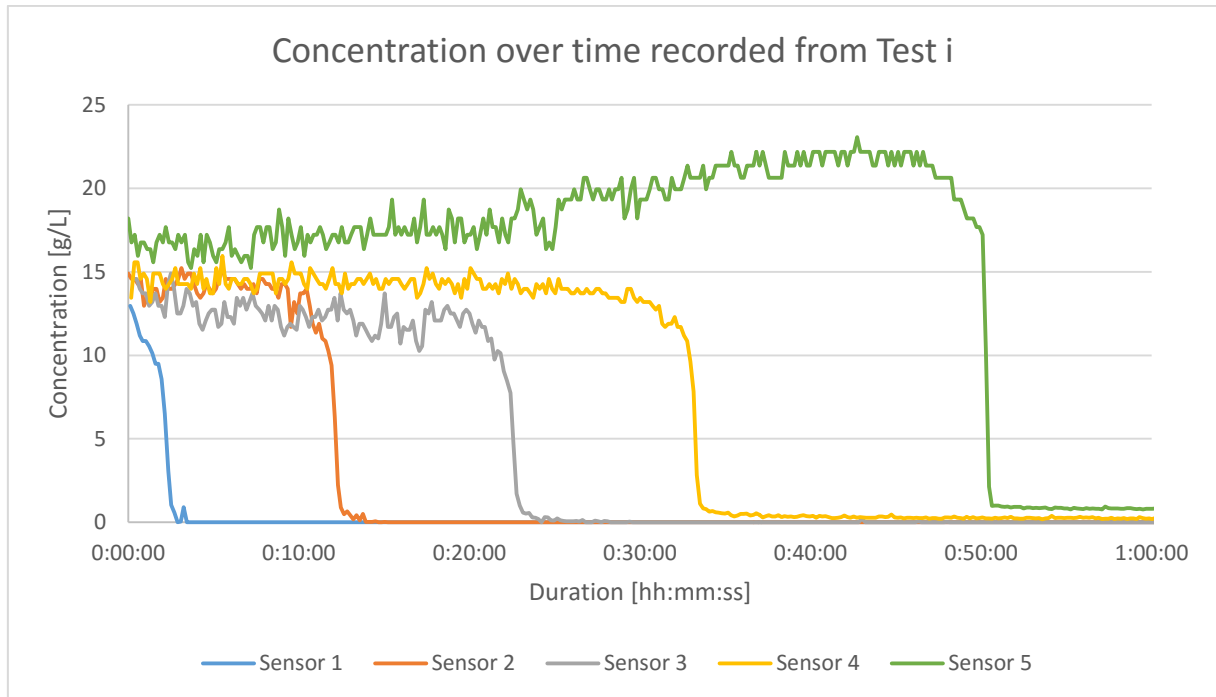


Figure 39: Concentration data from Test i over the first hour



Figure 40: Camera images of the interface passing each sensor

Based on the data presented in Figure 39, there are two key aspects that were observed. Firstly, the time taken for the passing of the interface appears to be consistent as it passes sensors 1 to 4, taking about 10 minutes to pass between each sensor. However, the time taken for the interface to pass from sensor 4 to 5 was much greater, requiring about 18 minutes. This slowing of the settling front provides an indication that hindered settling processes are occurring at this level in the column.

The second observation from the concentration data was the visible change in mixture concentration detected at sensor 5 prior to the passing of the settling front. This increase in concentration is another indicator of hindered settling processes occurring at this sensor during the sedimentation process.

Similar behaviour was also observed in the data from Test iv, as seen in Figure 41.

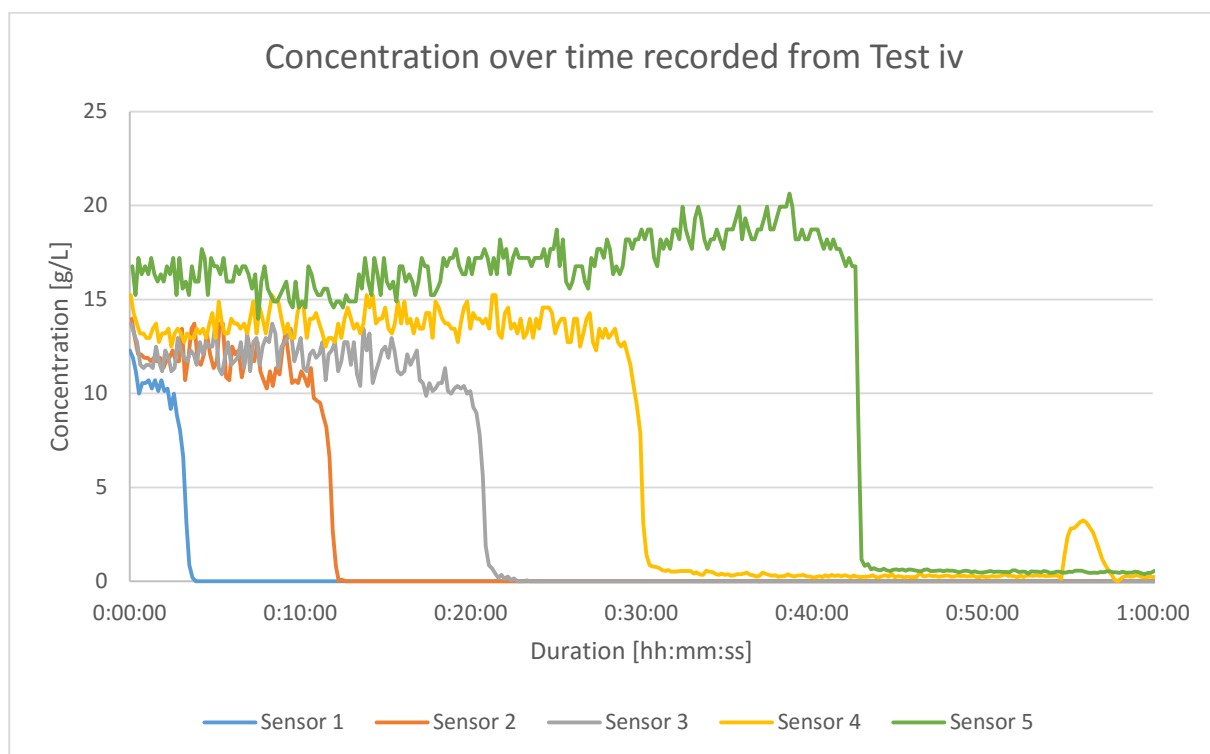


Figure 41: Concentration data from Test iv over the first hour

Again, an increase in the concentration detected at sensor 5 is visible. Also, the time required for the interface to pass between each of the first four sensors is a consistent 9 minutes, whereas the time between sensor 4 and 5 is about 13 minutes. These findings again imply the occurrence of hindered settling. It should be noted that the reduced settling time between sensors of Test iv compared to Test i implies that the mixture in Test iv settled under a slightly increased settling velocity. This is consistent with existing literature, as seen in Figure 3.

While capturing this behaviour was a good indication of the value of this type of settling column and this settling methodology, it was previously determined that the turbidity sensors were best suited for detecting low concentrations. As such, the concentration data obtained after the interface passed the sensors was also of interest, particularly to characterise the behaviour of the supernatant. Data from Test i is shown in Figure 42, noting the change in the y-axis scale compared to Figure 39.

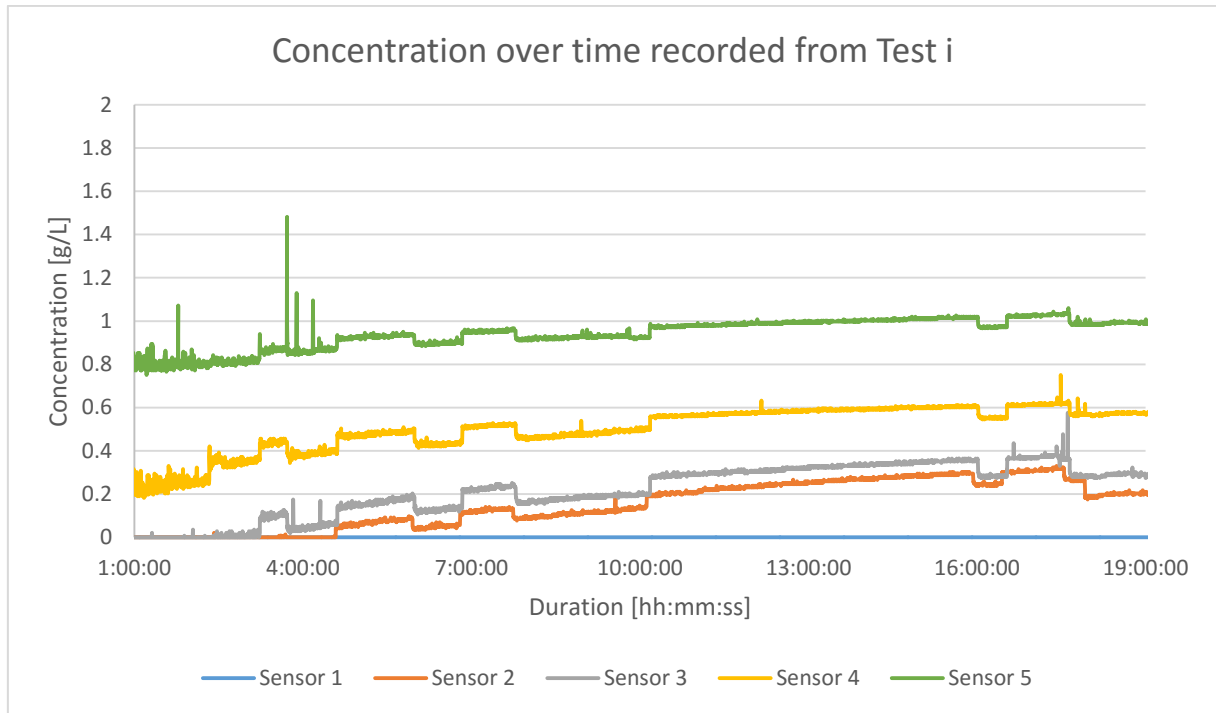


Figure 42: Concentration data from Test i after the first hour

From Figure 42, it is clear that the data indicates a steady increase in the concentration of the supernatant. This is contrary to expectations, as small particles would be expected to settle over time, reducing the concentration of the mixture measured at each sensor. The turbidity data also appears to conflict with the camera footage obtained, as seen in Figure 43 (note the visibility of the blue cable behind the column).

Evidently, there is a discrepancy between the overall behaviour of the material in the column and the local behaviour of material at each sensor. One explanation for the observed behaviour is the adherence of small kaolin particles to the turbidity sensors between the light transmitter and the light receiver. This would result in a reduction in the turbidity measurements in 'bits' over time, leading to a corresponding increase in the measured concentration. While this effect was expected to be minimal due to the vertical alignment of the sensors, any imperfection in its alignment could result in this. Additionally, flocculation behaviour of the particles could exacerbate this issue.

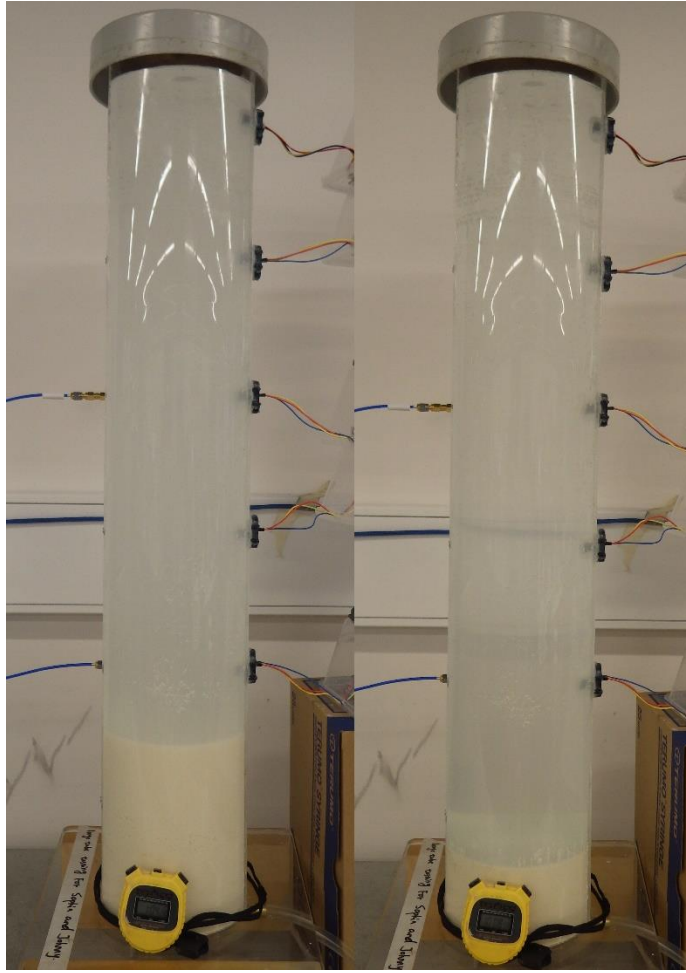


Figure 43: Observed changes in supernatant turbidity

Another important observation from Figure 42 is the occasional shift in the data obtained, stepping consistently up or down. By reviewing the camera images taken during the test, it was evident that this resulted from changing lighting conditions within the geomechanics laboratory, as noted in Figure 44.

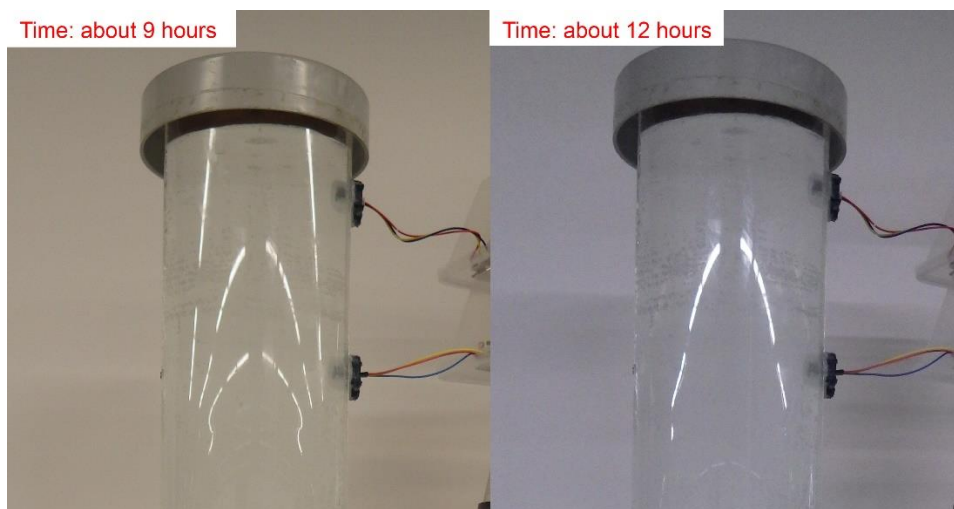


Figure 44: Changes in lighting conditions observed in column reflection

Another key objective of the model column tests was to attempt to align concentration measurements using dielectric methods with those using turbidity methods, especially when considering their different effective ranges. To do so, data from Test iii will be considered, with the graph of concentration obtained using turbidity measurements shown in Figure 45.

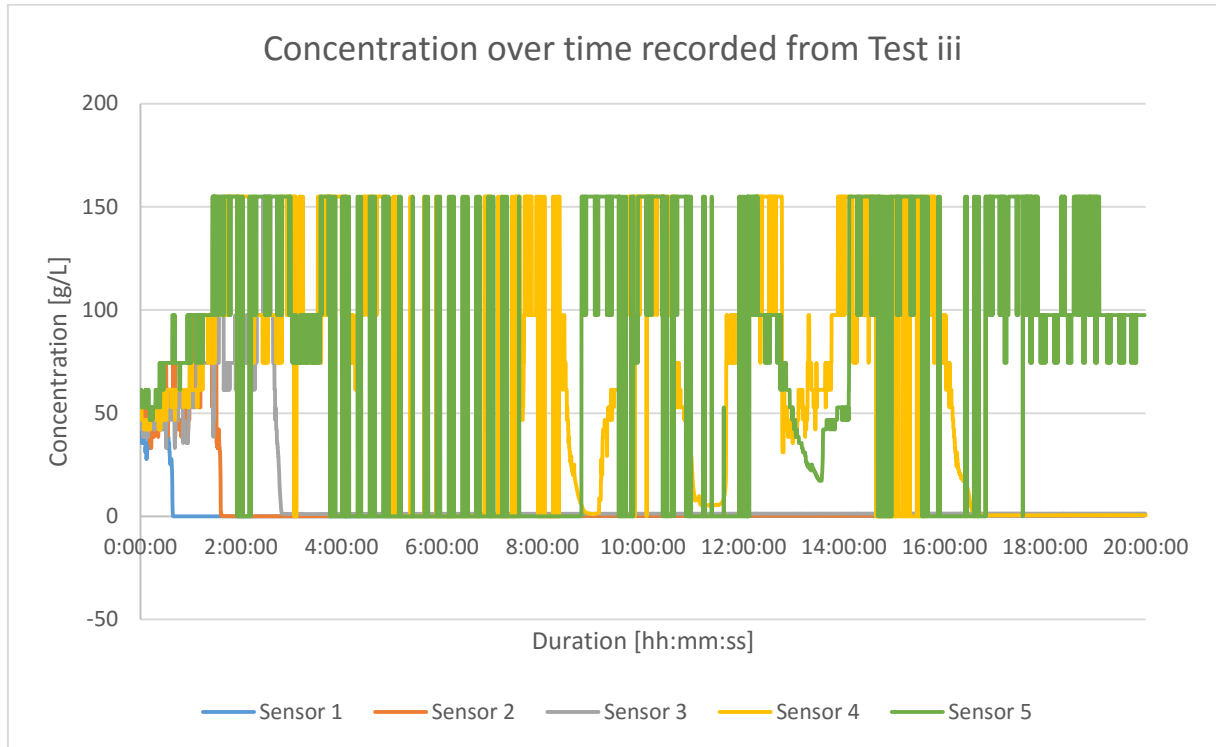


Figure 45: Plot of concentration over duration of Test iii from turbidity data

From Figure 45, it is immediately obvious that the concentrations measured by sensors 4 and 5 are particularly poorly defined by the turbidity data collected. This is due to the initial concentration of the mixture being high (80.56g/L), well outside the effective range of the TSD-10 turbidity sensors, as mentioned in Section 5.1.6.

As previously mentioned in Section 5.2.2, the use of turbidity sensors at high concentrations are a way to better observe the mixture concentration. In consultation with Dr. Thierry Bore, the calibrated concentration data over time was obtained for the dielectric sensors. It should be noted that only two dielectric sensors were used in Test iii and that these were aligned with turbidity sensors 3 and 4. The superimposition of these datasets is presented in Figures 46 and 47, showing the data obtained at the location of sensors 3 and 4 respectively. References to sensors '3' and '4' refer to the turbidity sensors and their positions and not those of the dielectric sensors (these were originally numbered differently during the experiments).

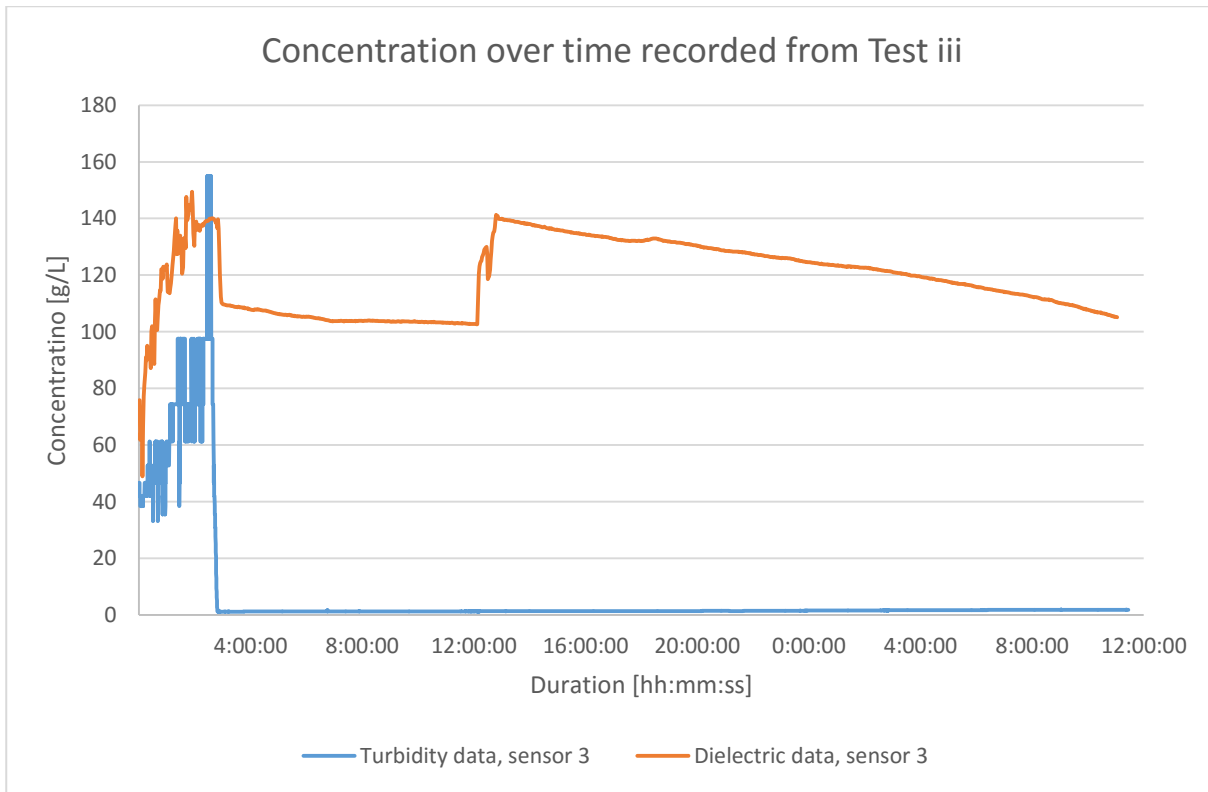


Figure 46: Concentration over time for Test iii at sensor 3 using turbidity and dielectric data

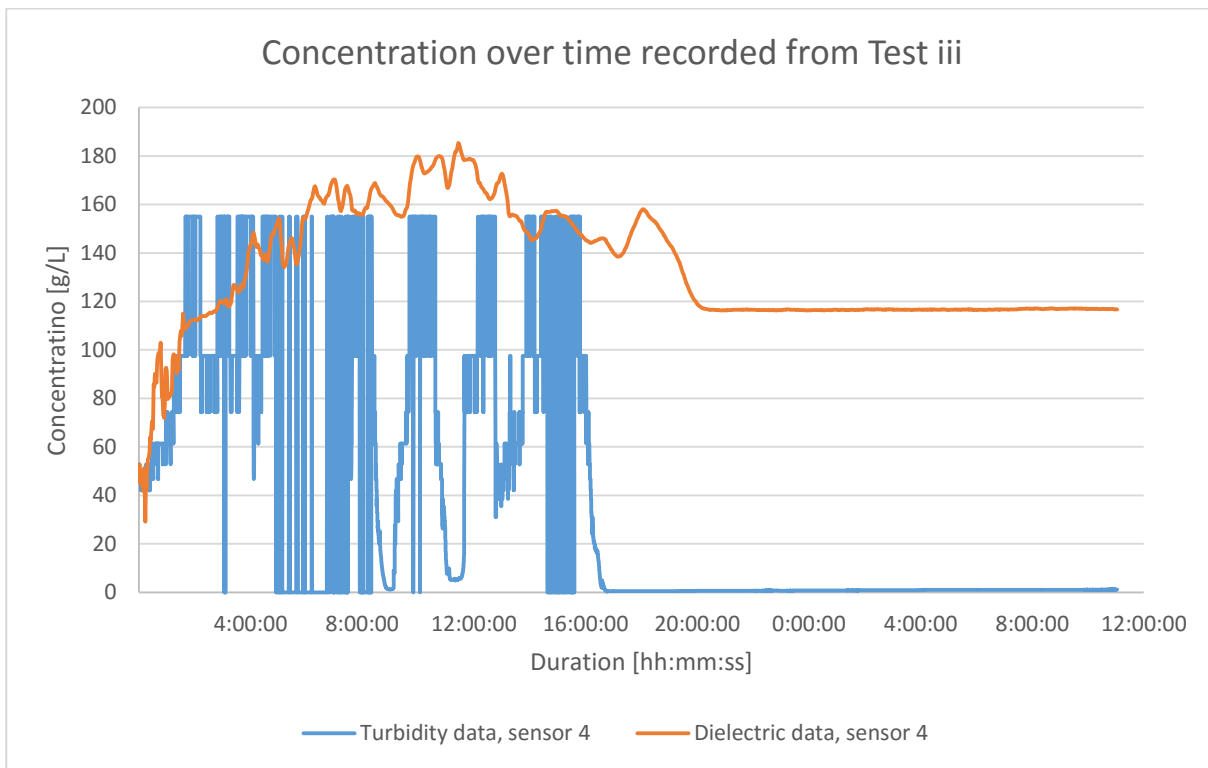


Figure 47: Concentration over time for Test iii at sensor 4 using turbidity and dielectric data

As seen in Figures 46 and 47, the plots of the mixture concentration calculated using dielectric and turbidity data appear to coincide rather well, particularly at sensor 4. The alignment of these calculated mixture concentrations at the start of the sedimentation process for sensor 4 indicates a good overlap of data while concentrations are still low enough to be detected by the turbidity sensors. Figure 48 shows this in greater detail.

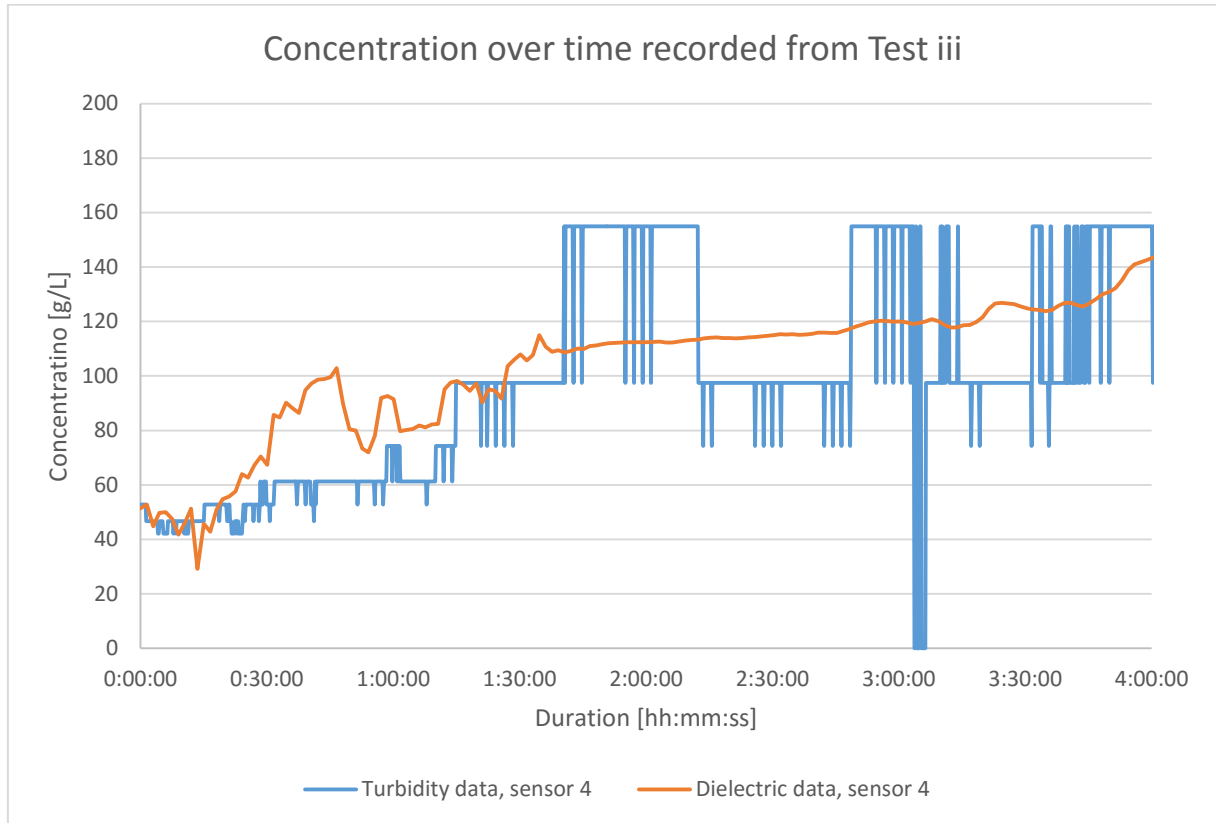


Figure 48: Concentration over the first four hours of Test iii at sensor 4, turbidity and dielectric data

As the concentration increases, it is clear that the dielectric measurements provide a much clearer understanding of the mixture's behaviour, given the erratic behaviour of the turbidity data plot. This demonstrates that the collation of these complementary sets of data together is beneficial for sedimentation testing.

One behaviour that is captured in Figure 46 is the passing of the settling front past the level of sensor 3, about 2 hours and 40 minutes into the test. Notably, this change to a lower concentration appears to have been detected in much greater detail with the turbidity sensors rather than the dielectric sensors. Observations of the column after the completion of the test indicated that some settling of material had occurred on the surface of the dielectric sensors. This is shown in Figure 49 and may describe the high concentrations detected by the dielectric sensors well after the interface had passed.

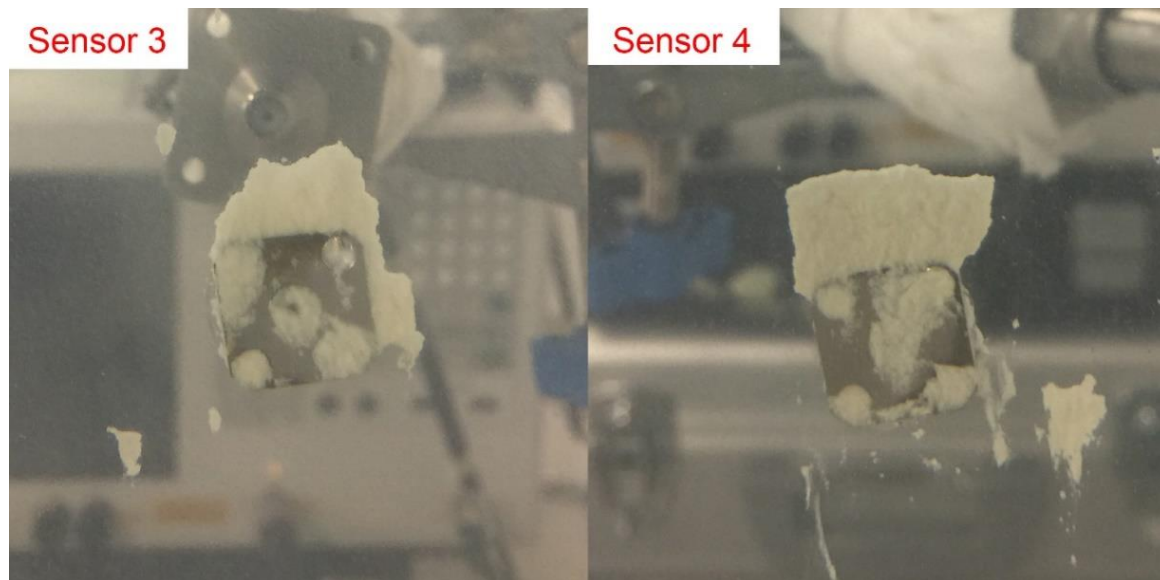


Figure 49: Observed build-up of material on dielectric sensors

Another discrepancy noted was the time that the passing interface was detected by each sensor. By inspecting the data, the concentration measurements at sensor 3 indicate that the dielectric measurements detected the passing of the settling front about 15 minutes after the turbidity sensors. This may have resulted from imprecisions in the sensor alignments, as the ports in the model column were aligned centre-to-centre instead of at the precise sensor height.

Measurements at sensor 4 indicate a 2 hour lag between these drops in concentration, with the turbidity sensors indicating the passing of the interface 16 hours into the test and the dielectric sensors detecting a significant drop starting at 18 hours. However, the validity of the dielectric measurements here is questionable, especially when considering the build-up of material on the sensors and the erroneously high concentration detected after the passing of the settling front.

While a number of limitations have been discussed already, there are a few further observations that describe other factors that may have also impacted upon the sedimentation behaviour of the suspension during the model column tests. These are listed below:

- Bubbles stuck to the inner wall of the column were observed throughout the tests, resulting from the turbulent filling process. In some tests, particles were observed to have settled onto these surfaces (see Figure 50). While it cannot be verified, this may have occurred on the sensors, affecting the validity of the measurements taken.

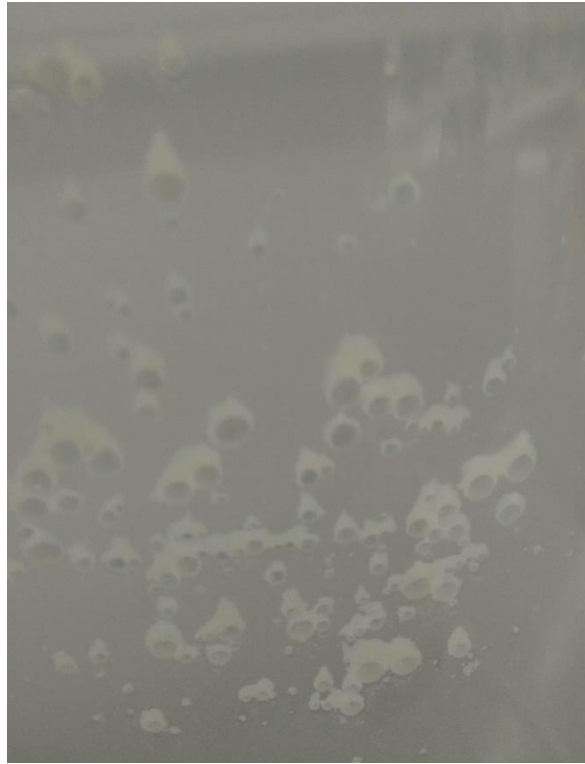


Figure 50: Bubbles observed inside the sedimentation column

- The settling of particles onto both the dielectric sensors and turbidity sensors was also observed (see Figures 49 and 51). This may have changed the dynamics of the particles settling within the column and hence, impacted upon the data obtained.

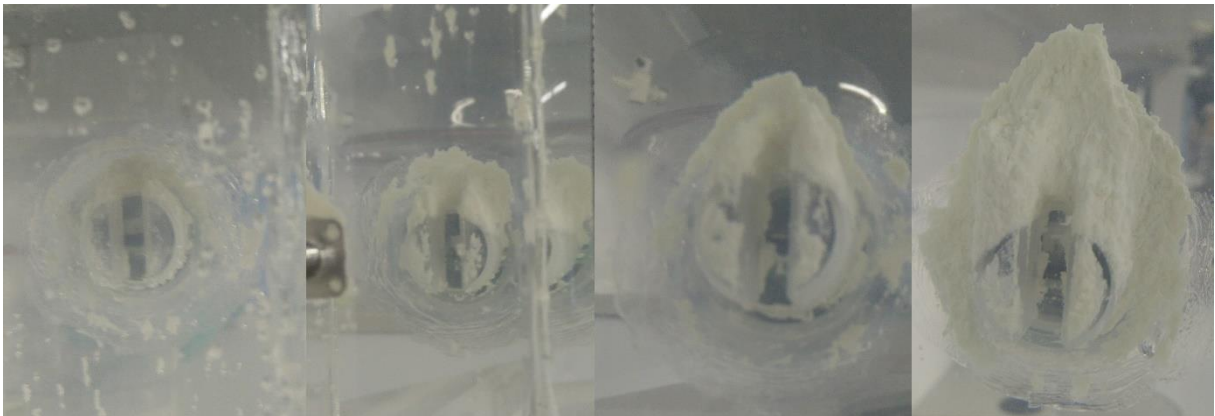


Figure 51: Settled material observed on top of turbidity sensors during the model column tests

Despite these shortcomings, the use of both dielectric and turbidity measurements for determining mixture concentration are complementary and appear to provide a better understanding of sedimentation processes. Based on the various conclusions drawn from the collected results, this approach towards characterising sedimentation is a valuable and effective methodology.

6.0 CONCLUSION AND EVALUATION

Given the broad scope of the project, there were a number of different objectives and hence, various conclusions can be drawn from the work undertaken. As such, the following subsections discuss the conclusions reached and considerations for further research with regards to the three key outcomes of this project.

6.1 Calibration tests

The calibration tests undertaken sought to establish a relationship between the measurements made using the TSD-10 turbidity sensors and the solid concentration of a mixture. By undertaking these calibration tests and obtaining the relationships for each mixture type, the aim of these tests was successfully achieved.

While this is the case, a number of limitations were identified during the discussion of these results. These are collated in Table 9, along with the impact of the limitation on the conclusions reached and proposed improvements for future iterations of this test.

Table 9: Limitations identified in the calibration tests

Limitation	Impact	Proposed improvements
Scattering of data from silica mixtures not well understood	The scattering of data points resulted in a poorer fit of the relationships for silica mixtures.	Undertake more calibration tests in future to understand if this scatter results from poor data collection.
Mixture leaked out of 'beakers' and into sensors	Some data collected was rejected and some sensors were disposed of. This limited the number of calibration tests that could be undertaken, providing lower accuracy in the fitting of the curves.	Ensure all joins are fully sealed with cured silicone prior to testing, with particular attention paid to the join between the clear and black plastic of the TSD-10 sensors.
Lighting conditions not consistent across calibration tests	Lighting conditions were shown to have an effect on the output from the TSD-10 sensors, as seen in Appendix F3. As such, the data obtained in these calibration tests is flawed due to this inconsistency.	Future studies should seek to perform all calibration tests under consistent lighting conditions.
Occasionally missing data from Arduino data loggers	As noted in Section 5.1.6, some calibration tests were abandoned due to apparent errors in the data collected by the Arduino loggers.	While this was not seen to be an issue during the model column tests, future occurrences of this issue should be investigated further.

Possible settling during mixing	While it cannot be verified, the settling of particles within the 'beakers' during mixing may have affected the sampling process, in turn affecting the concentration values calculated.	To minimise settling within the 'beakers' during mixing, further studies should be undertaken in an attempt to define better mixing parameters.
Reliance of calibration on limited data collected	The validity of the relationships derived is highly dependent on the limited data collected, increasing its sensitivity to random errors that may have occurred during the tests.	A greater number of calibration tests should be pursued to better define these relationships.
TSD-10 sensors unable to detect changes at high concentrations	The calibration relationships obtained indicate a poor definition of concentration correlations at high mixture concentrations. While this was expected, effectively no useful data can be obtained at these high concentrations.	Future studies should consider the use of other turbidity sensors with a higher effective range of measurements.

In addition to these suggestions, it was noted that the testing process for each sensor was quite arduous and time consuming, especially given the variables investigated. As such, the development of an improved methodology and apparatus to calibrate multiple sensors at once would be highly beneficial and is proposed for future studies.

6.2 Model column tests

The model column was designed as a proof-of-concept for the large column, with tests undertaken to demonstrate methods by which the large column could be used to characterise sedimentation processes. As seen in Section 5.2.6, evidence of hindered settling was detected during these tests using the turbidity data measured, both in the reduced settling velocity at the lower end of the column as well as the measured increase in concentration. Hence, this goal has been fulfilled.

The other aim of these tests was to attain a correlation of data between the dielectric measurements and the turbidity measurements of mixture concentration. From the tests undertaken, this goal was achieved, with the data from Test iii for the two sensor types complementing one another to better define concentration measurements. This provided a clearer understanding of the settling processes occurring and as such, both aims of the model column tests have been achieved.

Despite this, various limitations in the methodology were identified in the discussion of the model column test results. The impacts of these limitations and a range of proposed improvements for the test are collated in Table 10.

Table 10: Limitations identified in the model column tests

Limitation	Impact	Proposed improvements
Possible adherence of particles to turbidity sensors	Data captured for the supernatant was rendered invalid, preventing any notable observations of the supernatant behaviour.	Consider the application of anti-static sprays to the sensors or consider the use of different turbidity sensors.
Changes in lighting conditions during test	As seen in Appendix F3 and discussed in Section 5.2.6, varying lighting conditions cause fluctuations in the turbidity data obtained from the TSD-10 sensors, impacting the validity of the results.	Undertake future model column tests within a controlled lighting environment.
TSD-10 sensors unable to detect changes at high concentrations	The calibration relationships obtained indicate a poor definition of concentration correlations at high mixture concentrations. While this was expected, effectively no useful data can be obtained at these high concentrations.	Future studies should consider the use of other turbidity sensors with a higher effective range of measurements.
Possible imperfect sensor alignment	Imprecise alignment of the exact measurement location of the two types of sensors may have resulted in the time lag effects discussed in Section 5.2.6.	Both turbidity and dielectric sensors should be realigned to ensure precise comparisons can be made.
Limited timeframe for testing	A limited range of concentrations were tested and may not have been ideal to provide the correlation of data between dielectric and turbidity measurements. Furthermore, only one mixture type was tested, despite calibration data and relationships having been determined for all four different mixtures of material and solvent.	Additional model column tests should be pursued using a variety of different initial mixture concentrations and different mixture types.

Flawed column filling method	No particular methodology was investigated or specified for the filling of the column, resulting in variations in the initial conditions in the column. The presence of bubbles may have affected settling.	Investigate the effect of filling methods and initial conditions on sedimentation processes. Consider updating the column design to accommodate agitation of the mixture prior to settling.
Settling of particles on top of sensors within column	Changes in the settling dynamics within the column may have occurred due to these additional surfaces upon which particles could settle.	Other measurement methods without requiring the physical placement of sensors into the sedimentation column should be investigated.

The application of these improvements will assist in improving the accuracy, precision and validity of results obtained from future studies using this apparatus or this methodology. These considerations may also be applied to the methodology of the large column tests once testing and calibration of the apparatus begins.

6.3 Large column design

The large column design component of this project was aimed towards developing a new apparatus for sedimentation testing, allowing for various instrumentation to be installed along the column as well as interfacing with existing testing equipment of the GEC. From the developed designs of the six different component types, this aim has been achieved, with further design development currently in progress in preparation for fabrication.

Currently, the key design considerations to progress include:

- Specification of the sensors to be used in the large column and their required port diameters;
- Specification of connections for attaching sensors to the column; and
- Detailed design of the density base unit.

Following the completion of a final design, the fabrication of the column, calibration of the required sensors and testing using the proposed assemblies are to be pursued to further progress this novel approach towards sedimentation testing.

REFERENCES

- Alemayehu, Z., 2010. *Sedimentation - Water Treatment Course*. [Online]
Available at: <https://aaucivil.files.wordpress.com/2010/10/chapter-41.pdf>
[Accessed 29 September 2016].
- Amphenol Corporation, 2014. *TSD-10 Turbidity Sensor*. [Online]
Available at: <http://www.mouser.com/ds/2/18/AAS-920-616A-Thermometrics-TSD-10-TurbiditySensor--850586.pdf>
[Accessed 28 August 2016].
- Bhosale, K., 2015. *Sedimentation*. [Online]
Available at: <http://waterengineer.co.in/sedimentation/>
[Accessed 19 October 2016].
- Bose, P., 2009. *Settling*. [Online]
Available at: <http://nptel.ac.in/courses/105104102/Lecture%206.htm>
[Accessed 25 September 2016].
- Carlsson, B., 1998. *An introduction to sedimentation theory in wastewater treatment*. [Online]
Available at: www.it.uu.se/research/project/jass/material/sett98.pdf
[Accessed 20 October 2016].
- Casiday, R., Noelken, G. & Frey, R., 2008. *Treating the Public Water Supply: What Is In Your Water, and How Is It Made Safe to Drink?*. [Online]
Available at:
<http://www.chemistry.wustl.edu/~edudev/LabTutorials/Water/PublicWaterSupply/PublicWaterSupply.html>
[Accessed 25 September 2016].
- Chapuis, R. P., Duhaime, F. & Weber, S., 2015. Simplifying the calculation of equivalent diameter in sedimentation tests. *Canadian Geotechnical Journal*, 52(8), pp. 1186-1189.
- Crittenden, J. C. et al., 2012. Gravity Separation. In: *MWH's Water Treatment: Principles and Design*. Hoboken(NJ): Wiley & Sons, Inc., pp. 641-725.

Dearnaley, M. P., 1991. *Flocculation and settling of cohesive sediments*, Oxfordshire: HR Wallingford.

Dodane, P.-H. & Bassan, M., 2014. Settling-Thickening Tanks. In: L. Strande, M. Ronteltap & D. Brdjanovic, eds. *Faecal Sludge Management*. London: IWA Publishing, pp. 123-140.

Fisher, P. L., 2015. *Code for Turbidity Monitoring Super Node*. s.l.:s.n.

Kocamemi, B. A., n.d. *Sedimentation*. [Online]

Available at:

http://mimoza.marmara.edu.tr/~bilge.alpaslan/enve301/Lectures/Chp_10.pdf

[Accessed 20 April 2016].

Law, J. & Rennie, R., 2015. *A Dictionary of Physics*. s.l.:Oxford University Press.

Minnesota Rural Water Association, 2009. *Sedimentation*. [Online]

Available at:

<http://www.mrwa.com/WaterWorksMnl/Chapter%2013%20Sedimentation.pdf>

[Accessed 10 October 2016].

Montgomery, R. L., 1980. *Design of Fine-Grained Dredged Material Sedimentation Basins*. College Station, Texas A&M University.

New Mexico Environment Department, 2007. Sedimentation. In: *Wastewater Systems Operator Certification Study Manual*. Santa Fe: New Mexico Environment Department, pp. 70-78.

Owen, M. W., 1976. *Determination of the settling velocities of cohesive muds*, Oxfordshire: HR Wallingford.

Peavy, H. S., Rowe, D. R. & Tchobanoglous, G., 1985. *Environmental Engineering*. United States of America: McGraw-Hill.

Pise, C. P. & Halkude, S. A., 2011. A modified method for settling column data analysis. *International Journal of Engineering Science and Technology*, 3(4), pp. 3177-3183.

Samdani, S. A. & Kapoor, S., n.d. *Numerical Analysis of Type I Settling*. [Online]
Available at: http://www.oocities.org/saurabhsamdani/sourcecodes_files/settling-report.pdf

[Accessed 29 September 2016].

Sarmiento, G. & Uhlherr, P. H. T., 1979. The Effect of Temperature on the Sedimentation Parameters of Flocculated Suspensions. *Powder Technology*, 22(1), pp. 139-142.

Scheuermann, A., 2015. *Laboratory experiments on the sedimentation behaviour of fine-grained soils*, s.l.: s.n.

Schroepfer, G. J., 1933. Factors Affecting the Efficiency of Sewage Sedimentation. *Sewage Works Journal*, 5(2), pp. 209-232.

Sithebe, N. P., Methula, B. G. & Chirwa, E. M. N., 2014. A finite velocity simulation of sedimentation behaviour of flocculating particles - A real-time model evaluation. *Water SA*, 40(1), pp. 109-116.

Standards Australia, 2003. *Method 3.6.3: Soil classification tests - Determination of the particle size distribution of a soil - Standard method of fine analysis using a hydrometer*. Sydney: SAI Global Limited.

Stricker, A. -E., Takács, I. & Marquot, A., 2007. Hindered and compression settling: parameter measurement and modelling. *Water Science & Technology*, 56(12), pp. 101-110.

Templeton, M. R. & Butler, D., 2011. *Introduction to Wastewater Treatment*. s.l.:s.n.

The World Bank Group, 2016. *Introduction to Wastewater Treatment Processes*.

[Online]

Available at: <http://water.worldbank.org/shw-resource-guide/infrastructure/menu-technical-options/wastewater-treatment>

[Accessed 27 September 2016].

USACE, 1987. *Confined Disposal of Dredged Material*, Washington, DC: Department of the Army.

USACE, 2015. *Dredging and Dredged Material Management*, Washington, DC: Department of the Army.

Whitehouse, R. J. S., Soulsby, R. L., Roberts, W. & Mitchener, H., 2000. Suspension of mud in the water column. In: *Dynamics of estuarine muds: A manual for practical applications*. London: Thomas Telford Publishing, pp. 76-101.

Wolanski, E., Asaeda, T. & Imberger, J., 1989. Mixing across a lutocline. *Limnology and Oceanography*, 34(5), pp. 931-938.

Wolanski, E. et al., 1992. The Role of Turbulence in the Settling of Mud Flocs. *Journal of Coastal Research*, 8(1), pp. 35-46.

Xu, G.-Z., Gao, Y.-F., Hong, Z.-S. & Ding, J.-W., 2012. Sedimentation Behavior of Four Dredged Slurries in China. *Marine Georesources and Geotechnology*, 30(2), pp. 143-156.

APPENDICES

Appendix A: USACE settling test methodology

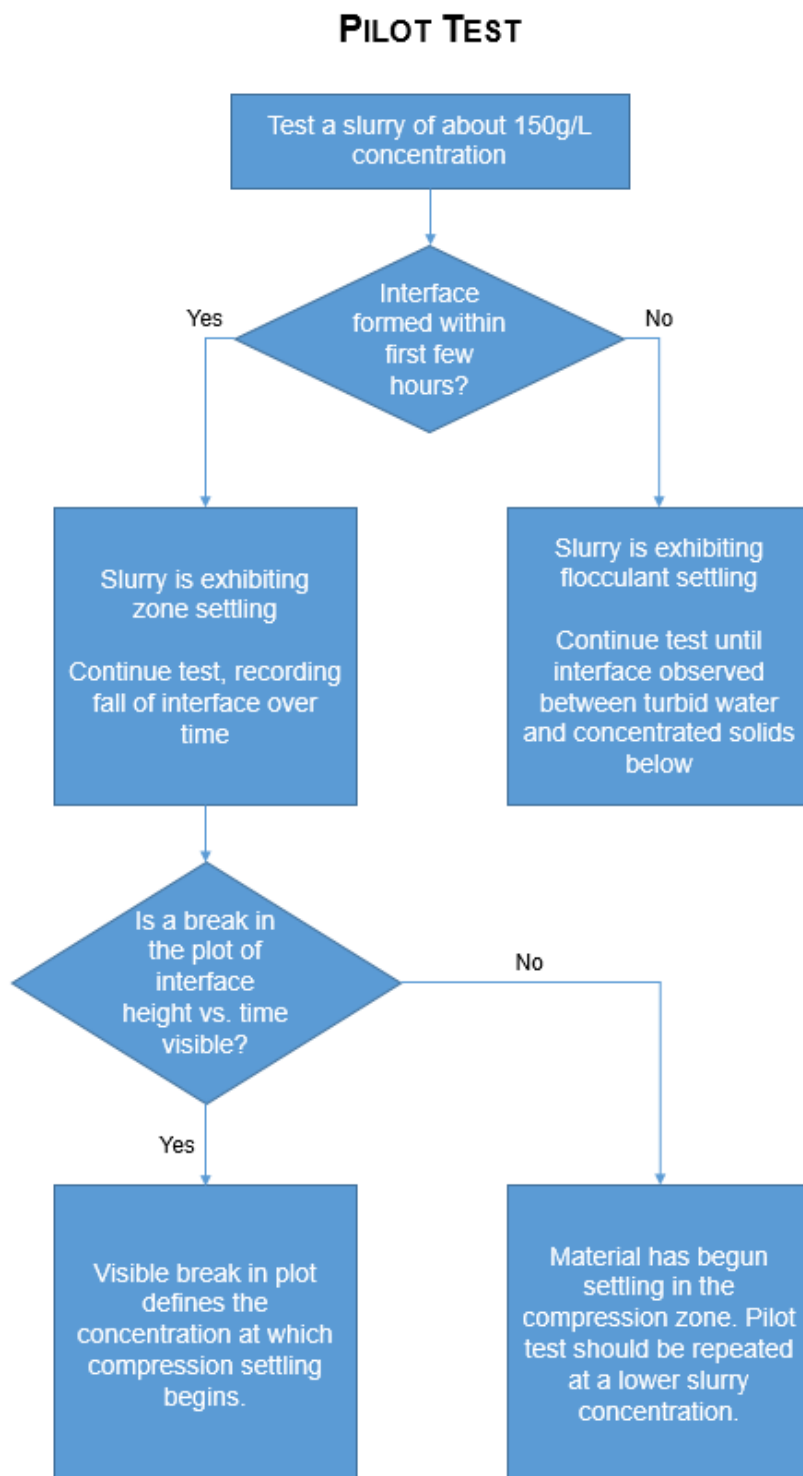


Figure A1: Flowchart describing pilot settling test of USACE methodology

FLOCCULANT SETTLING TEST

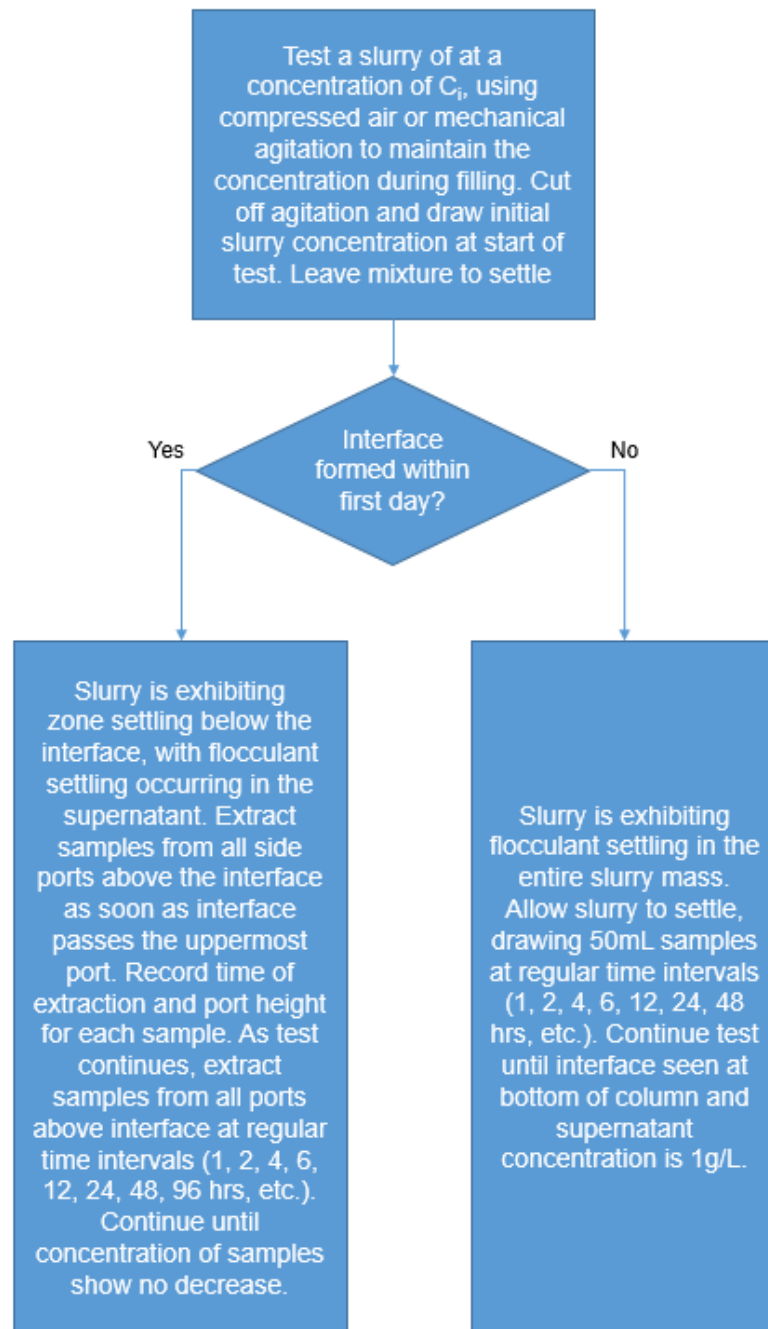


Figure A2: Flowchart describing flocculant settling test of USACE methodology

ZONE SETTLING TEST

Mix slurry to desired concentration and pump/pour into the test column. Agitate using compressed air if filling time is greater than 1 minute. Record the depth to the solid-liquid interface as a function of time with readings taken at regular intervals, sufficient to define the curve of depth of interface versus time. Continue readings until sufficient data are available to define the maximum point of curvature of the plot (the test may require 8 to 48 hours to complete).

Figure A3: Flowchart describing zone settling test of USACE methodology

COMPRESSION SETTLING TEST

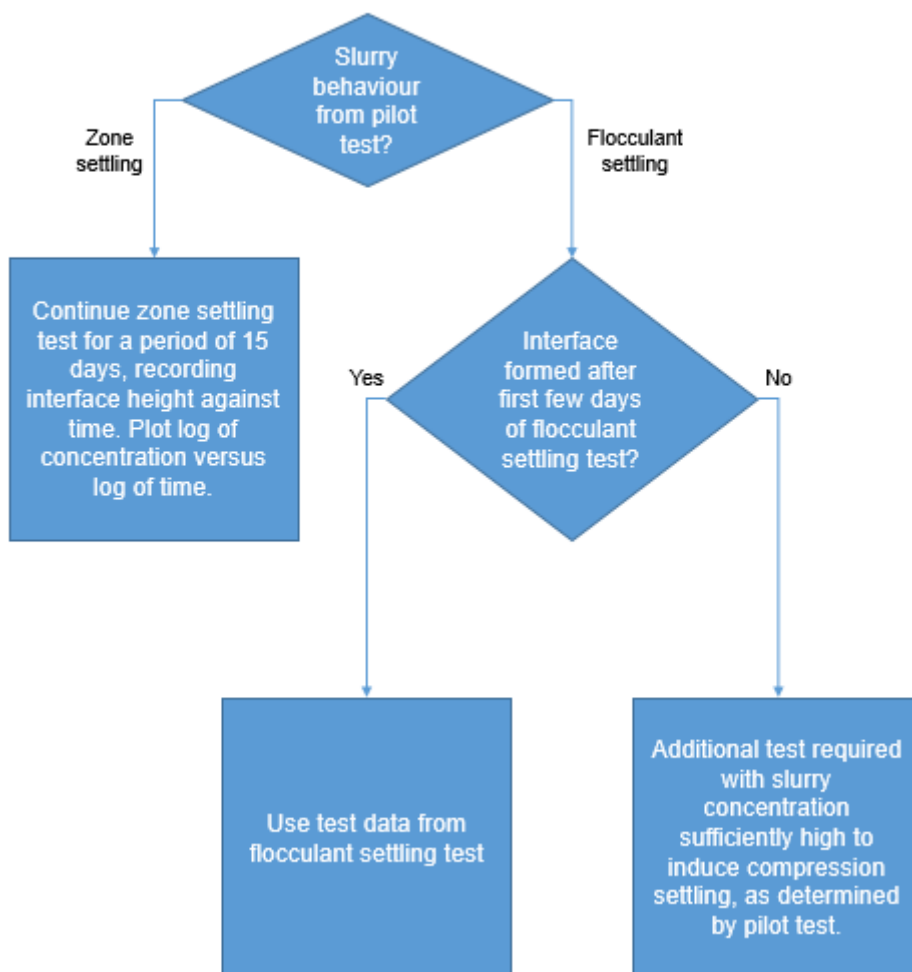


Figure A4: Flowchart describing compression settling test of USACE methodology

Appendix B: Summer research project details

B1: Project overview

The aim of the summer research project was to observe the movement of a settling front for prepared mixtures of varying materials at different concentrations and to calculate the settling velocity based on these measurements. The variations in the mixture types, materials and concentrations are listed below:

- Material types: kaolin, silica
- Solvent types: tap water, deionised water, salt water
- Concentrations: 400g/L, 100g/L, 40g/L, 10g/L

This appendix contains a brief summation of the research findings relevant to this thesis project.

B2: Equipment

The specific equipment used in these small column settling tests are listed below:

- 3 x 1000mL glass measuring cylinders with lids
- 3 x large oven drying tins
- 1 x 20L bucket with valve situated about 10cm above base
- 1 x electronic balance
- 1 x digital camera with tripod
- 1 x electronic stopwatch
- Electric drill with mixer attachment
- Masking tape, permanent marker

B3 Methodology

The methodology used is an adapted version of AS1289.3.6.3 (Standards Australia, 2003) as described by Scheuermann (2015) in an internal report. The experimental method for this is described below:

(A) Mixture preparation

1. Prepare 400g/L sample for a particular mixture of material and solvent in the 20L bucket and mix using electric drill. Leave to saturate for at least 24 hours.

(B) Settling test

1. Re-agitate the mixture using the electric drill. Using the valve, fill the three glass measuring cylinders to the 1000mL gradation and place lid on column. Invert column continually to ensure mixture is well mixed
2. Set up the tripod and camera. Set the camera to 'interval shooting' mode at regular intervals. Reset the stopwatch.
3. To start the test, place the column on a flat surface within the camera's field of view, start the stopwatch and the camera's 'interval shooting'.
4. Measure the height of the interface using the gradations on the measuring cylinder at the following specific time intervals: 0mins, 0.5mins, 1min, 2mins, 4mins, 8mins, 15mins, 30mins, 1hr, 2hrs and 4hrs. After the 4hr mark, take at least two measurements every 24 hours until the interface stops moving.
5. Repeat steps 3 and 4 for the other two columns of the same concentration.
6. To prepare mixtures of a different concentration, add additional solvent to the 20L bucket and repeat step 1 to prepare the columns. Repeat steps 3 to 5 until no more columns can fit within the camera's field of view.
7. Repeat step 6 as required for the other concentrations.



Figure B2.1: Experimental setup during sedimentation

B4 Results

During the tests, it was noted that determining the height of the interface for the settling tests of silica mixtures was often very difficult, as unclear interface heights or numerous interfaces were visible. These also seemed to be prone to minor disturbances, such as vibrations in the room, resulting in the realistic measurement of the interface height being highly hindered.

The collection of quantitative results for the mixtures containing kaolin were much simpler, with a well-defined interface visible throughout the test. Figure B4.1 is a log-log plot of the settling velocity data obtained from these tests. It should be noted that data from the 400g/L tests could not be obtained, as significant sticking of the mixture to the walls of the column resulted in an inability to measure the interface height.

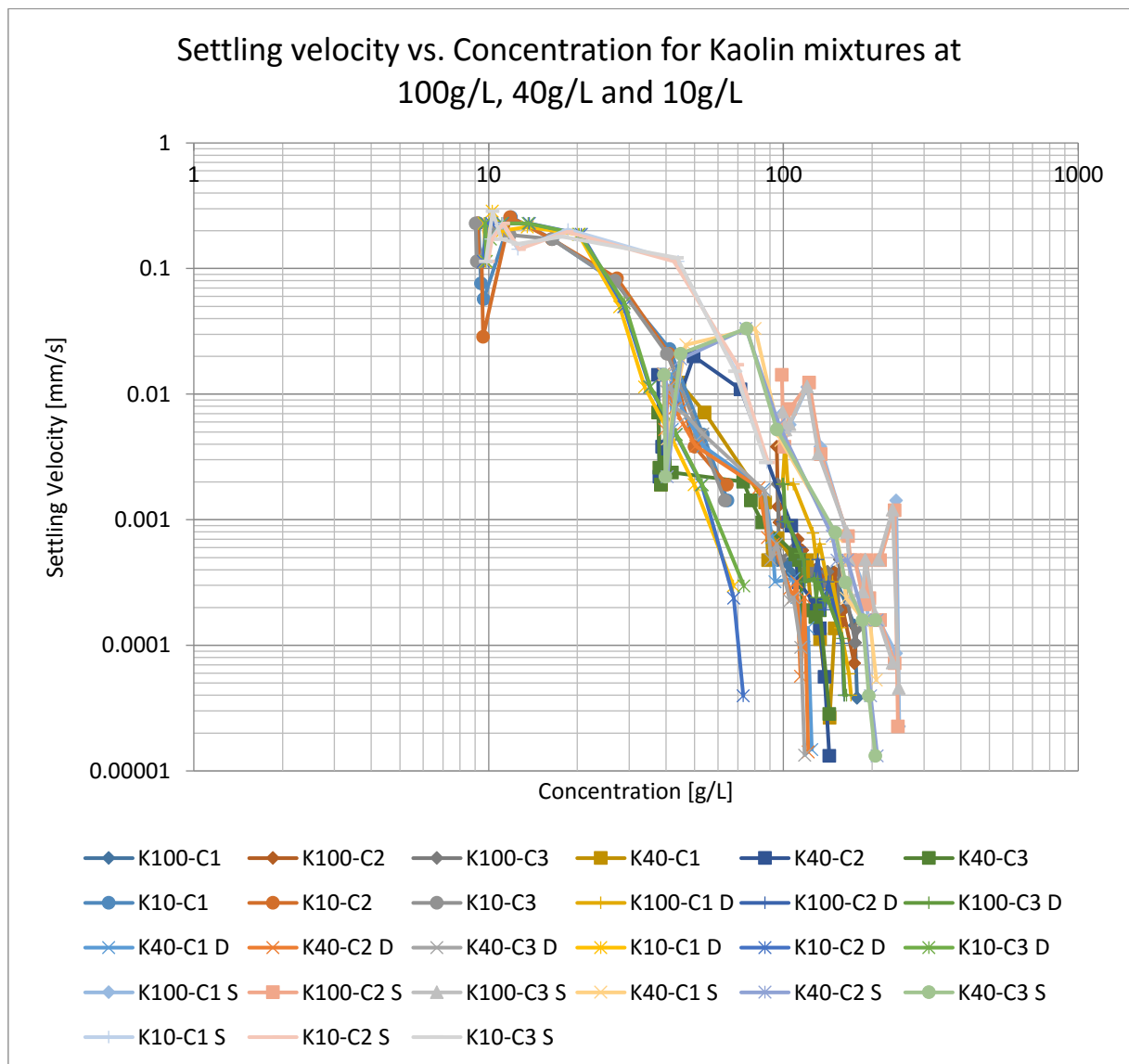


Figure B4.1: Graph of settling velocity against mixture concentration

B5 Conclusion and evaluation

As the aim of the project was to measure the height of the interface and to calculate the settling velocity based on these measurements, the project was mostly successful. That is, the relevant data was successfully obtained for mixtures containing kaolin, with the overall shape of the plotted data appearing to be consistent with existing studies.

While the results of the small column sedimentation tests for kaolin appeared to be acceptable, there were a number of issues encountered with this method of measuring sedimentation processes. These include:

- Poor definition of the interface for silica suspensions and prone to disturbance from vibrations in the laboratory
- Interface of low concentration kaolin mixtures occasionally passed the bottommost gradation, making any measurements past this point impossible
- Concavity of the interface was observed, indicating that some wall friction may have slowed the settling of the suspension
- Some tests showed signs of differential settlement, with an uneven interface
- While data processing assumed that the concentration of the material below the interface is constant, observations from some tests with kaolin showed visible signs of higher porosity closer to the interface and lower porosity near the base of the column

Future investigations of sedimentation processes should seek to address some of these issues.

APPENDIX G
Plans and Specifications for Settling Columns

G.1 Purpose. This appendix contains figures showing plans and specifications for settling columns.

G.2 Side-View Sedimentation Column Plan and Specifications. Figure G-1 presents a side view plan and specifications for a settling column.

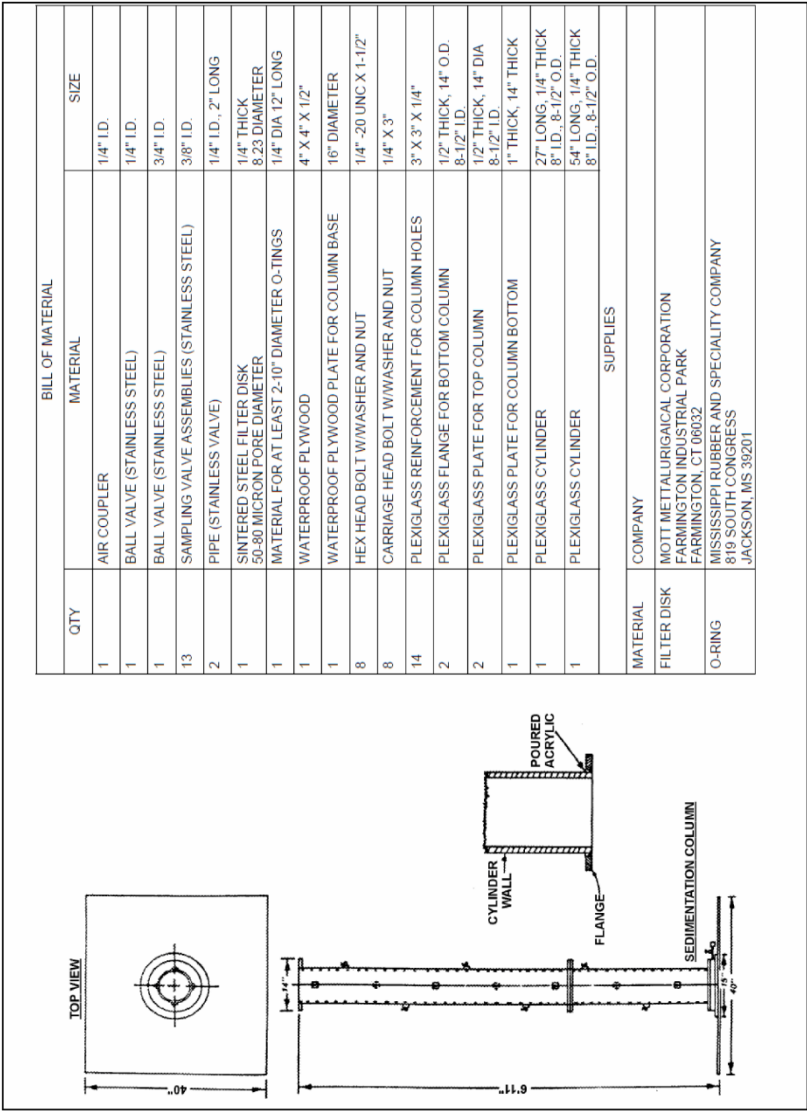


Figure G-1. Plan for Sedimentation Column and Specifications for Settling Column

Note: taken from (USACE, 2015)

G.3 Top and Bottom Sedimentation Column Plans. Figure G-2 presents plans for top and bottom columns.

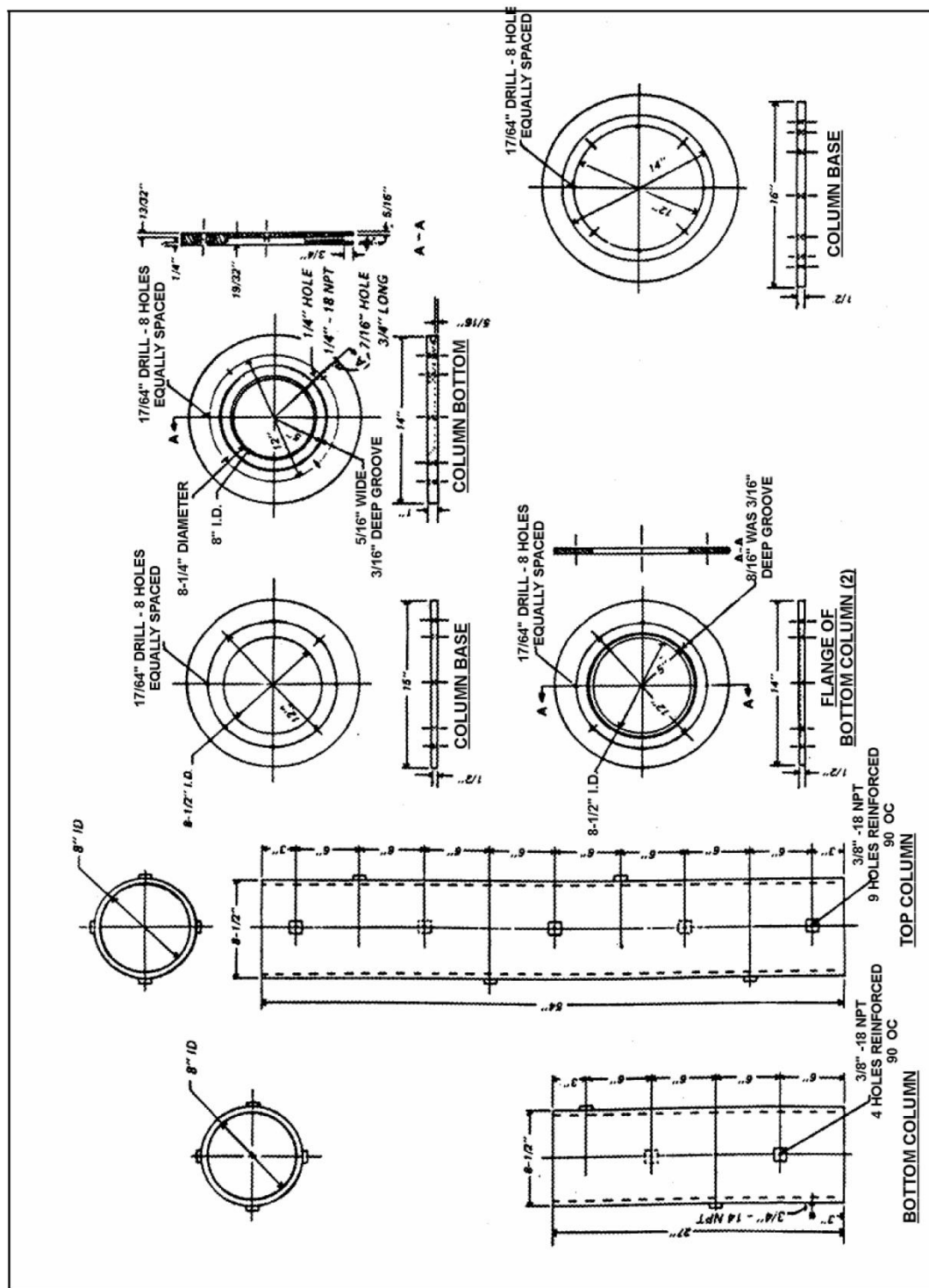
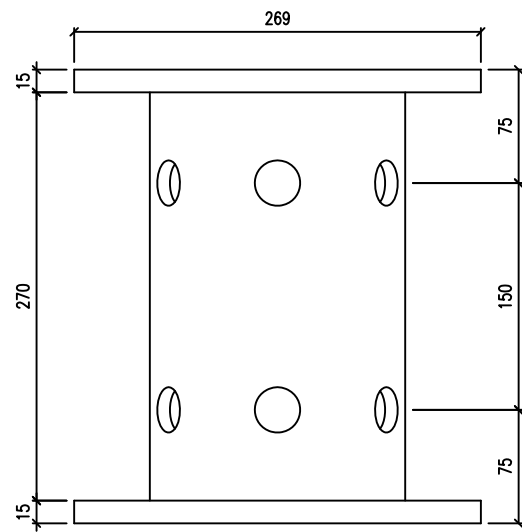


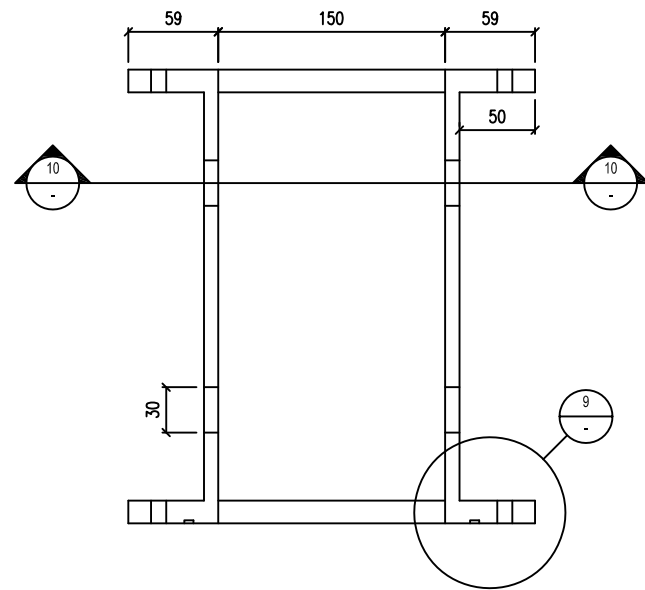
Figure G-2. Plans for Top and Bottom Columns

Note: taken from (USACE, 2015)

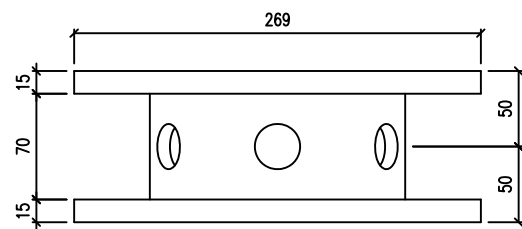
Appendix D: Large column design drawings, version 1 (23rd May 2016)



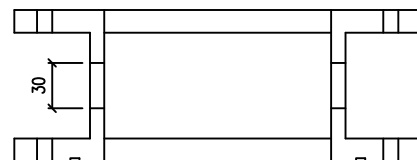
1 TYPICAL 30cm UNIT ELEVATION
SCALE 1:5



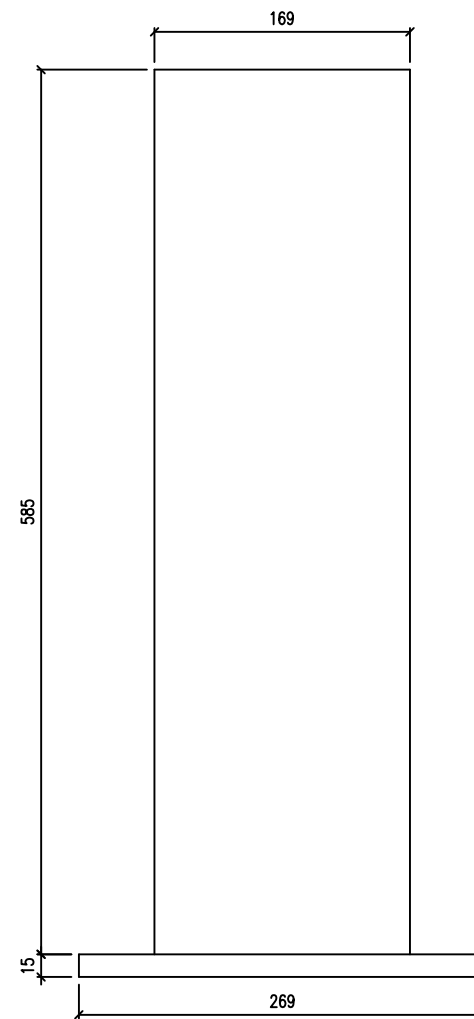
2 TYPICAL 30cm UNIT SECTION
SCALE 1:5



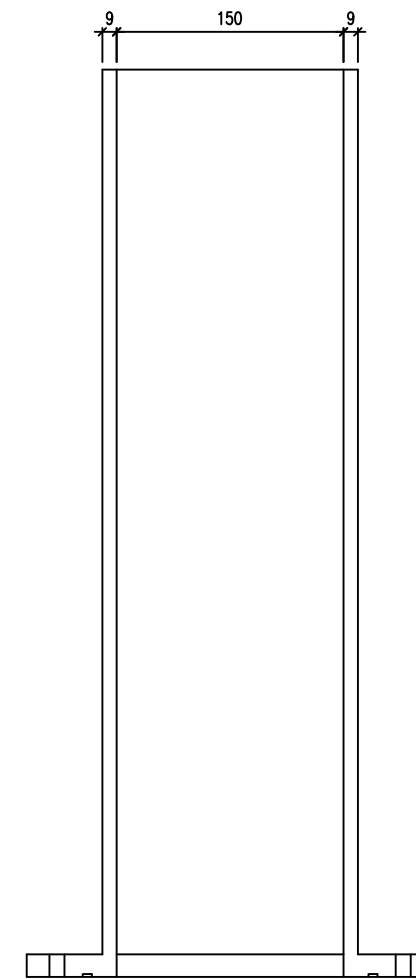
3 10cm DENSITY UNIT ELEVATION
SCALE 1:5



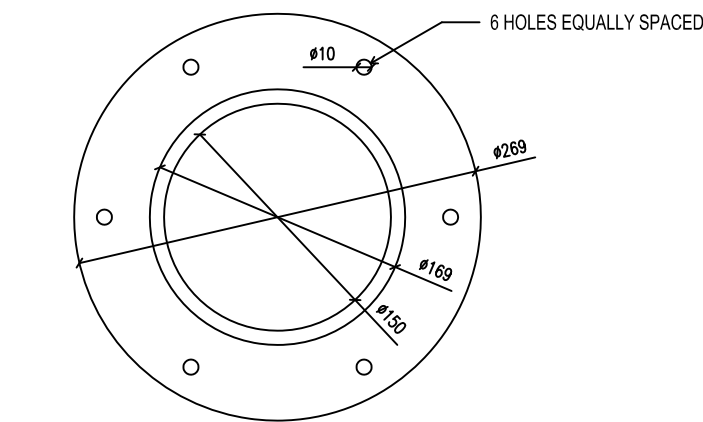
4 10cm DENSITY UNIT SECTION
SCALE 1:5



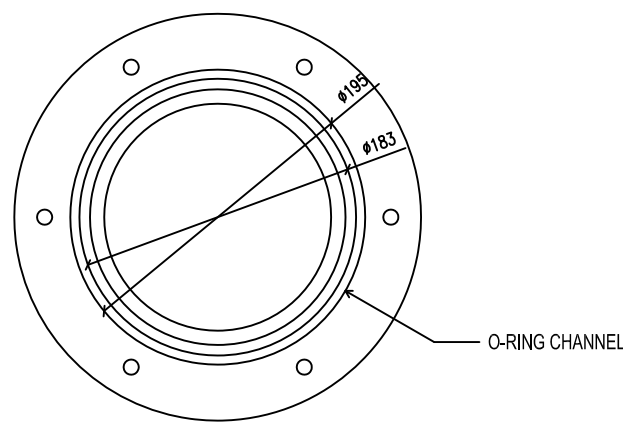
7 60cm HEIGHT UNIT ELEVATION
SCALE 1:5



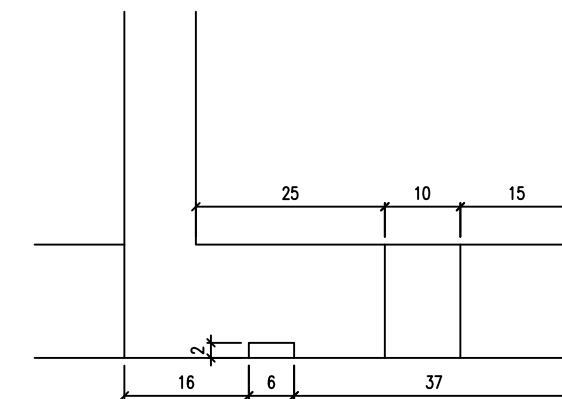
8 60cm HEIGHT UNIT SECTION
SCALE 1:5



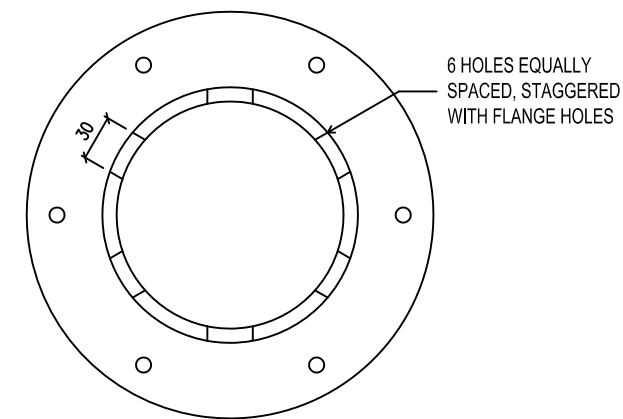
5 TOP FLANGE ELEVATION
SCALE 1:5



6 BOTTOM FLANGE ELEVATION
SCALE 1:5

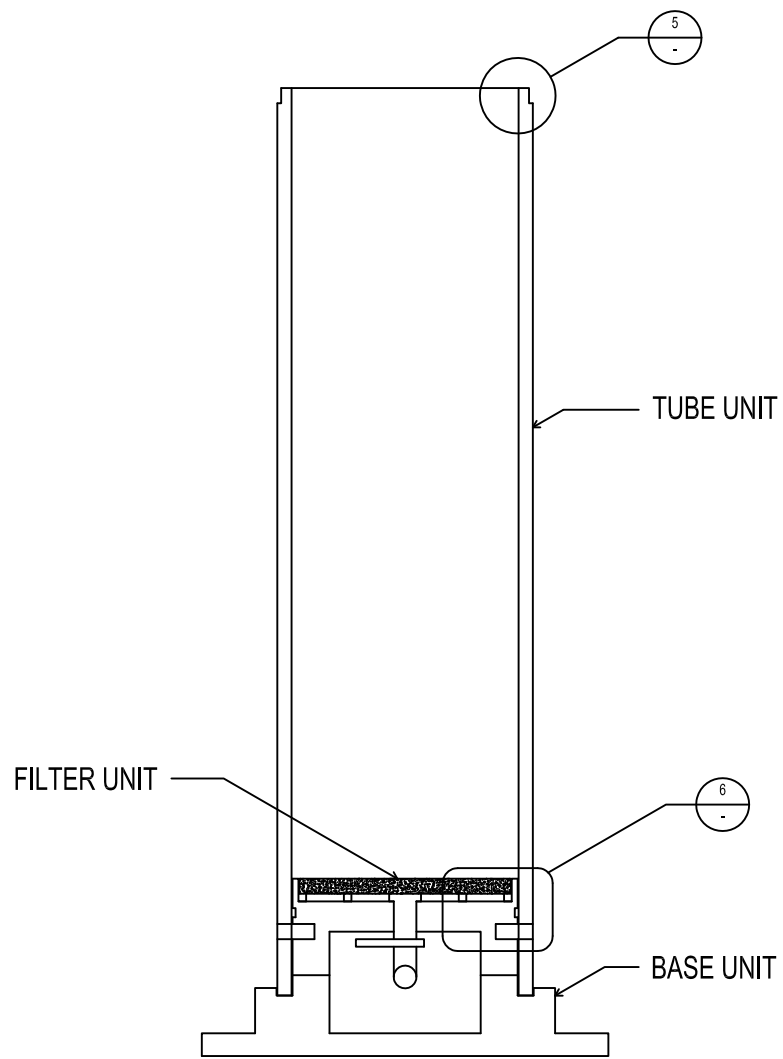


9 BOTTOM FLANGE DETAIL
SCALE 1:1

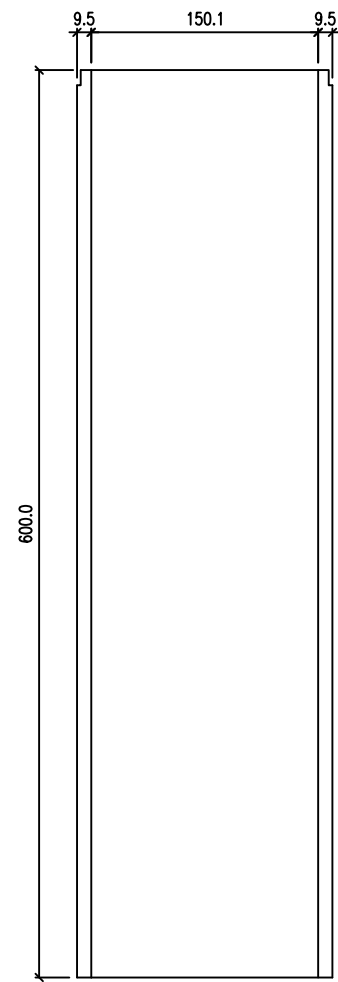


10 SECTION A-A
SCALE 1:5

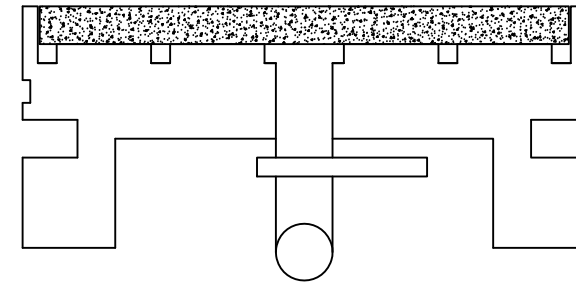
THE UNIVERSITY OF QUEENSLAND - EAIT FACULTY, SCHOOL OF CIVIL ENGINEERING					
GENERAL NOTES: ALL DIMENSIONS IN MM UNLESS OTHERWISE NOTED DO NOT SCALE		TITLE: LARGE COLUMN FOR SEDIMENTATION TESTING			
		DATE: 23/05/2016	DRAWN: JG	DRAWING No: DWG-01	
		SCALE: AS NOTED	SHEET SIZE: A3	SHEET No: SHEET 1 OF 2	REV: 1



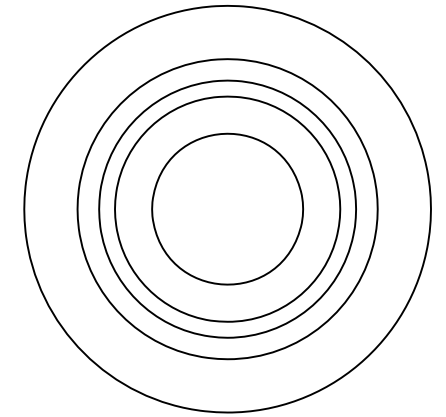
1 ASSEMBLED CONSOLIDOMETER UNIT
SCALE 1:5



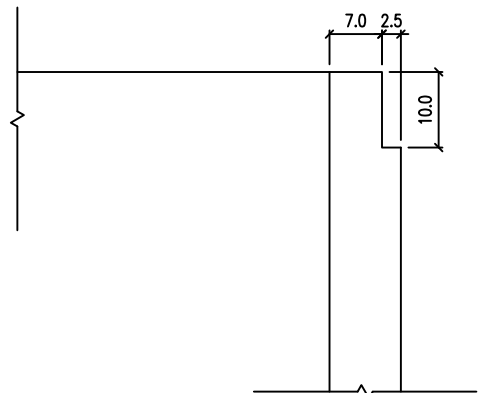
2 TUBE UNIT
SCALE 1:5



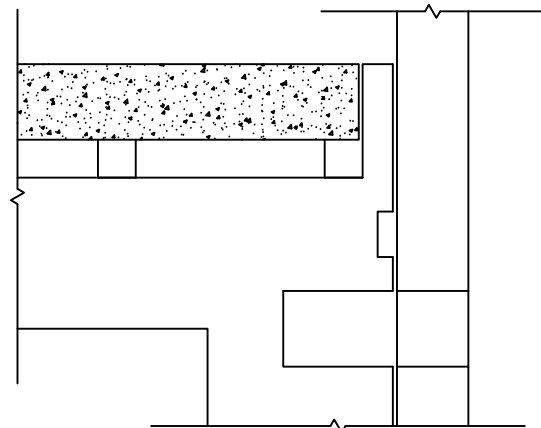
3 FILTER UNIT COMPONENTS
SCALE 1:2



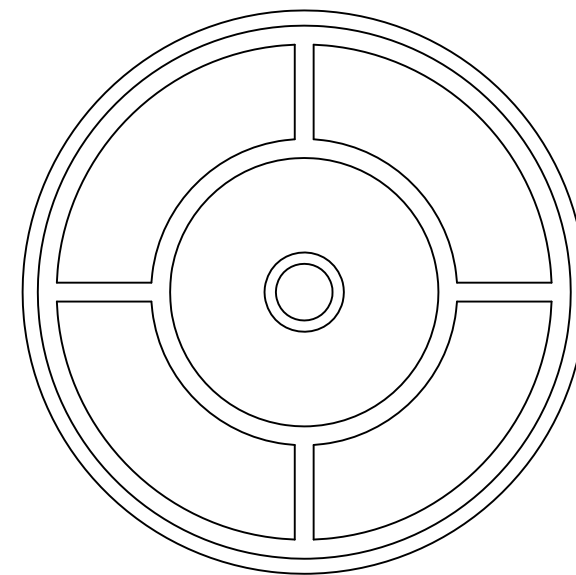
4 PLAN VIEW OF BASE UNIT
SCALE 1:5



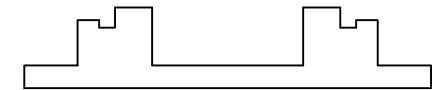
5 TUBE UNIT LIP DETAIL
SCALE 1:1



6 FILTER UNIT DETAIL
SCALE 1:1



1 FILTER UNIT CHANNELS
SCALE 1:2



1 BASE SUPPORT UNIT
SCALE 1:5

THE UNIVERSITY OF QUEENSLAND - EAIT FACULTY, SCHOOL OF CIVIL ENGINEERING						
GENERAL NOTES: ALL DIMENSIONS IN MM UNLESS OTHERWISE NOTED DO NOT SCALE	TITLE: LARGE COLUMN FOR SEDIMENTATION TESTING - CONSOLIDOMETER UNIT					
	DATE: 23/05/2016	DRAWN: JG	DRAWING No: DWG-02			
	SCALE: AS NOTED	SHEET SIZE: A3	SHEET No: SHEET 2 OF 2	REV: 1		

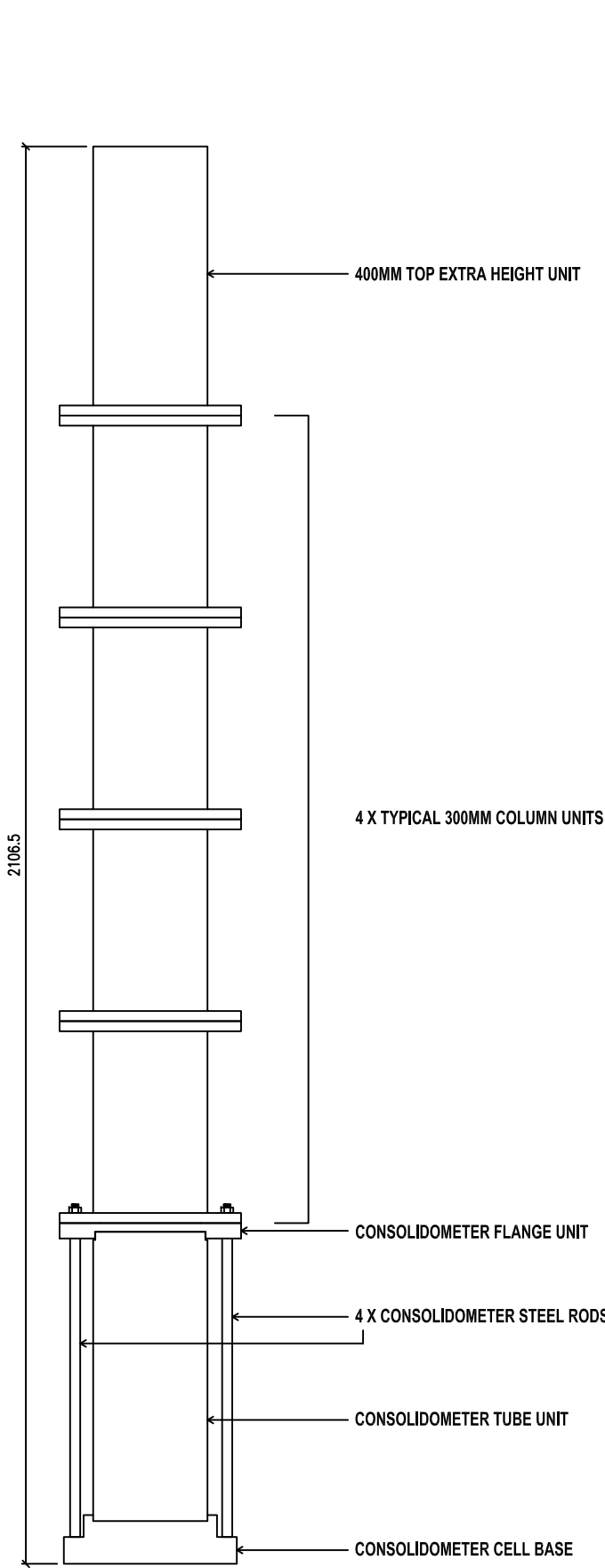
Appendix E: Large column design drawings, version 2 (13th August 2016)

DRAWING INDEX

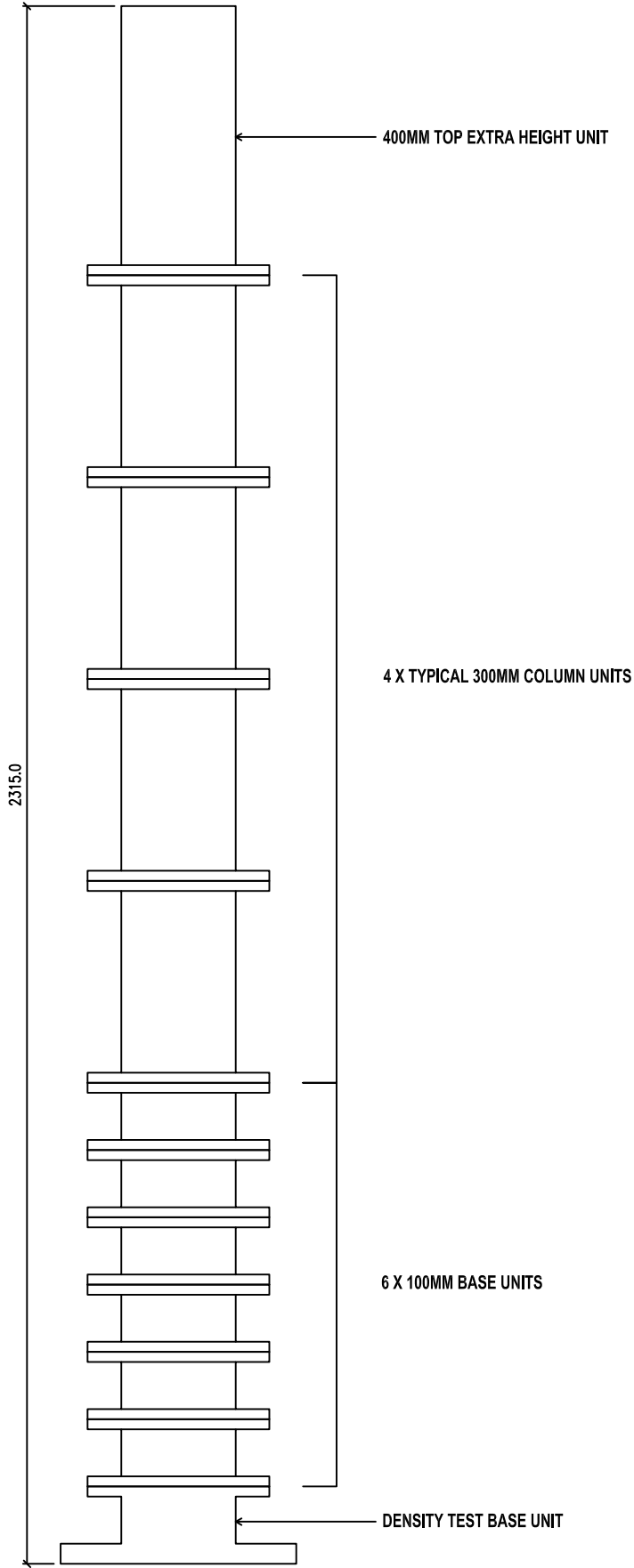
DRAWING NO.	TITLE
DWG 1-0	ASSEMBLY
DWG 1-1	TYPICAL 300MM COLUMN UNIT
DWG 1-2	100MM BASE UNIT
DWG 1-3	400MM TOP EXTRA HEIGHT UNIT
DWG 1-4	CONSOLIDOMETER TUBE UNIT
DWG 1-5	CONSOLIDOMETER FLANGE UNIT
DWG 1-6	DENSITY TEST BASE UNIT

QUANTITIES

COMPONENT	QTY REQ'D
TYPICAL 300MM COLUMN UNIT	8
100MM BASE UNIT	6
400MM TOP EXTRA HEIGHT UNIT	2
CONSOLIDOMETER TUBE UNIT	1
CONSOLIDOMETER FLANGE UNIT	1
DENSITY TEST BASE UNIT	1

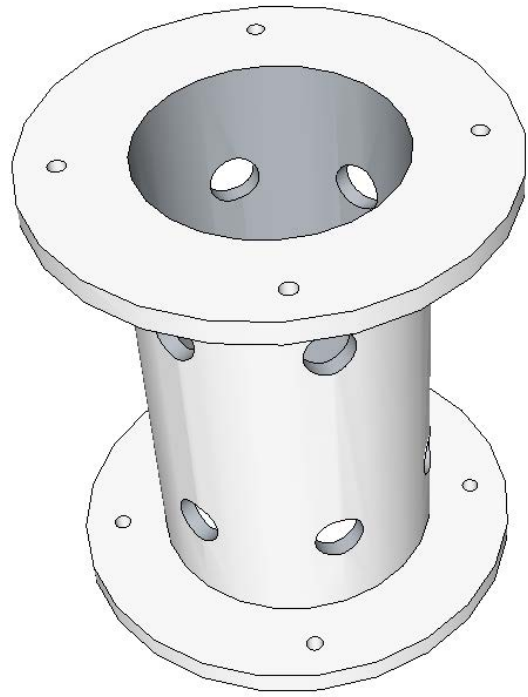


1 COLUMN ASSEMBLY - CONSOLIDOMETER
SCALE 1:10

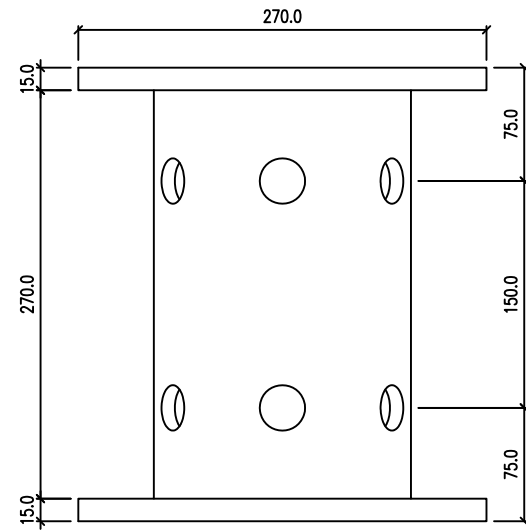


2 COLUMN ASSEMBLY - DENSITY
SCALE 1:10

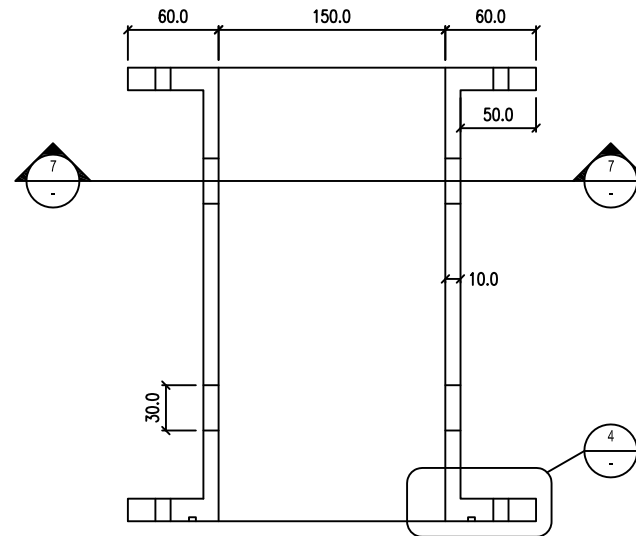
THE UNIVERSITY OF QUEENSLAND - EAIT FACULTY, SCHOOL OF CIVIL ENGINEERING				
GENERAL NOTES: ALL DIMENSIONS IN MM UNLESS OTHERWISE NOTED DO NOT SCALE	TITLE: LARGE COLUMN FOR SEDIMENTATION TESTING - ASSEMBLY			
	DATE: 13/08/2016	DRAWN: JG	DRAWING No: DWG 1-0	
	SCALE: AS NOTED	SHEET SIZE: A3	SHEET No: SHEET 1 OF 7	REV: 2



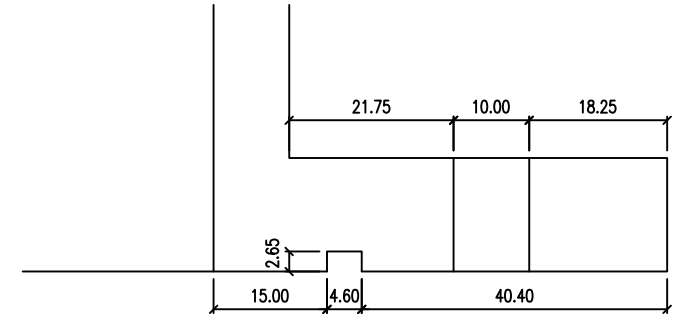
1 300MM UNIT PERSPECTIVE
NOT TO SCALE



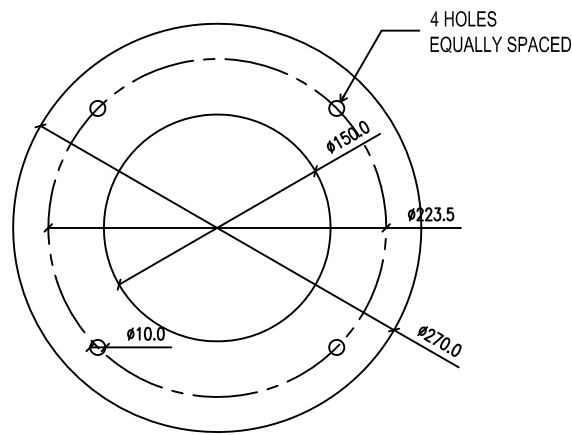
2 300MM UNIT ELEVATION
SCALE 1:5



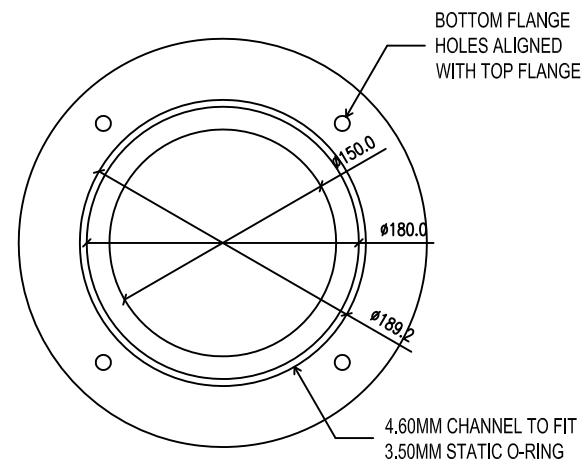
3 300MM UNIT SECTION
SCALE 1:5



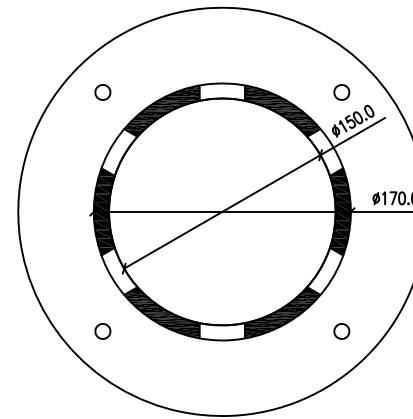
4 BOTTOM FLANGE DETAIL
SCALE 1:1



5 TOP FLANGE ELEVATION
SCALE 1:5

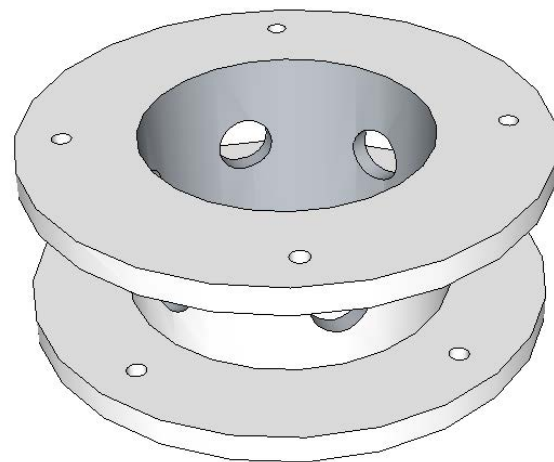


6 BOTTOM FLANGE ELEVATION
SCALE 1:5

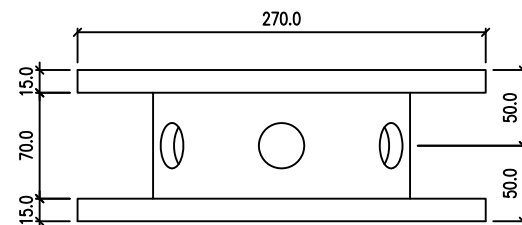


7 SECTION A-A
SCALE 1:5

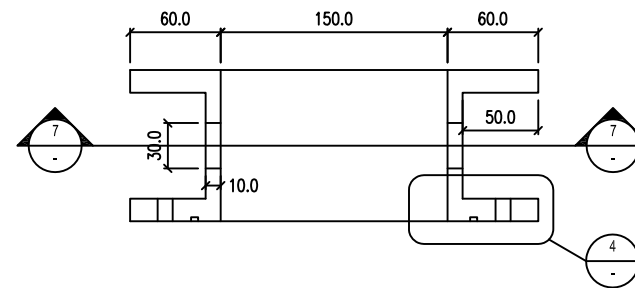
THE UNIVERSITY OF QUEENSLAND - EAIT FACULTY, SCHOOL OF CIVIL ENGINEERING					
GENERAL NOTES: ALL DIMENSIONS IN MM UNLESS OTHERWISE NOTED DO NOT SCALE		TITLE: LARGE COLUMN FOR SEDIMENTATION TESTING - TYPICAL 300MM COLUMN UNIT			
		DATE: 13/08/2016	DRAWN: JG	DRAWING No: DWG 1-1	
		SCALE: AS NOTED	SHEET SIZE: A3	SHEET No: SHEET 2 OF 7	REV: 3



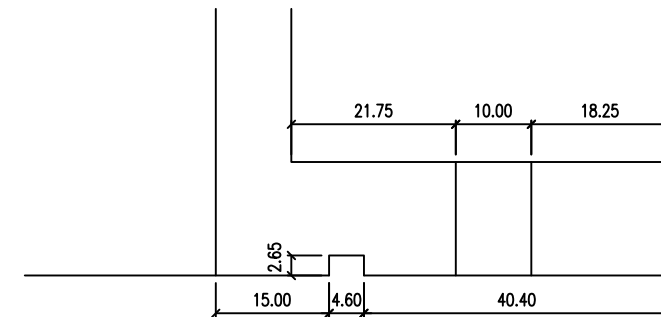
1 100MM UNIT PERSPECTIVE
NOT TO SCALE



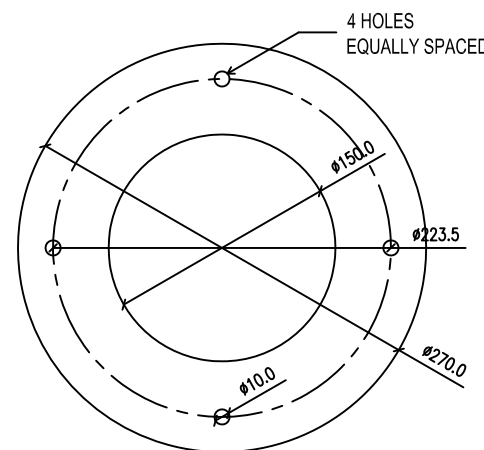
2 100MM UNIT ELEVATION
SCALE 1:5



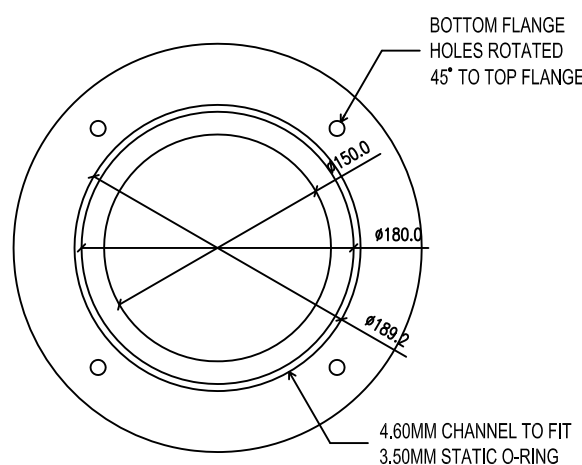
3 100MM UNIT SECTION
SCALE 1:5



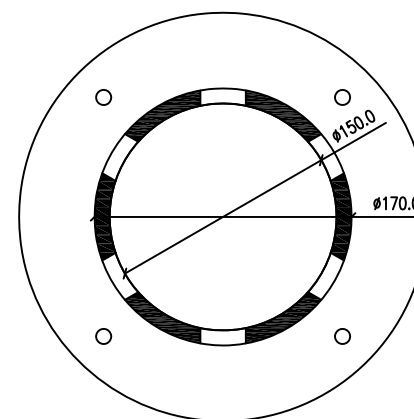
4 BOTTOM FLANGE DETAIL
SCALE 1:1



5 TOP FLANGE ELEVATION
SCALE 1:5

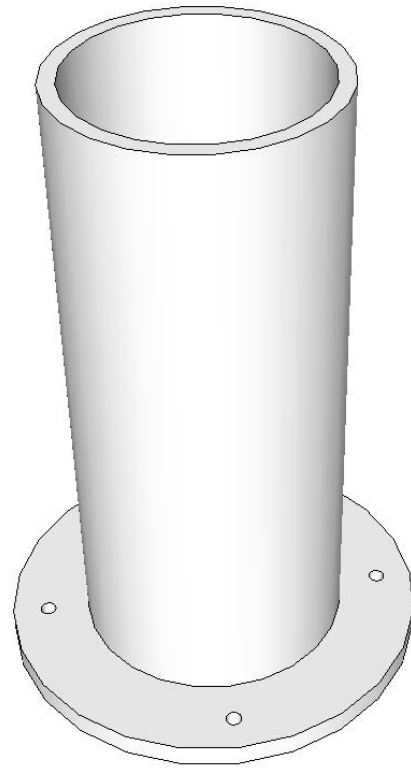


6 BOTTOM FLANGE ELEVATION
SCALE 1:5

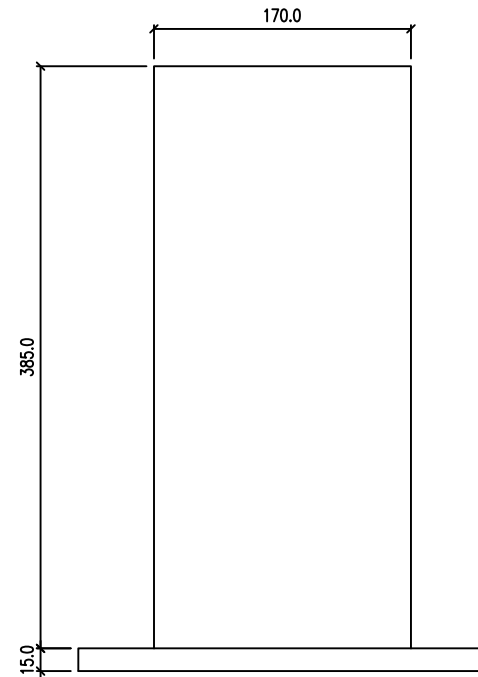


7 SECTION A-A
SCALE 1:5

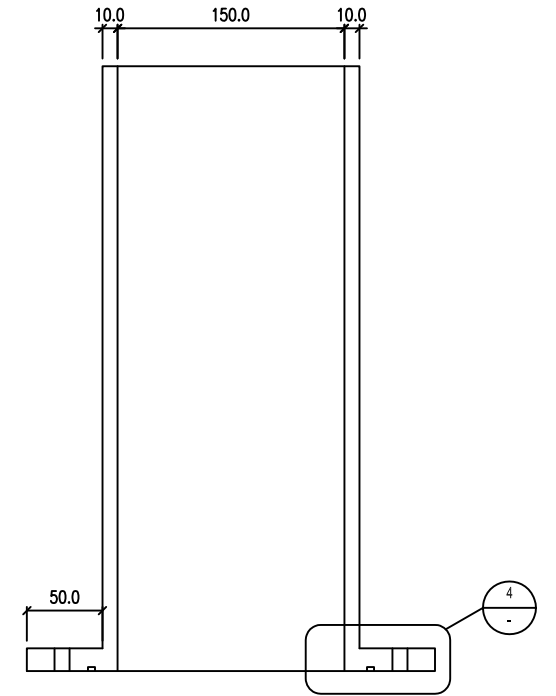
THE UNIVERSITY OF QUEENSLAND - EAIT FACULTY, SCHOOL OF CIVIL ENGINEERING					
GENERAL NOTES: ALL DIMENSIONS IN MM UNLESS OTHERWISE NOTED DO NOT SCALE	TITLE: LARGE COLUMN FOR SEDIMENTATION TESTING - 100MM BASE UNIT				
	DATE: 13/08/2016	DRAWN: JG	DRAWING No: DWG 1-2		
	SCALE: AS NOTED	SHEET SIZE: A3	SHEET No: SHEET 3 OF 7	REV:	3



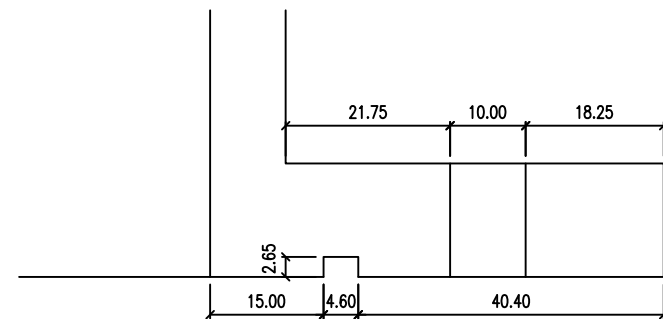
1 400MM TOP EXTRA HEIGHT UNIT PERSPECTIVE
NOT TO SCALE



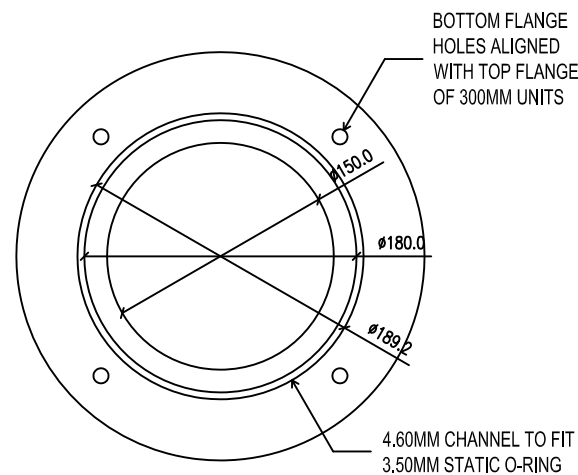
2 400MM TOP EXTRA HEIGHT UNIT ELEVATION
SCALE 1:5



3 400MM TOP EXTRA HEIGHT UNIT SECTION
SCALE 1:5



4 BOTTOM FLANGE DETAIL
SCALE 1:1

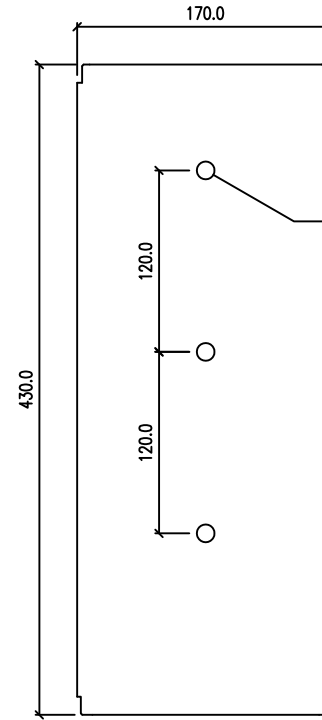


5 BOTTOM FLANGE ELEVATION
SCALE 1:5

THE UNIVERSITY OF QUEENSLAND - EAIT FACULTY, SCHOOL OF CIVIL ENGINEERING					
GENERAL NOTES: ALL DIMENSIONS IN MM UNLESS OTHERWISE NOTED DO NOT SCALE		TITLE: LARGE COLUMN FOR SEDIMENTATION TESTING - 400MM TOP EXTRA HEIGHT UNIT			
		DATE: 13/08/2016	DRAWN: JG	DRAWING No: DWG 1-3	
		SCALE: AS NOTED	SHEET SIZE: A3	SHEET No: SHEET 4 OF 7	REV: 3

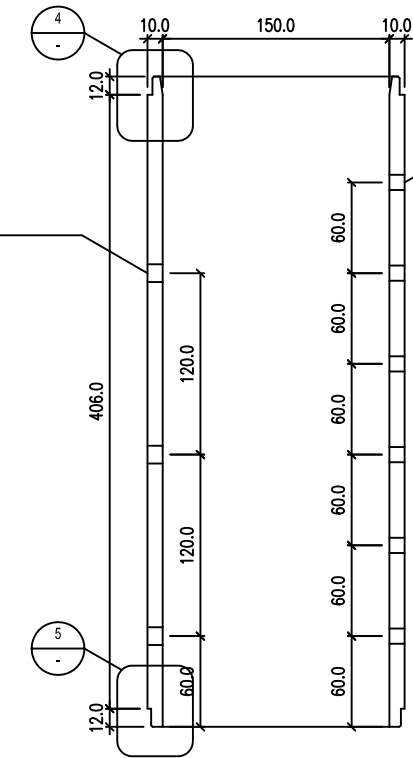


1 CONSOLIDOMETER TUBE UNIT PERSPECTIVE
NOT TO SCALE



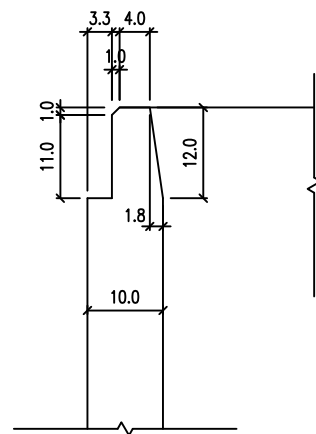
2 CONSOLIDOMETER TUBE UNIT ELEVATION
SCALE 1:5

SIX 11.7MM DIAMETER HOLES
FOR EXISTING CONSOLIDOMETER
PRESSURE SENSORS, STAGGERED
DOWN THE TUBE

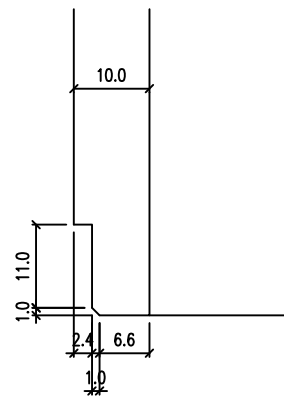


SIX 10MM DIAMETER HOLES
FOR DIELECTRIC COAXIALS,
POSITIONED LINEARLY
DOWN THE TUBE

3 CONSOLIDOMETER TUBE UNIT SECTION
SCALE 1:5

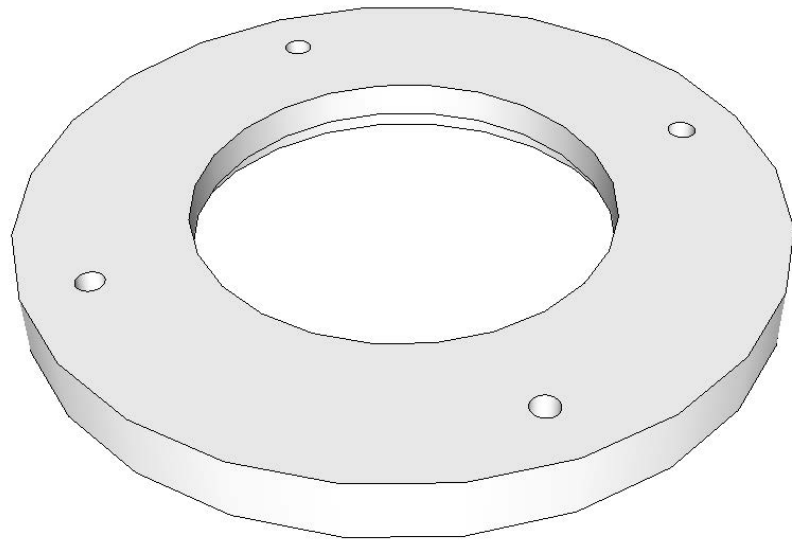


4 TOP LIP SECTION
SCALE 1:1

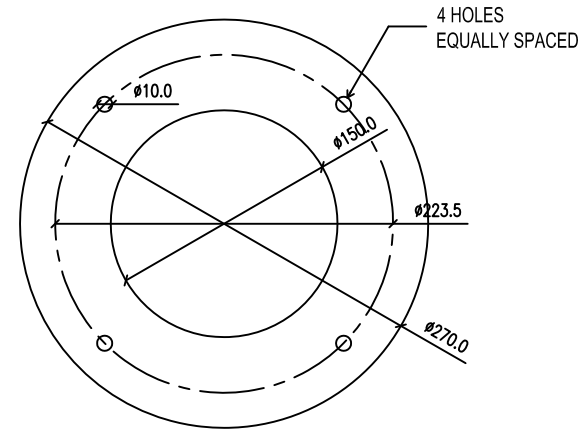


5 BOTTOM LIP SECTION
SCALE 1:1

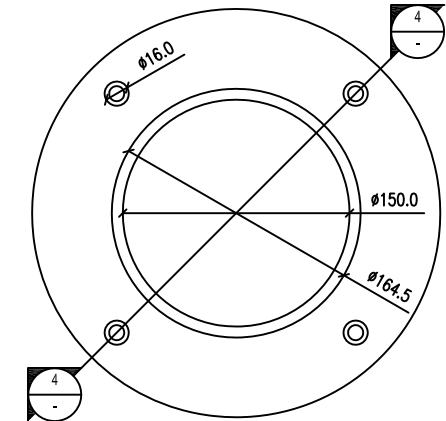
THE UNIVERSITY OF QUEENSLAND - EAIT FACULTY, SCHOOL OF CIVIL ENGINEERING					
GENERAL NOTES: ALL DIMENSIONS IN MM UNLESS OTHERWISE NOTED DO NOT SCALE	TITLE: LARGE COLUMN FOR SEDIMENTATION TESTING - CONSOLIDOMETER TUBE UNIT				
	DATE: 13/08/2016	DRAWN: JG	DRAWING No: DWG 1-4		
	SCALE: AS NOTED	SHEET SIZE: A3	SHEET No: SHEET 5 OF 7	REV: 3	



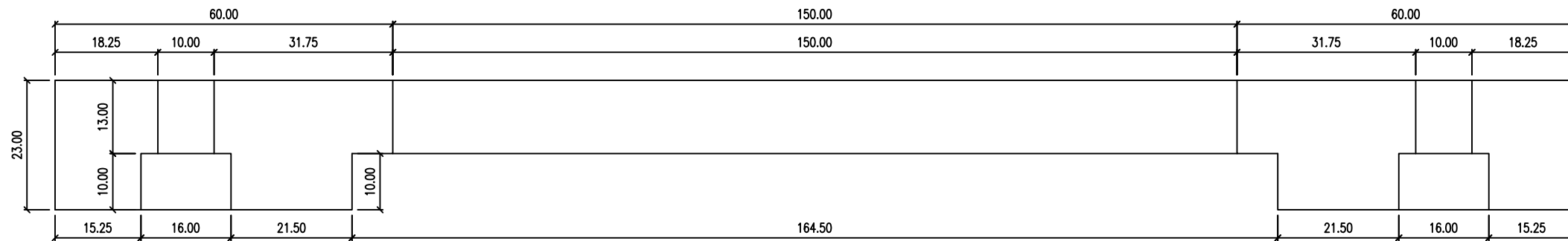
1 CONSOLIDOMETER FLANGE UNIT PERSPECTIVE
NOT TO SCALE



2 TOP ELEVATION
SCALE 1:5

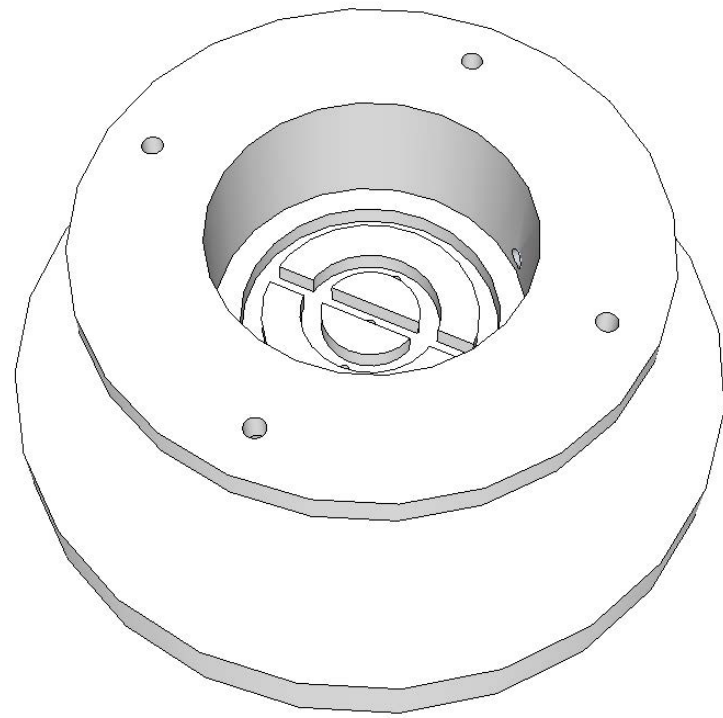


3 BOTTOM ELEVATION
SCALE 1:5

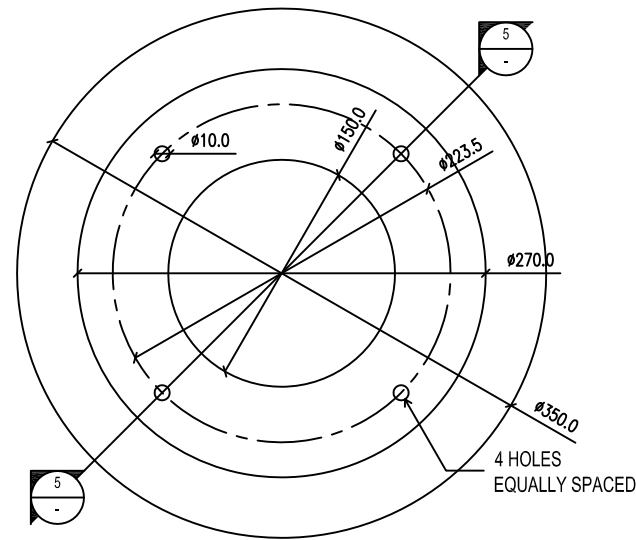


4 SECTION
SCALE 1:1

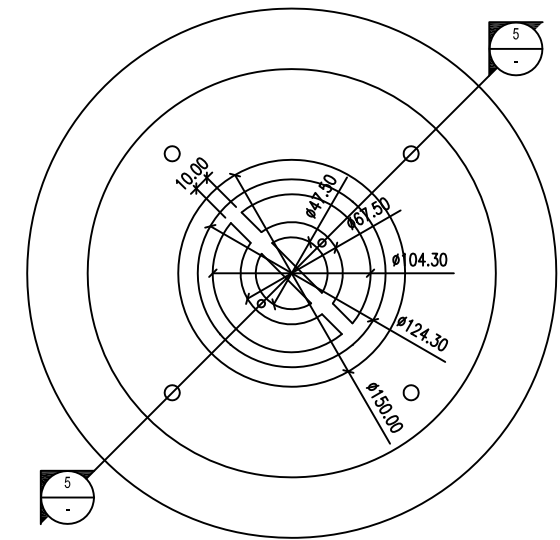
THE UNIVERSITY OF QUEENSLAND - EAIT FACULTY, SCHOOL OF CIVIL ENGINEERING					
GENERAL NOTES: ALL DIMENSIONS IN MM UNLESS OTHERWISE NOTED DO NOT SCALE		TITLE: LARGE COLUMN FOR SEDIMENTATION TESTING - CONSOLIDOMETER FLANGE UNIT			
		DATE: 13/08/2016	DRAWN: JG	DRAWING No: DWG 1-5	
		SCALE: AS NOTED	SHEET SIZE: A3	SHEET No: SHEET 6 OF 7	REV: 3



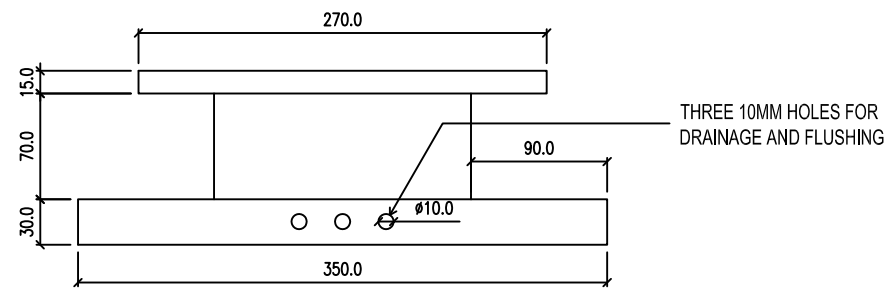
1 DENSITY BASE UNIT PERSPECTIVE
NOT TO SCALE



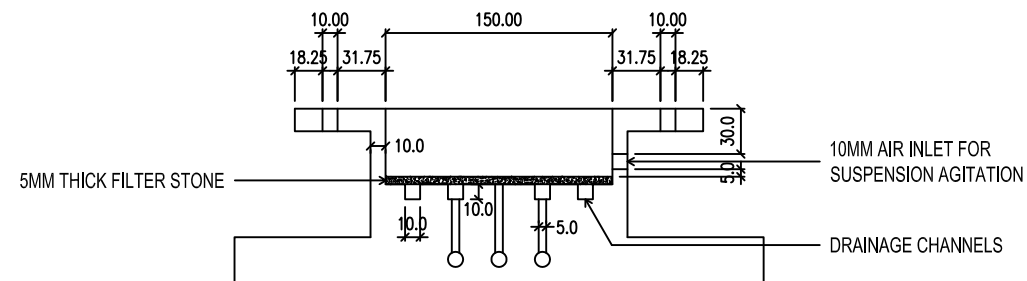
2 TOP ELEVATION OF ASSEMBLY
SCALE 1:5



3 TOP ELEVATION OF FILTER CHANNELS
SCALE 1:5



4 DENSITY BASE UNIT ELEVATION
SCALE 1:5



5 DENSITY BASE UNIT SECTION
SCALE 1:5

THE UNIVERSITY OF QUEENSLAND - EAIT FACULTY, SCHOOL OF CIVIL ENGINEERING					
GENERAL NOTES: ALL DIMENSIONS IN MM UNLESS OTHERWISE NOTED DO NOT SCALE	TITLE: LARGE COLUMN FOR SEDIMENTATION TESTING - DENSITY TEST BASE UNIT				
	DATE: 13/08/2016	DRAWN: JG	DRAWING No: DWG 1-6		
	SCALE: AS NOTED	SHEET SIZE: A3	SHEET No: SHEET 7 OF 7	REV: 1	

Appendix F: Preliminary calibration tests

F1: Magnetic stirrer speed

A preliminary test varying the mixing speed of the magnetic stirrer was undertaken in order to determine an appropriate setting on the IKA C-MAG MS 7 magnetic stirrer. This was an important consideration, as a mixing speed too slow will not agitate the mixture sufficiently and will result in settling occurring within the container while it is mixing. However, a mixing speed too high will also affect the test result, as air will be entrained into the solution and affect the results of the test.

This preliminary test was a qualitative test and sought to determine a sensible mixing speed by finding the maximum and minimum mixing speeds that can be used without air entrainment or significant settling occurring.

To begin, a test was undertaken with plain tap water and a medium sized stirrer bar seeking to determine the maximum mixing speed before air entrainment occurs. Mixing speeds between 1 and 3 were tested, with observations and photos taken of the mixing at each speed. Table F1.1 summarises these findings, with photos in Figure F1.1.

Table F1.1: Air entrainment observations at different mixing speeds

Mixing speed:	1.0	1.5	2.0	2.5	3.0
Air entrainment observed?	No	No	No	Yes	Yes



Figure F1.1: Photos of air entrainment test with mixer speeds of 1.0, 1.5, 2.0, 2.5 and 3.0 from left to right

From this, it was noted that air entrainment appeared to occur at mixing speeds greater than 2.0. As such, the maximum mixing speed should not exceed 2.0.

To seek the lower bound, a mixing test was undertaken, testing the mixer speeds of 1.0 and 2.0 and using a 150g/L mixture and observing whether or not there was a build-up of settled material at the end of the test. This is particularly important given the horizontal orientation of the sensor, as vertical settling will occur on the sensor and will impede measurements. Photos of the observed test results are presented in Figure F1.2.

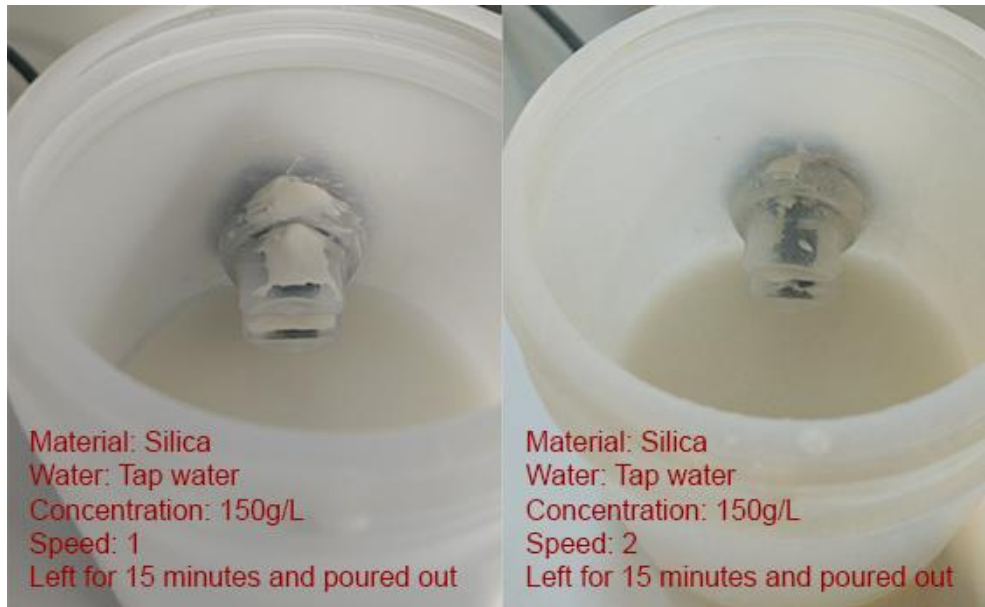


Figure F1.2: Photos of turbidity sensor after mixing test undertaken for 15 minutes.

From this, it was clear that there was a significant layer of settled material on the sensor where a mixer speed of 1.0 was adopted. In contrast, there was hardly any settled material observed on the sensor where a mixer speed of 2.0 was used.

In conclusion, a mixer speed of 2.0 should be adopted for all calibration tests.

F2: Magnetic stirrer bar size

It was noted that various stirrer bar sizes were available for the magnetic stirrer (see Figure F2.1) and, given their size relative to the diameter of the 'beakers', tests were undertaken using different bar sizes to determine the most effective choice for minimising sedimentation of the material. The magnetic stirrer speed was set to 2, while a mixture at 150g/L was used for the test. The observations made during this test are collated in Table F2.1.

Table F2.1: Observations of stirrer bar size test

Bar Size:	Observations:
Small	Significant amount of settled material observed, forming a layer at the base of the 'beaker' across most of the base
Medium	Some settled material observed at the edges of the base of the 'beaker'
Large	Stirrer bar not stably rotating at the base of the container, resulting in unsteady flow within container as stirrer bar shifted significantly during the test, occasionally impacting upon the sensor



Figure F2.1: Different magnetic stirrer bar sizes available

Based on these tests, it is recommended that the medium sized magnetic stirrer bar is adopted for all of the calibration tests.

F3: Lighting conditions

Given that the TSD-10 sensor is an optical sensor, a series of tests were conducted to investigate the effect of lighting conditions on the output from the sensors. To do so, a standard “additional mixing test” was undertaken (see Section 5.1.5), with each concentration being left for 5 minutes under normal ambient laboratory lighting conditions before being left for 5 minutes while being covered by an opaque box. The output from the sensor for this test is presented in Figure F3.1, with the average turbidity readings (in bits) collated in Table F3.1.

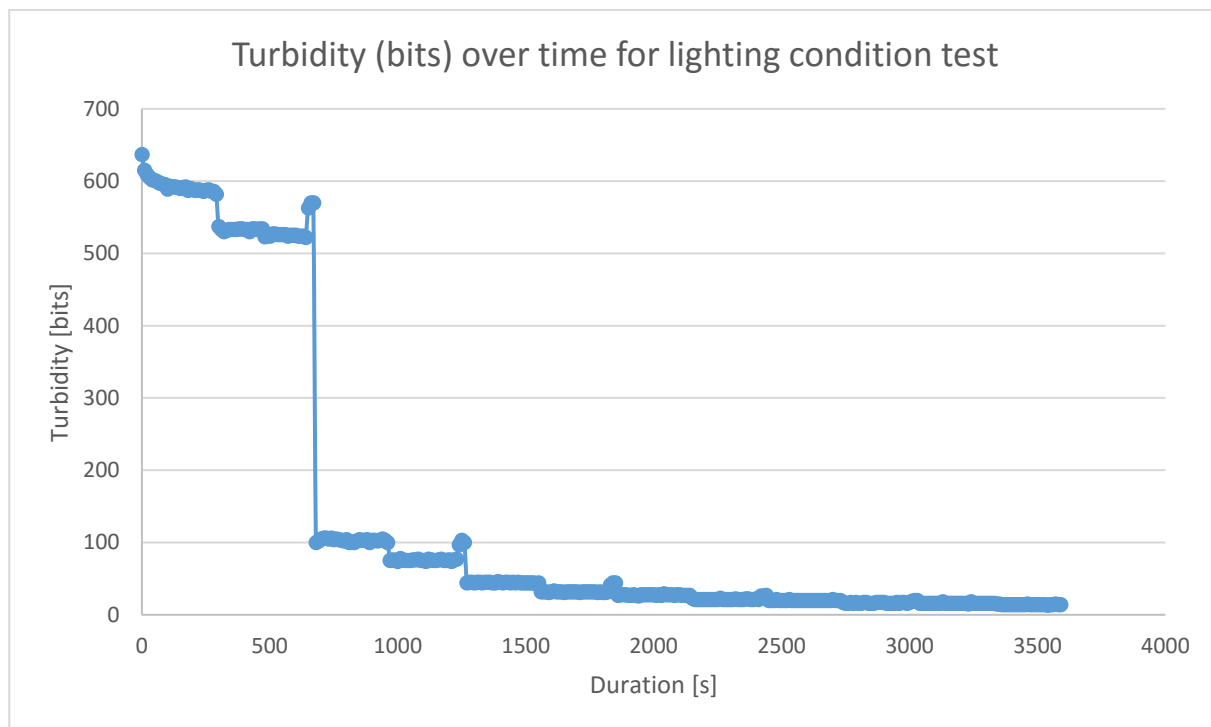


Figure F3.1: Graph of raw data from lighting condition test

Table F3.1: Data collected from raw data

Mix	Lighting condition:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	Ambient	0 – 300	50 – 250	591
1	Covered	300 – 600	350 – 550	530
2	Ambient	641 – 960	700 – 900	103
2	Covered	960 – 1260	1000 – 1200	76
3	Ambient	1294 – 1620	1300 – 1500	45
3	Covered	1620 – 1920	1600 – 1800	32
4	Ambient	1955 – 2280	1900 – 2100	28
4	Covered	2280 – 2580	2200 – 2400	21
5	Ambient	2613 – 2940	2500 – 2700	20
5	Covered	2940 – 3240	2800 – 3000	16
6	Ambient	3275 – 3600	3100 – 3300	16
6	Covered	3600 – 3900	3400 – 3550	14

A comparison of differences between these measurements is presented in Table F3.2.

Table F3.2: Differences in turbidity measurements

Mix	Turbidity (Ambient)	Turbidity (Covered)	Difference	Difference from ambient value:
1	591	530	61	10%
2	103	76	27	26%
3	45	32	13	29%
4	28	21	7	25%
5	20	16	4	20%
6	16	14	2	13%

Following the oven drying process, true concentrations for these mixtures were calculated (see Table F3.3) and a comparison of the difference in the measured values could be seen, as presented in Figure F3.2.

Table F3.3: Oven drying data and true concentration

Mixture:	Average Tin mass [g]	Average Tin + Sample mass [g]	Sample mass [g]	True concentration [g/L]
1	8.58	8.59	0.01	0.5
2	19.17	19.27	0.10	5.2
3	18.42	18.61	0.19	9.7
4	17.87	18.15	0.27	13.7
5	12.13	12.49	0.36	18.0
6	13.40	13.84	0.44	21.8

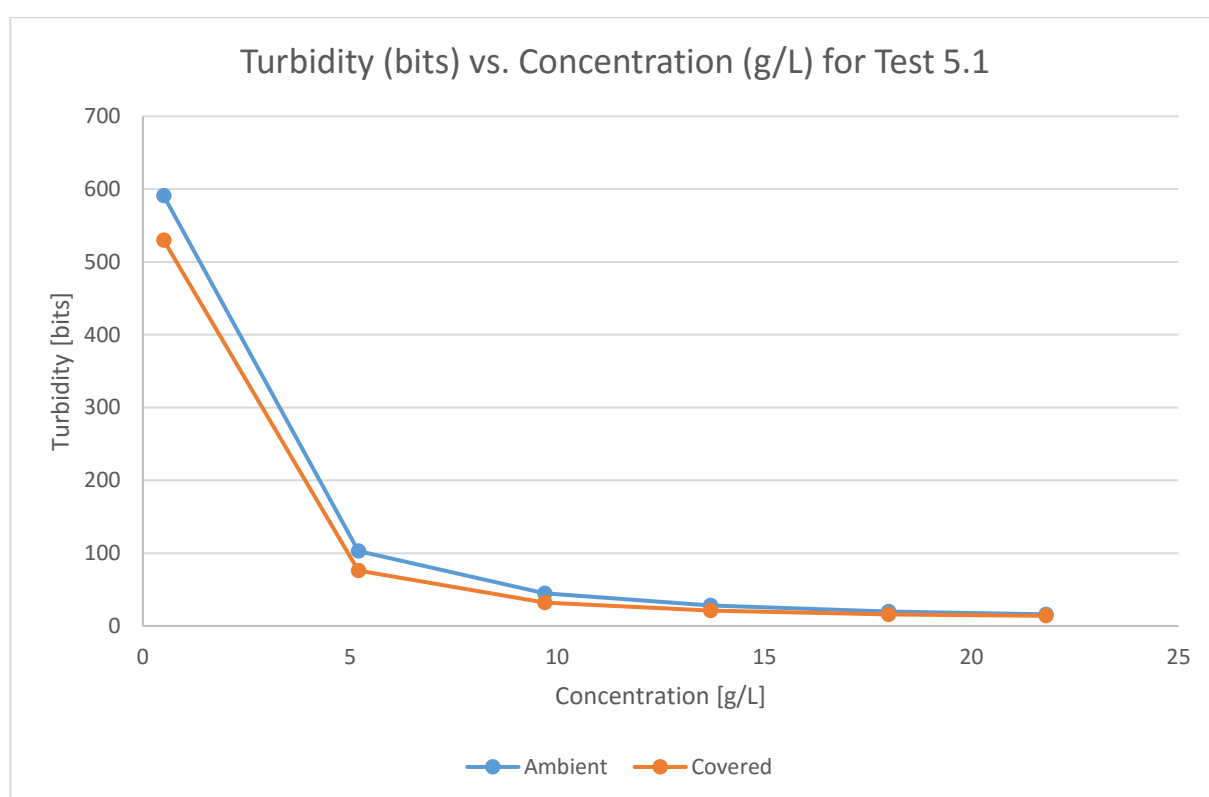


Figure F3.2: Comparison of results from lighting condition test

Based on this comparison, it is clear that the lighting condition affects the output from the turbidity sensors, with a covered environment resulting in a lower number of ‘bits’ detected and measured. However, this impact is not quantifiable, as seen by the significantly different deviation values calculated and presented in Table F3.2. As such, it is recommended that lighting conditions are kept as similar as possible during the calibration tests.

Appendix G: Example of calibration test data processing

From the methodology outlined in Section 5.1.5, the calibration tests were undertaken to obtain data to define a relationship between the output of the TSD-10 sensors and mixture concentration. This appendix outlines the detailed approach taken towards the data processing, using the example of Test B.

Initially, the mass of the empty tins (with labels applied) was found by measuring the mass of each tin three times and averaging these measurements. This process was adopted in an attempt to minimise random errors associated with these measurements. These are presented in Table G1.

Table G1: Mass measurements of empty tins

	Item:	Measurement 1 [g]	Measurement 2 [g]	Measurement 3 [g]	Average [g]
Measured, 15/09/16	Tin mass (1)	13.43	13.43	13.43	13.43
	Tin mass (2)	20.95	20.96	20.96	20.96
	Tin mass (3)	15.88	15.87	15.86	15.87
	Tin mass (4)	15.90	15.91	15.91	15.91
	Tin mass (5)	16.50	16.50	16.50	16.50
	Tin mass (6)	15.24	15.24	15.24	15.24
	Tin mass (7)	15.50	15.51	15.50	15.50
	Tin mass (8)	14.14	14.12	14.13	14.13
	Tin mass (9)	16.28	16.27	16.27	16.27
	Tin mass (10)	13.33	13.34	13.33	13.33
	Tin mass (11)	14.83	14.83	14.82	14.83

Having found these masses, the mixing tests can be undertaken. The raw data measured by the TSD-10 sensor is then plotted over the duration of the test. This was based on the assumption that data points were collected at 10 second increments, as intended by the Arduino code by Fisher (2015). It is noted that, while a time component was not directly measured by the data logger for the calibration tests, this function was enabled for the model column tests.

Figure G1 presents this plot.

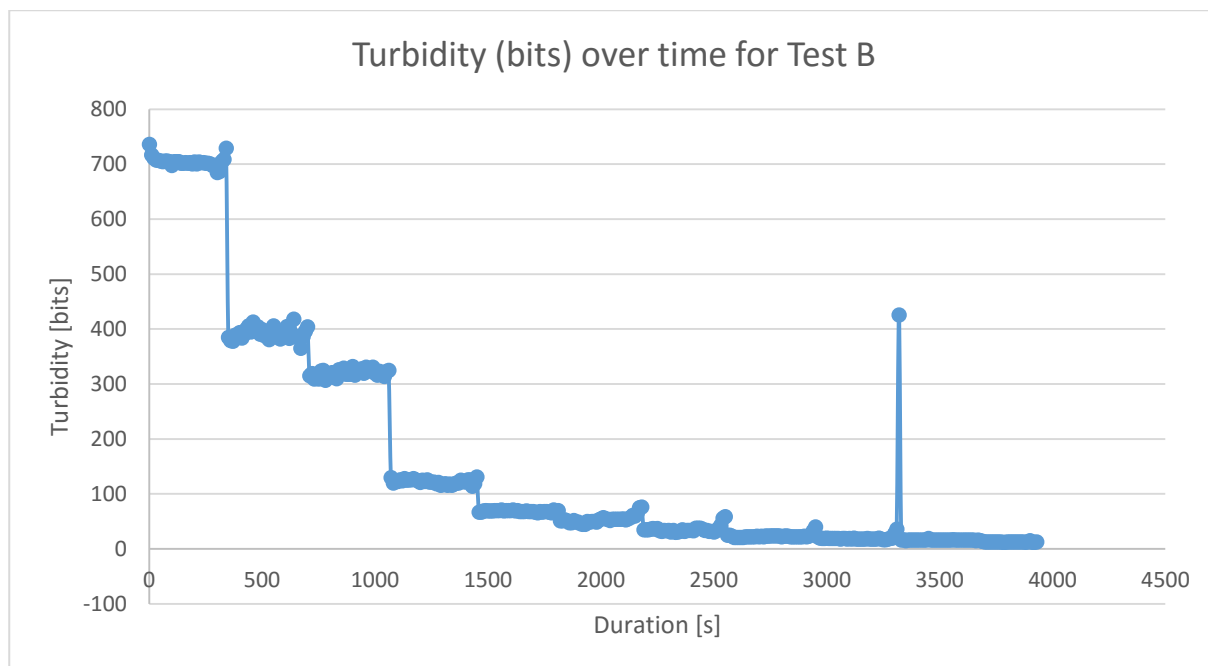


Figure G1: Raw data measured by TSD-10 sensor

Based on this data, the graph was analysed and a range of data for each mixture concentration was selected visually. From these selected durations, the average turbidity reading from the sensor was calculated. Table G2 presents these values.

Table G2: Selected durations and calculated average turbidity in 'bits'

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	703
2	353 – 660	400 – 600	394
3	712 – 1020	750 – 1000	321
4	1085 – 1440	1100 – 1400	122
5	1476 – 1800	1500 – 1750	69
6	1840 – 2160	1900 – 2100	52
7	2207 – 2520	2250 – 2500	34
8	2587 – 2940	2600 – 2900	23
9	2948 – 3300	3000 – 3250	19
10	3364 – 3680	3400 – 3650	16
11	3690 – 3930	3750 – 3900	13

Having found the turbidity reading for each mixture, the concentration needs to be determined. This was achieved using the oven drying process of the 20mL samples extracted during the mixing test. These dried samples for each mixture was weighed regularly until the average mass of the tin with dried sample was found to deviate by no more than 0.01g. At this point, it was assumed that the samples were all completely dry and hence, the mass and concentration of the sample (and, by extension, the mixture) could be calculated. These measurements for Test B are presented in Table G3, with the calculated sample masses and concentrations shown in Table G4.

Table G3: Raw mass measurements of tins containing the oven dried samples

Item:		Measurement 1 [g]	Measurement 2 [g]	Measurement 3 [g]	Average [g]
Measured at 10:05am, 16/09/16	Tin + sample (1)	13.42	13.43	13.43	13.43
	Tin + sample (2)	21.03	21.03	21.03	21.03
	Tin + sample (3)	15.97	15.97	15.97	15.97
	Tin + sample (4)	16.19	16.20	16.20	16.20
	Tin + sample (5)	16.97	16.97	16.97	16.97
	Tin + sample (6)	15.87	15.87	15.88	15.87
	Tin + sample (7)	16.47	16.47	16.47	16.47
	Tin + sample (8)	15.47	15.48	15.48	15.48
	Tin + sample (9)	17.76	17.77	17.76	17.76
	Tin + sample (10)	15.10	15.10	15.10	15.10
	Tin + sample (11)	16.74	16.74	16.74	16.74
Measured at 4:05pm, 16/09/16	Tin + sample (1)	13.42	13.43	13.44	13.43
	Tin + sample (2)	21.02	21.03	21.03	21.03
	Tin + sample (3)	15.96	15.97	15.97	15.97
	Tin + sample (4)	16.19	16.20	16.20	16.20
	Tin + sample (5)	16.97	16.97	16.97	16.97
	Tin + sample (6)	15.87	15.87	15.88	15.87
	Tin + sample (7)	16.47	16.47	16.46	16.47
	Tin + sample (8)	15.48	15.48	15.49	15.48
	Tin + sample (9)	17.76	17.77	17.76	17.76
	Tin + sample (10)	15.10	15.08	15.09	15.09
	Tin + sample (11)	16.73	16.74	16.74	16.74

Table G4: Calculated sample masses and mixture concentrations

Mix:	Average Tin mass [g]	Average Tin + Sample mass [g]	Sample mass [g]	True concentration [g/L]
1	13.43	13.43	0.00	0.0
2	20.96	21.03	0.07	3.5
3	15.87	15.97	0.10	4.8
4	15.91	16.20	0.29	14.5
5	16.50	16.97	0.47	23.5
6	15.24	15.87	0.63	31.7
7	15.50	16.47	0.97	48.2
8	14.13	15.48	1.35	67.7
9	16.27	17.76	1.49	74.5
10	13.33	15.09	1.76	87.8
11	14.83	16.74	1.91	95.5

Note: This example (Test B) involves a tap water mixture. Where a salt water mixture is used, the additional mass resulting from the concentration of NaCl in the water must be considered.

With the concentration and average turbidity readings for each mixture, a plot of the data points can be generated. This is shown in Figure G2 and concludes the data processing required for the calibration tests.

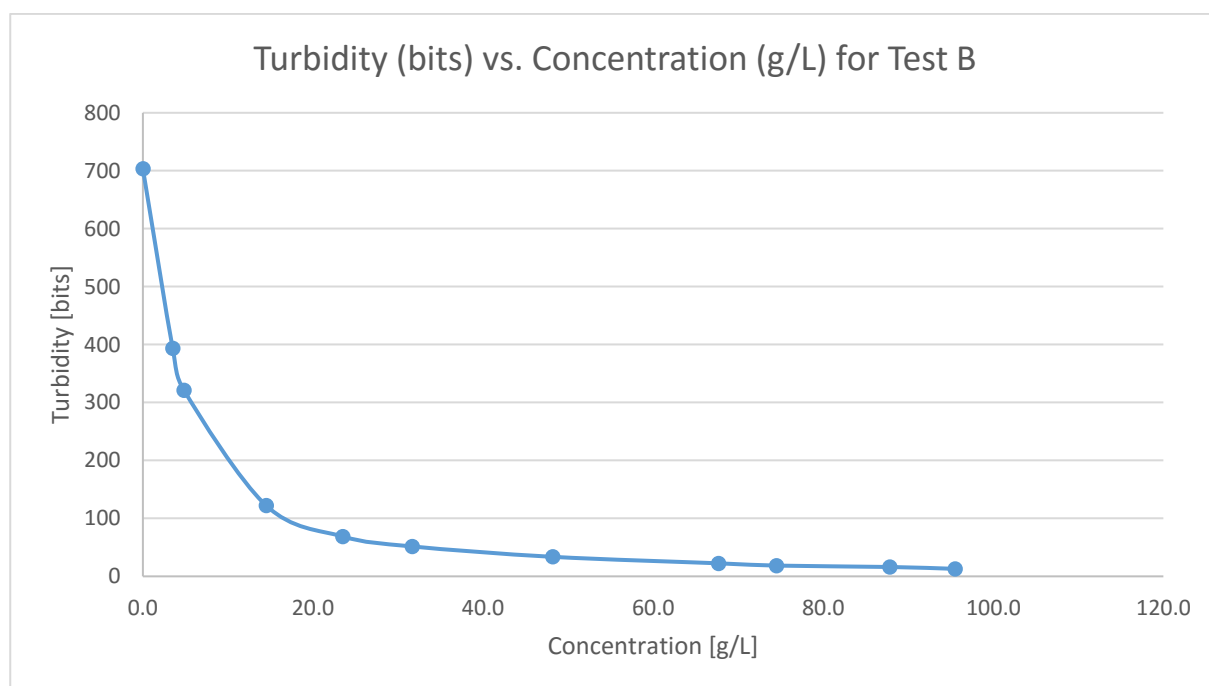


Figure G2: Plot of turbidity data against concentration

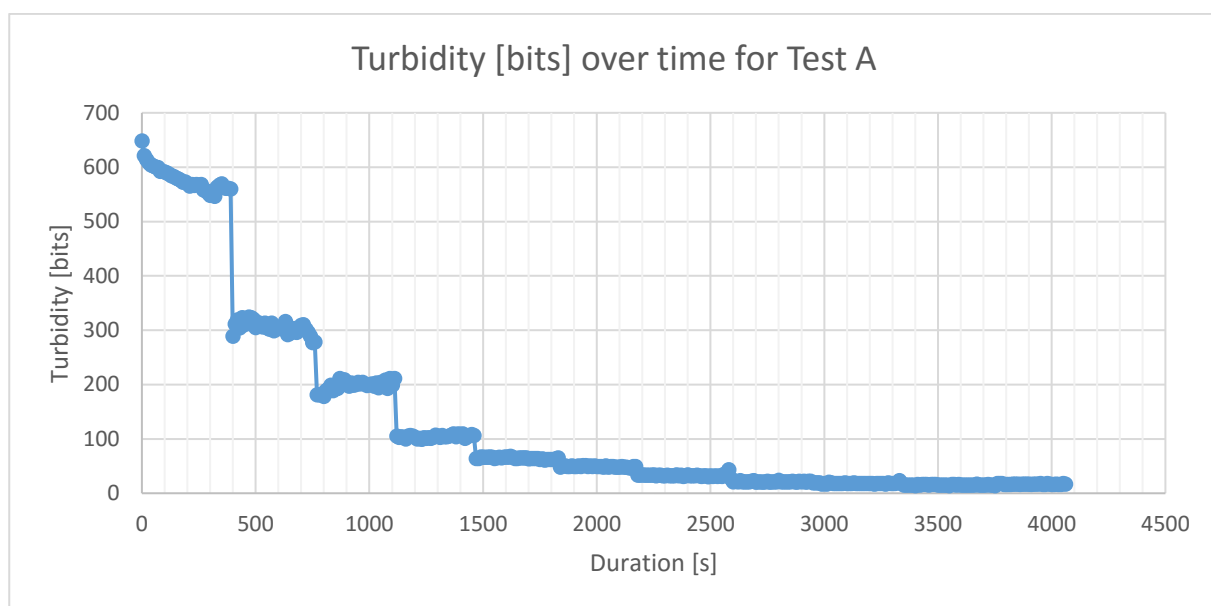
Appendix H: Turbidity calibration test results

H1: Test A

Test details:

- Date of test: 07/09/2016
- Material being tested: Silica in tap water
- Sensor being tested: 1
- Start time of 150g/L test: 3:52pm
- Start time of mixing test: 4:09pm

Raw data measured by turbidity sensor:



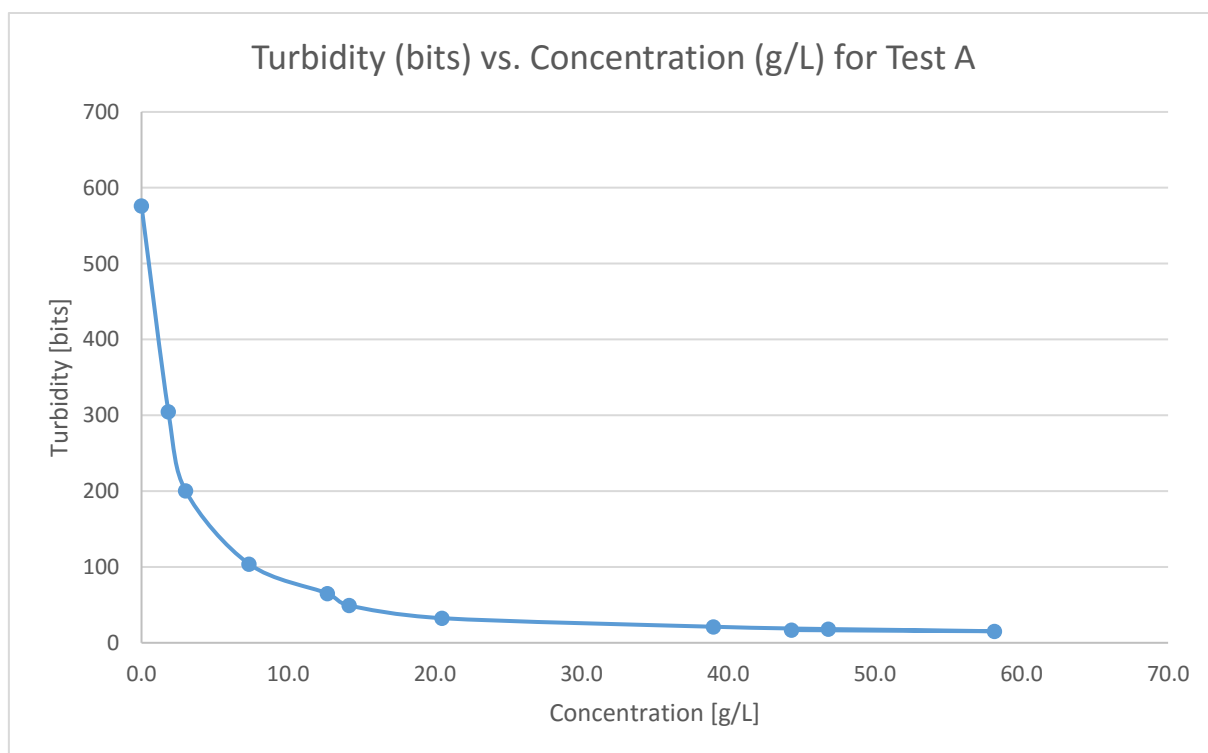
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	100 – 250	576
2	405 – 720	500 – 700	305
3	770 – 1080	900 – 1050	201
4	1130 – 1440	1200 – 1400	104
5	1480 – 1800	1500 – 1750	65
6	1850 – 2160	1900 – 2100	49
7	2190 – 2520	2250 – 2450	32
8	2580 – 2940	2650 – 2850	21
9	2970 – 3300	3050 – 3200	18
10	3372 – 3750	3450 – 3650	15
11	3760 – 4060	3850 – 4000	17

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	16.41	16.41	0.00	0.0
2	17.19	17.29	0.10	5.2
3	15.40	15.51	0.10	5.2
4	14.79	15.01	0.22	11.2
5	15.17	15.53	0.36	17.8
6	15.73	16.18	0.45	22.5
7	14.75	15.51	0.76	38.0
8	15.85	17.41	1.57	78.3
9	15.85	17.50	1.64	82.2
10	13.28	15.27	1.99	99.7
11	16.19	18.31	2.12	105.8

Plot of turbidity data vs. concentration:

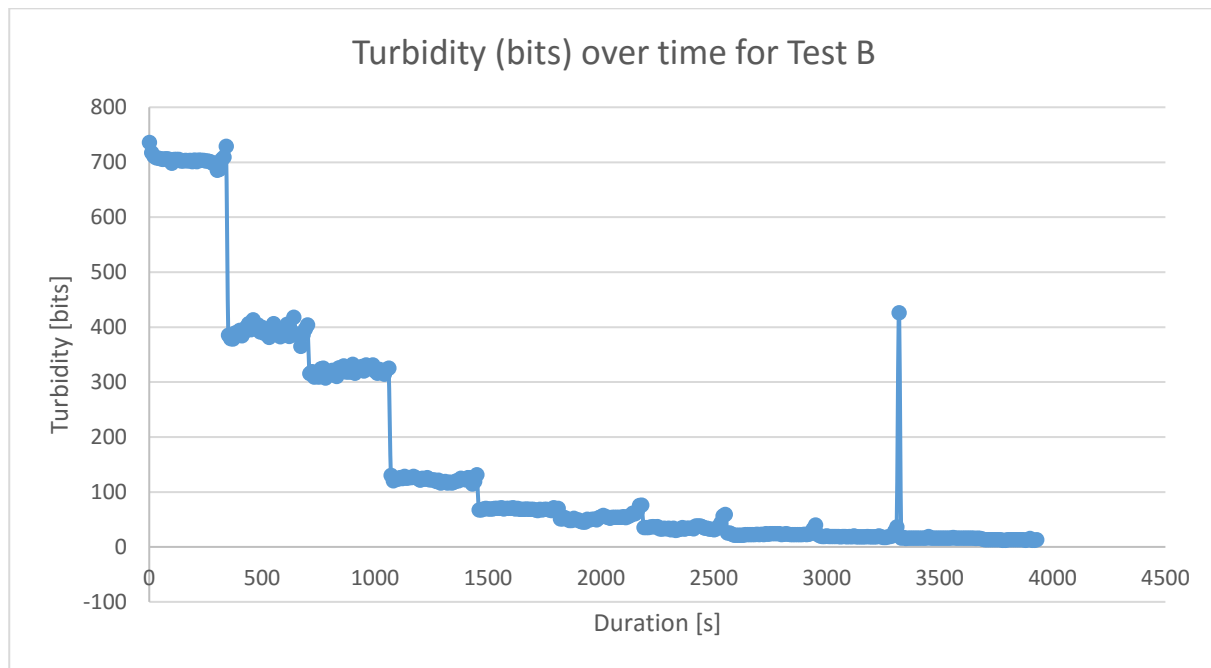


H2: Test B

Test details:

- Date of test: 15/09/2016
- Material being tested: Silica in tap water
- Sensor being tested: 2
- Start time of 150g/L test: 9:22am
- Start time of mixing test: 9:36am

Raw data measured by turbidity sensor:



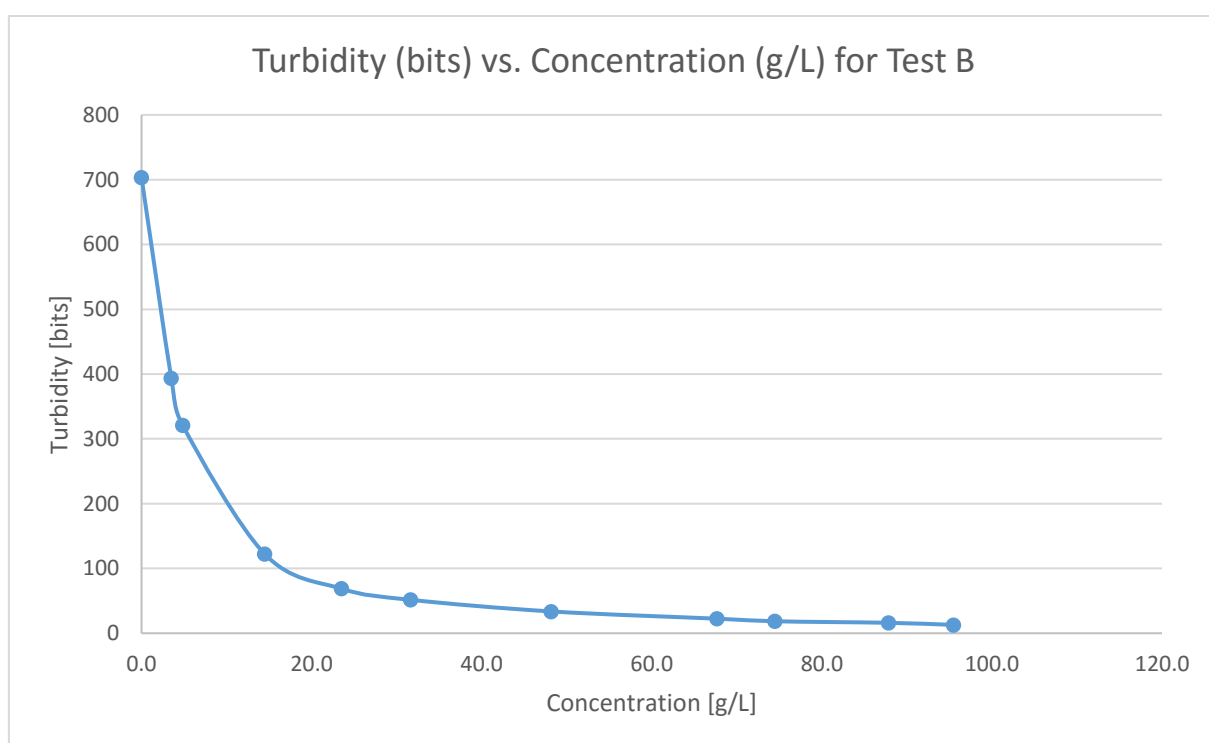
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	703
2	353 – 660	400 – 600	394
3	712 – 1020	750 – 1000	321
4	1085 – 1440	1100 – 1400	122
5	1476 – 1800	1500 – 1750	69
6	1840 – 2160	1900 – 2100	52
7	2207 – 2520	2250 – 2500	34
8	2587 – 2940	2600 – 2900	23
9	2948 – 3300	3000 – 3250	19
10	3364 – 3680	3400 – 3650	16
11	3690 – 3930	3750 – 3900	13

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	13.43	13.43	0.00	0.0
2	20.96	21.03	0.07	3.5
3	15.87	15.97	0.10	4.8
4	15.91	16.20	0.29	14.5
5	16.50	16.97	0.47	23.5
6	15.24	15.87	0.63	31.7
7	15.50	16.47	0.97	48.2
8	14.13	15.48	1.35	67.7
9	16.27	17.76	1.49	74.5
10	13.33	15.09	1.76	87.8
11	14.83	16.74	1.91	95.5

Plot of turbidity data vs. concentration:

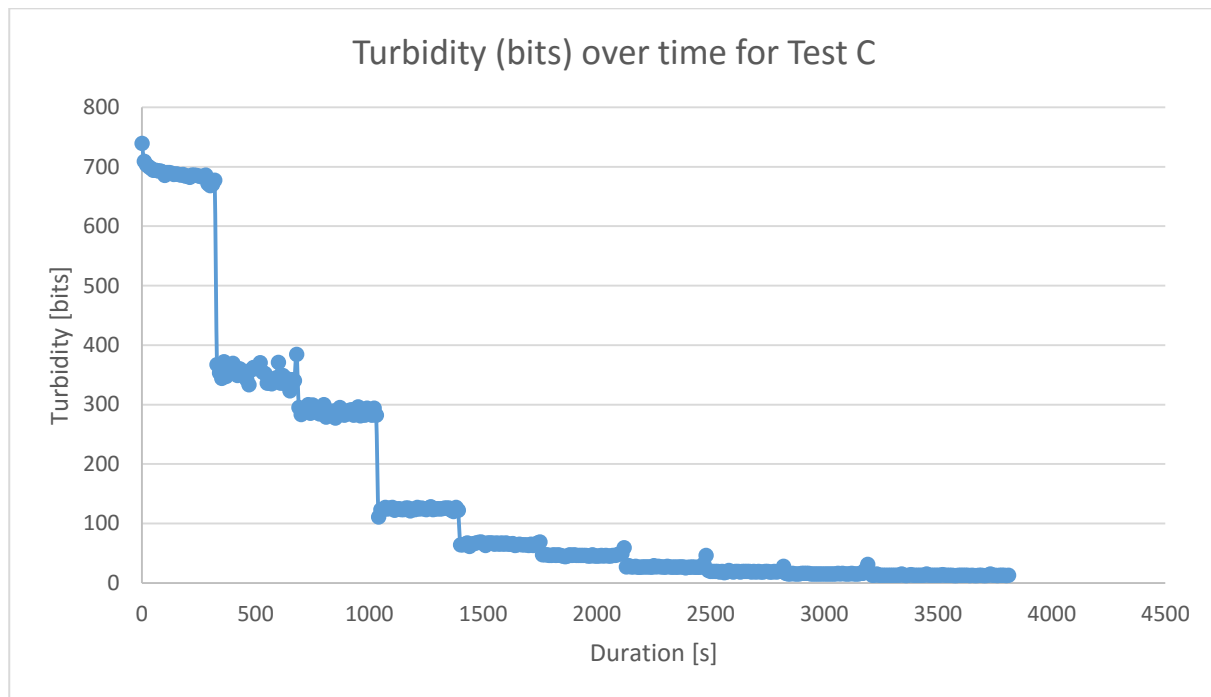


H3: Test C

Test details:

- Date of test: 26/09/2016
- Material being tested: Silica in tap water
- Sensor being tested: 3
- Start time of 150g/L test: 1:50pm
- Start time of mixing test: 2:01pm

Raw data measured by turbidity sensor:



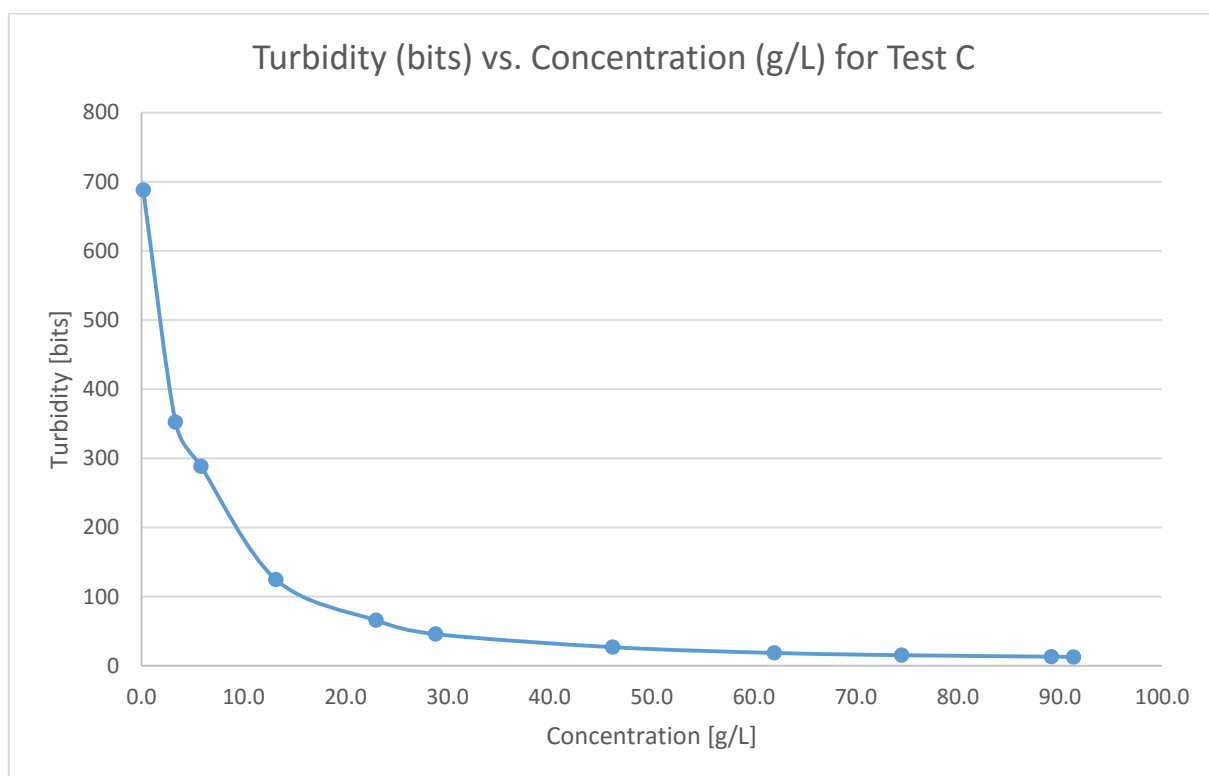
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	688
2	331 – 660	400 – 600	352
3	692 – 1020	750 – 1000	288
4	1052 – 1380	1100 – 1350	125
5	1409 – 1740	1450 – 1700	66
6	1769 – 2100	1800 – 2050	46
7	2150 – 2460	2200 – 2400	27
8	2513 – 2820	2600 – 2800	19
9	2857 – 3180	2900 – 3150	15
10	3237 – 3510	3300 – 3500	13
11	3520 – 3810	3550 – 3800	13

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	18.77	18.78	0.00	0.2
2	18.41	18.48	0.07	3.3
3	8.55	8.67	0.12	5.8
4	13.38	13.64	0.26	13.2
5	15.66	16.12	0.46	23.0
6	13.26	13.83	0.58	28.8
7	12.11	13.04	0.92	46.2
8	19.15	20.39	1.24	62.0
9	17.85	19.34	1.49	74.5
10	13.47	15.25	1.78	89.2
11	15.53	17.36	1.83	91.3

Plot of turbidity data vs. concentration:

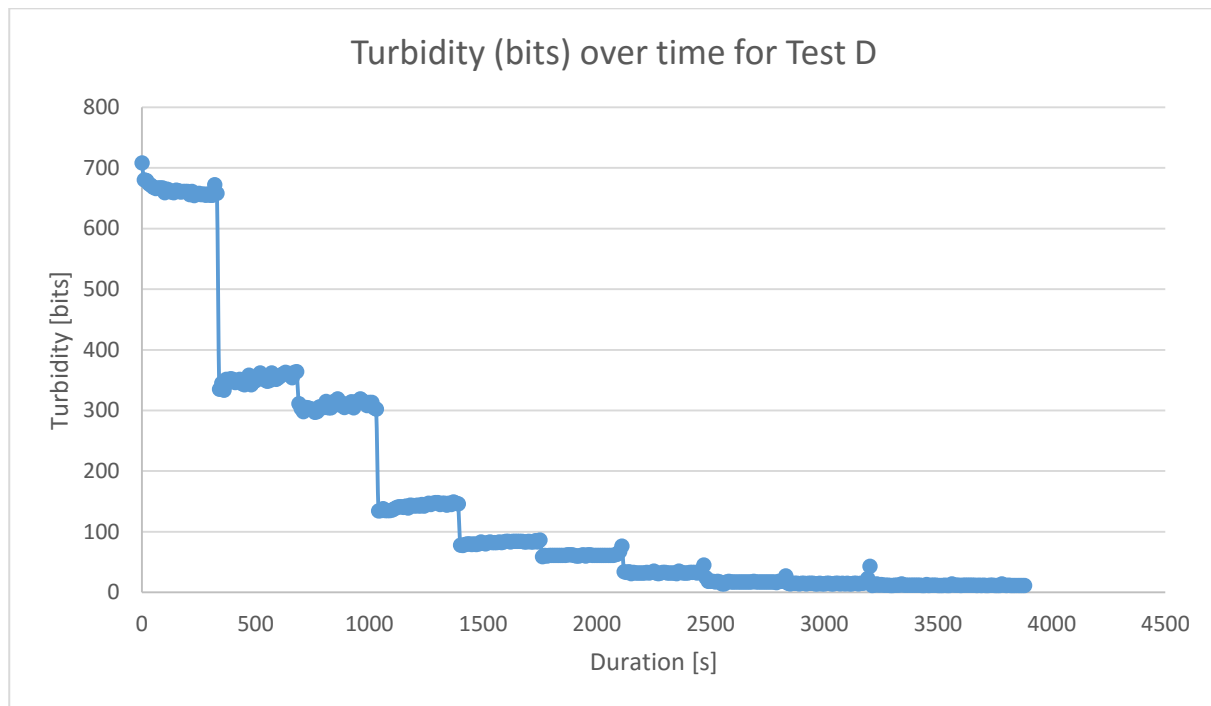


H4: Test D

Test details:

- Date of test: 28/09/2016
- Material being tested: Silica in tap water
- Sensor being tested: 4
- Start time of 150g/L test: 12:33pm
- Start time of mixing test: 12:45pm

Raw data measured by turbidity sensor:



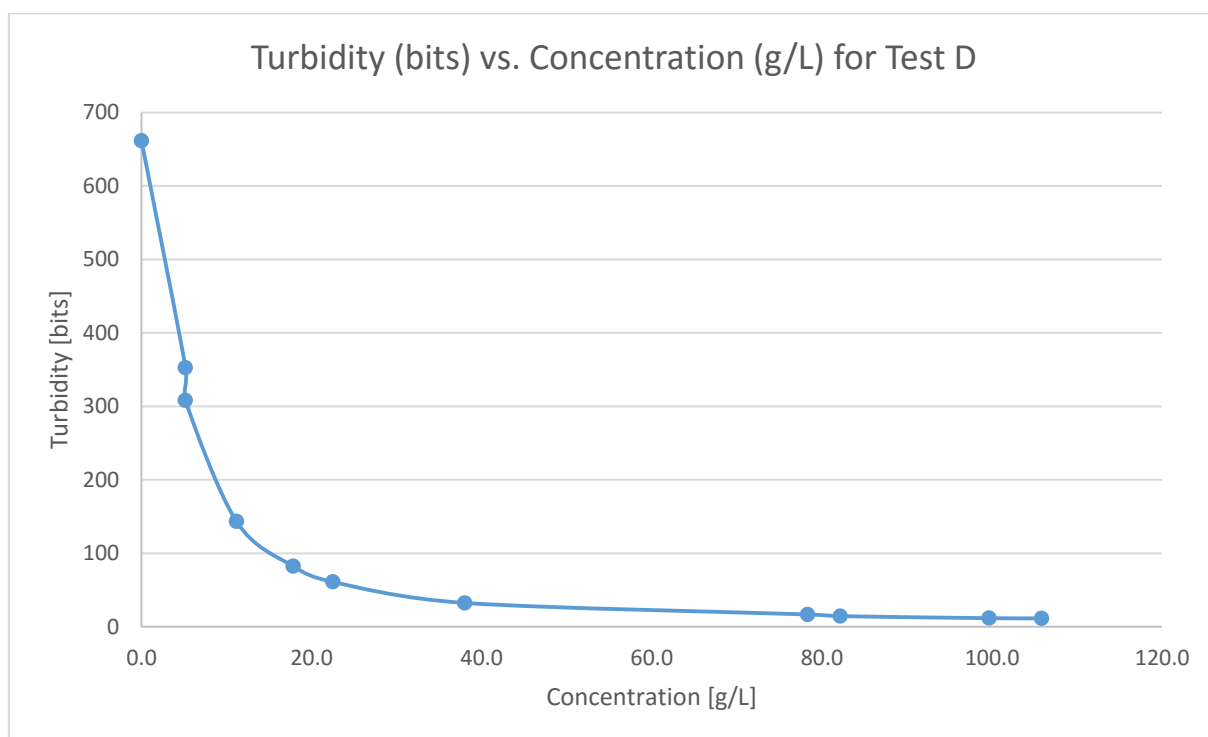
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	662
2	343 – 660	400 – 650	353
3	700 – 1020	750 – 950	308
4	1052 – 1380	1100 – 1350	143
5	1409 – 1740	1450 – 1700	82
6	1779 – 2100	1800 – 2050	61
7	2144 – 2460	2200 – 2450	33
8	2508 – 2820	2550 – 2800	17
9	2867 – 3180	2900 – 3150	15
10	3241 – 3560	3300 – 3550	12
11	3570 – 3880	3600 – 3850	12

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	16.41	16.41	0.00	0.0
2	17.19	17.29	0.10	5.2
3	15.40	15.51	0.10	5.2
4	14.79	15.01	0.22	11.2
5	15.17	15.53	0.36	17.8
6	15.73	16.18	0.45	22.5
7	14.75	15.51	0.76	38.0
8	15.85	17.41	1.57	78.3
9	15.85	17.50	1.64	82.2
10	13.28	15.27	1.99	99.7
11	16.19	18.31	2.12	105.8

Plot of turbidity data vs. concentration:

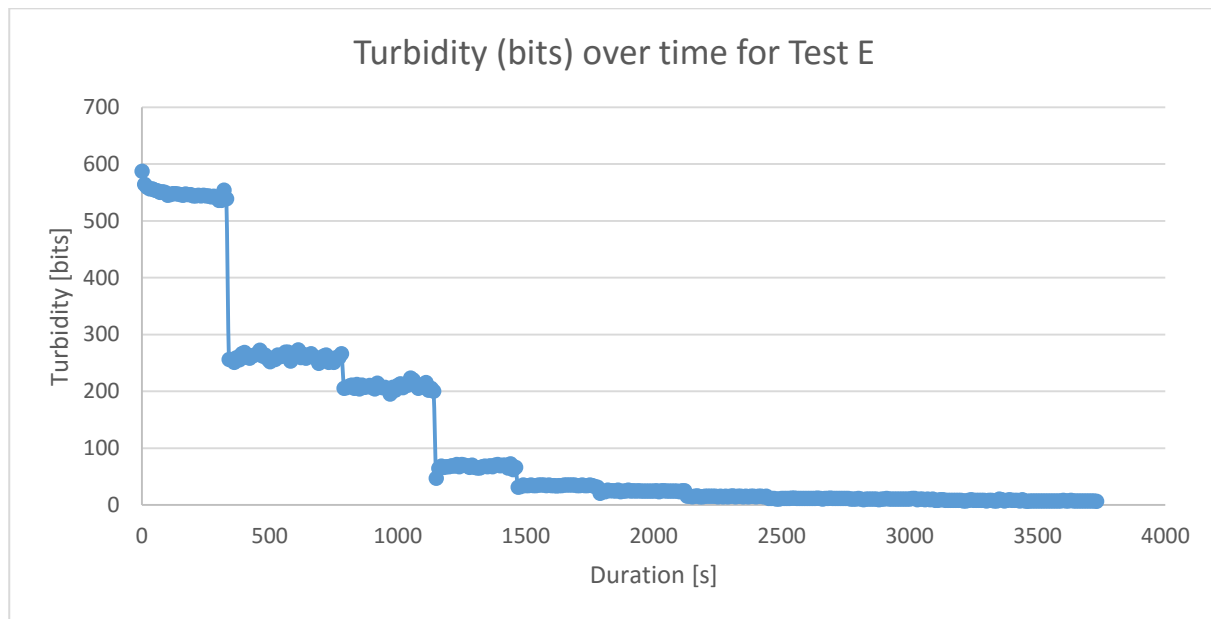


H5: Test E

Test details:

- Date of test: 29/09/2016
- Material being tested: Silica in tap water
- Sensor being tested: 5
- Start time of 150g/L test: 7:00pm
- Start time of mixing test: 7:10m

Raw data measured by turbidity sensor:



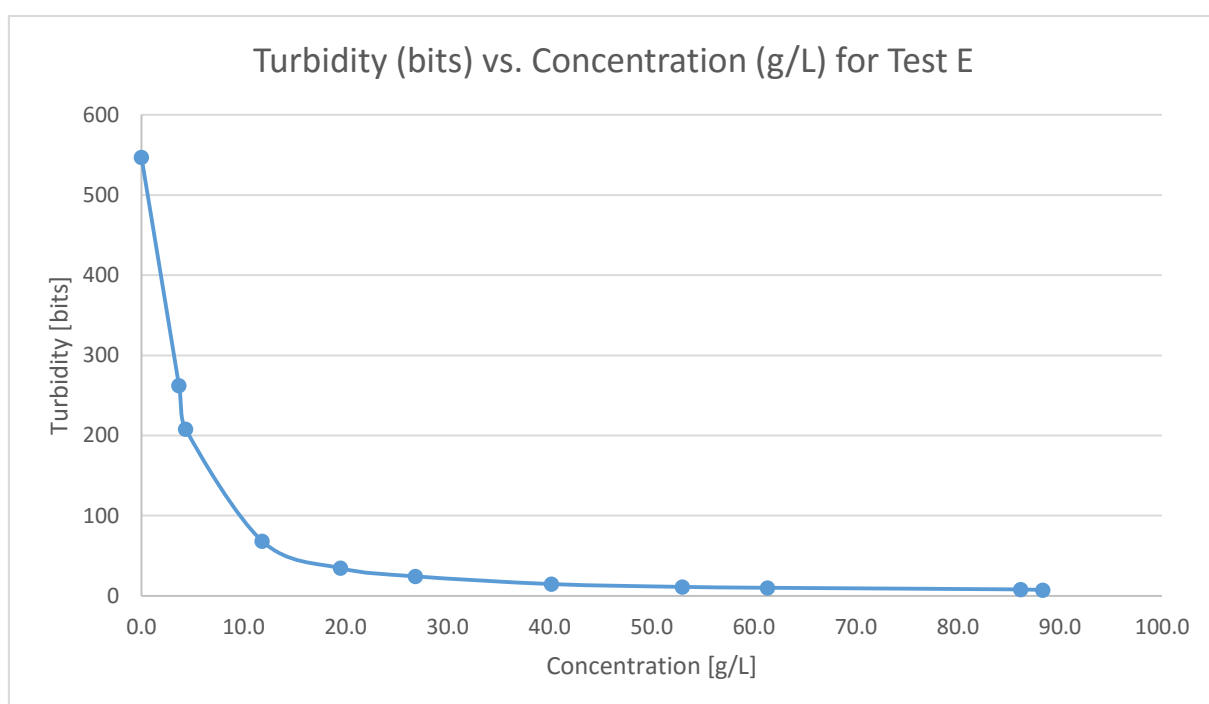
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	547
2	339 – 660	400 – 650	262
3	699 – 1080	850 – 1050	208
4	1111 – 1440	1200 – 1400	68
5	1465 – 1800	1500 – 1750	34
6	1824 – 2160	1900 – 2100	24
7	2200 – 2520	2250 – 2400	15
8	2569 – 2880	2500 – 2750	11
9	2919 – 3240	2800 – 3000	10
10	3297 – 3430	3150 – 3400	8
11	3440 – 3730	3500 – 3700	7

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	18.43	18.43	0.00	0.0
2	20.88	20.96	0.07	3.7
3	13.25	13.34	0.09	4.3
4	19.14	19.38	0.24	11.8
5	15.04	15.43	0.39	19.5
6	18.74	19.28	0.54	26.8
7	17.85	18.66	0.80	40.2
8	13.39	14.45	1.06	53.0
9	8.56	9.79	1.23	61.3
10	13.48	15.20	1.72	86.2
11	12.12	13.89	1.77	88.3

Plot of turbidity data vs. concentration:

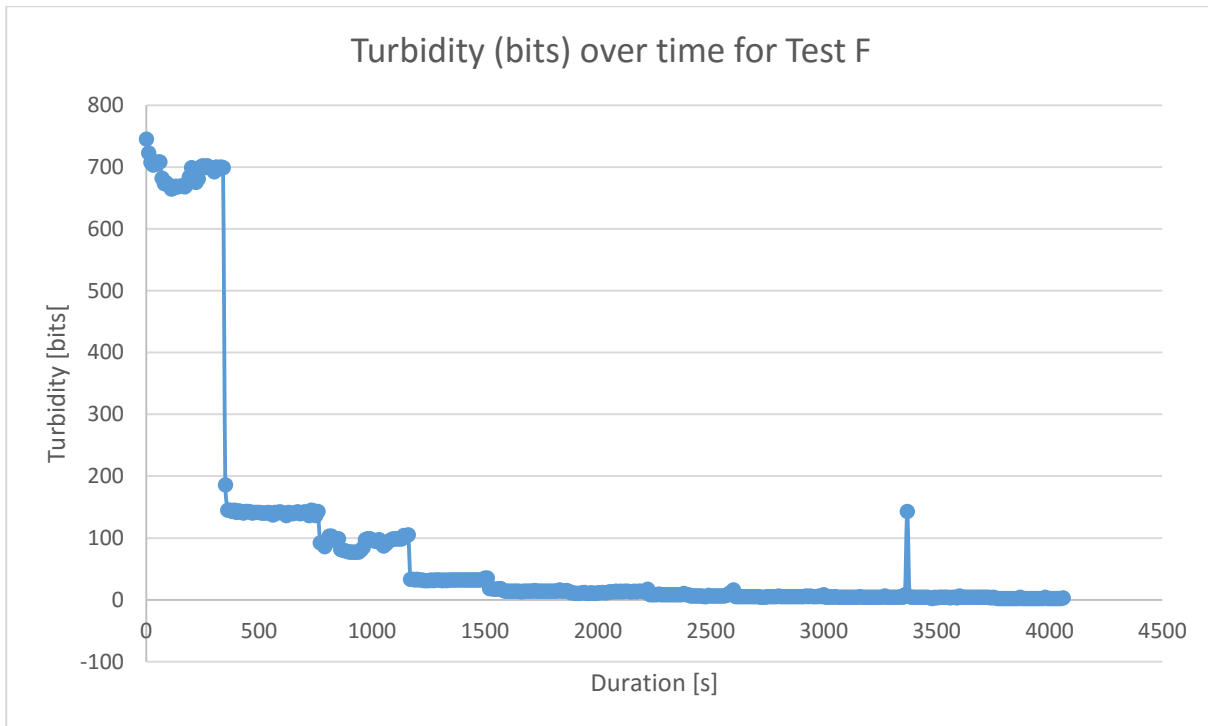


H6: Test F

Test details:

- Date of test: 12/09/2016
- Material being tested: Kaolin in tap water
- Sensor being tested: 1
- Start time of 150g/L test: 10:44am
- Start time of mixing test: 11:04am

Raw data measured by turbidity sensor:



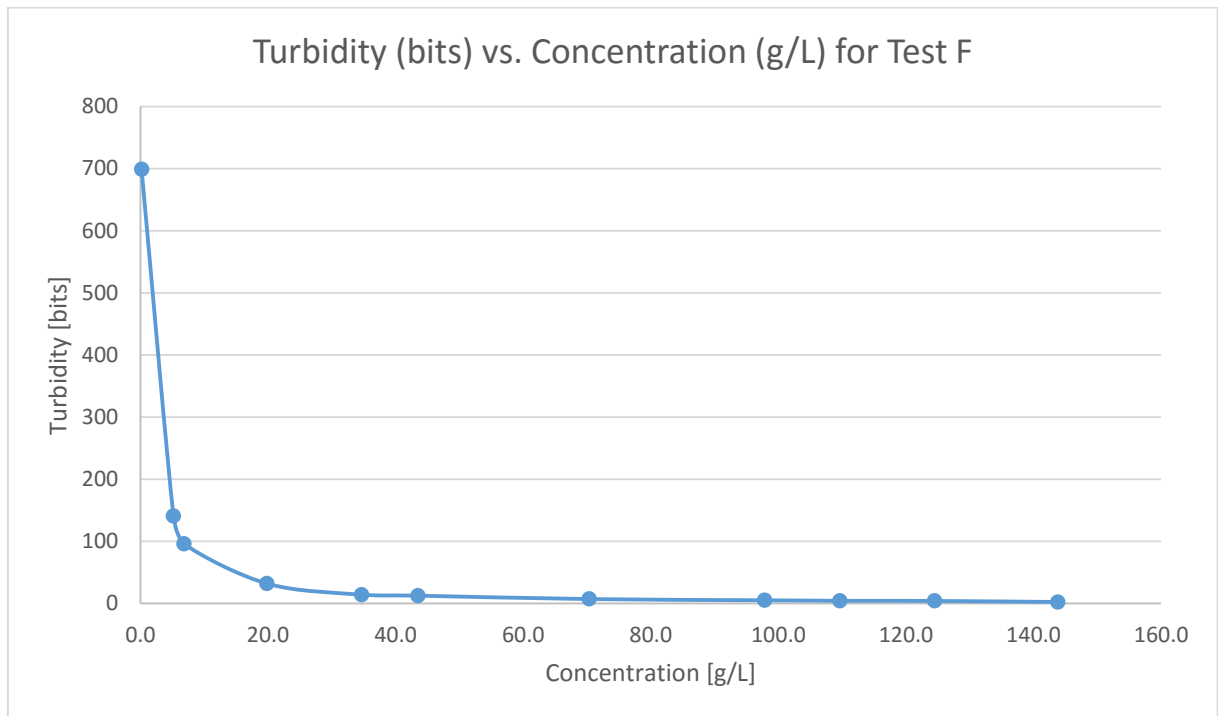
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	20 – 60, 200 – 270	699
2	357 – 720	400 – 650	141
3	780 – 1140	800 – 850, 1000 – 1100	96
4	1184 – 1500	1200 – 1450	32
5	1540 – 1860	1600 – 1800	14
6	1904 – 2220	1950 – 2200	12
7	2258 – 2580	2300 – 2550	7
8	2635 – 3000	2650 – 2950	5
9	3042 – 3360	3100 – 3300	4
10	3414 – 3750	3400 – 3700	4
11	3760 – 4060	3800 – 4000	2

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	20.91	20.92	0.01	0.5
2	16.24	16.35	0.11	5.5
3	16.49	16.63	0.14	7.0
4	14.81	15.21	0.40	20.0
5	15.91	16.61	0.70	35.0
6	15.48	16.35	0.87	43.5
7	14.12	15.52	1.40	70.0
8	15.25	17.21	1.96	98.0
9	13.33	15.52	2.19	109.5
10	13.44	15.93	2.49	124.5
11	15.87	18.75	2.88	144.0

Plot of turbidity data vs. concentration:

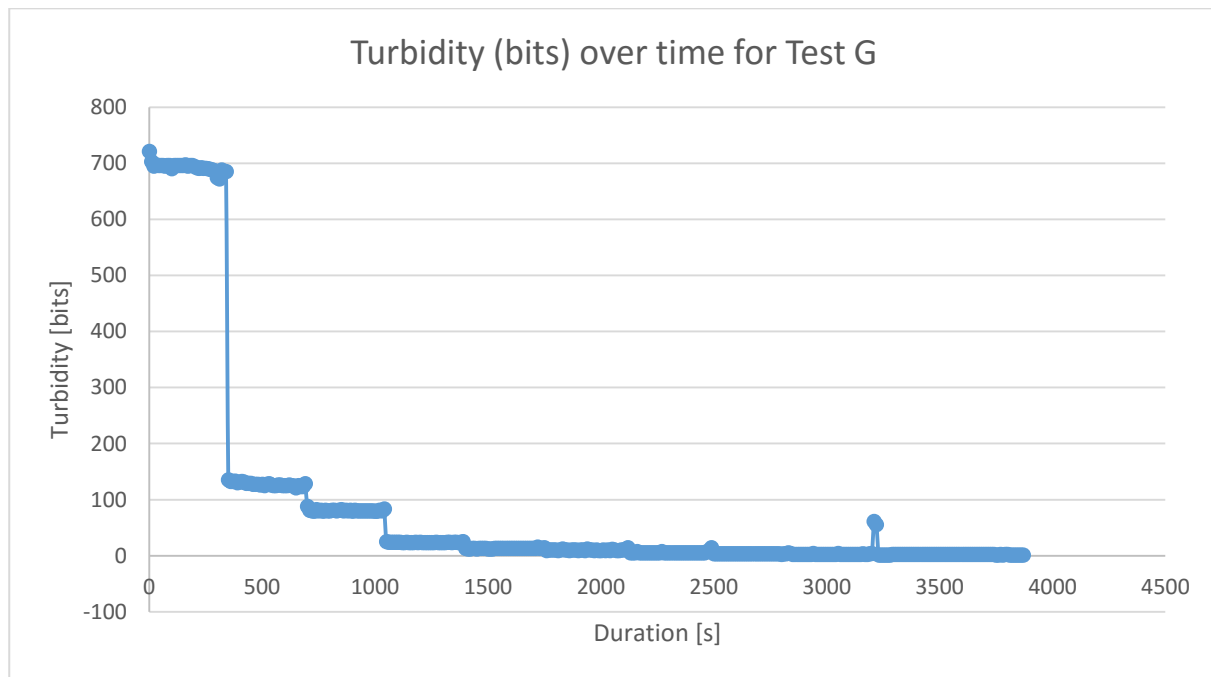


H7: Test G

Test details:

- Date of test: 15/09/2016
- Material being tested: Kaolin in tap water
- Sensor being tested: 2
- Start time of 150g/L test: 11:18am
- Start time of mixing test: 11:31am

Raw data measured by turbidity sensor:



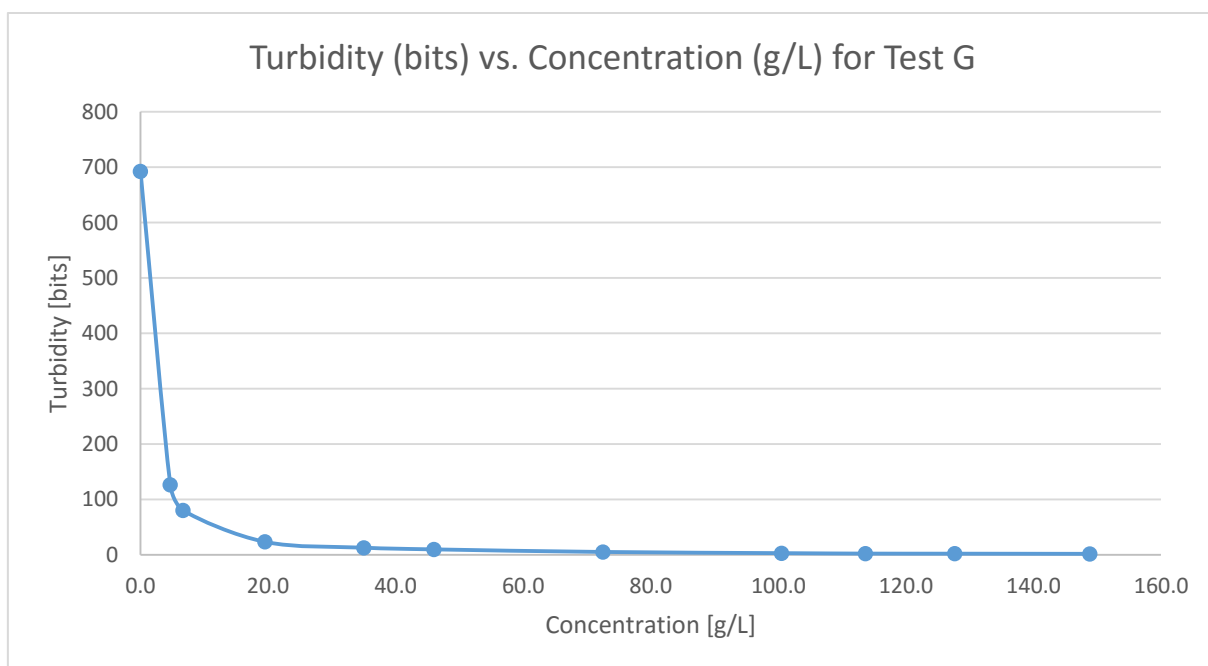
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 300	693
2	356 – 660	400 – 650	127
3	713 – 1020	750 – 1000	80
4	1068 – 1380	1100 – 1350	23
5	1424 – 1740	1450 – 1700	13
6	1787 – 2100	1850 – 2050	10
7	2154 – 2460	2200 – 2400	5
8	2519 – 2820	2550 – 2800	3
9	2873 – 3180	2900 – 3150	2
10	3261 – 3570	3350 – 3550	2
11	3580 – 3870	3600 – 3850	2

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	14.38	14.37	-0.01	0.0
2	18.37	18.46	0.09	4.7
3	15.14	15.27	0.13	6.7
4	14.01	14.40	0.39	19.5
5	14.93	15.63	0.7	35.0
6	18.82	19.74	0.92	46.0
7	15.92	17.37	1.45	72.5
8	15.69	17.70	2.01	100.5
9	15.69	17.97	2.28	113.7
10	14.27	16.82	2.55	127.7
11	13.57	16.55	2.98	148.8

Plot of turbidity data vs. concentration:

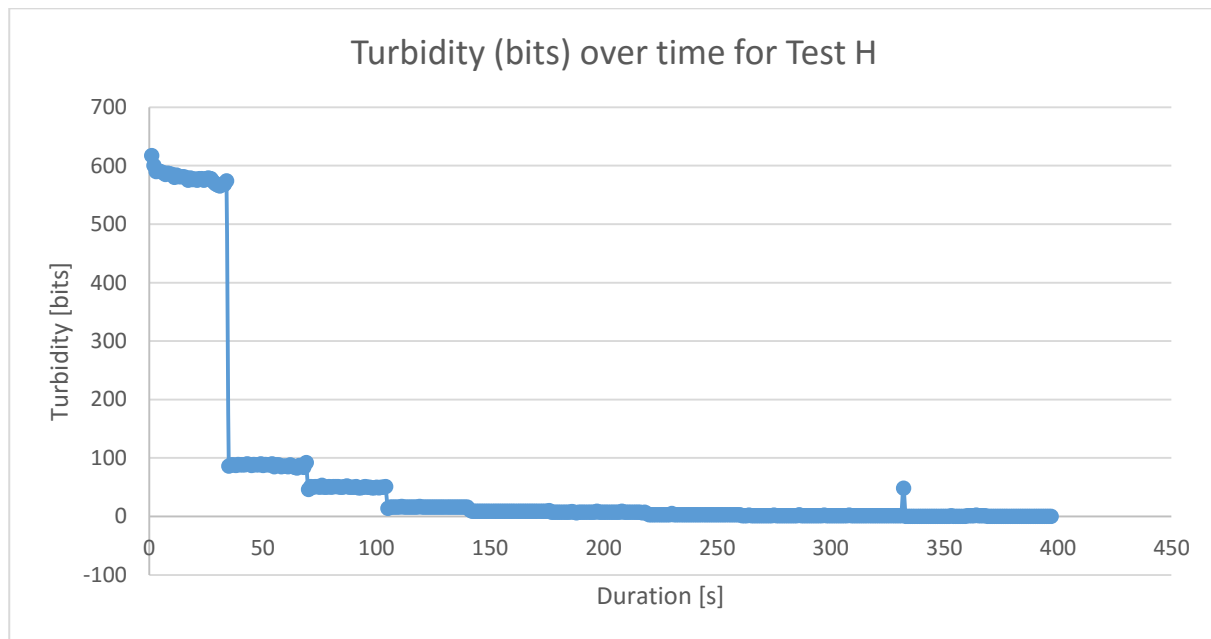


H8: Test H

Test details:

- Date of test: 26/09/2016
- Material being tested: Kaolin in tap water
- Sensor being tested: 3
- Start time of 150g/L test: 5:07pm
- Start time of mixing test: 5:23pm

Raw data measured by turbidity sensor:



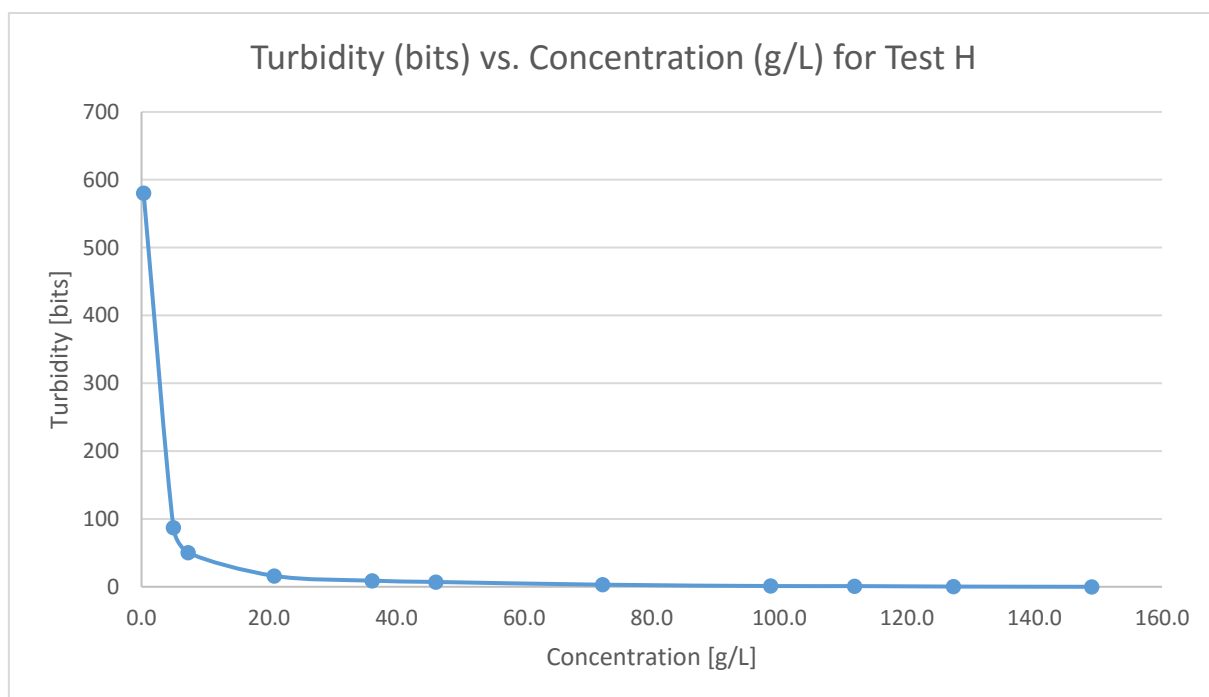
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	580
2	340 – 660	400 – 650	87
3	701 – 1020	750 – 1000	50
4	1055 – 1380	1100 – 1350	16
5	1412 – 1740	1450 – 1700	9
6	1776 – 2160	1800 – 2100	7
7	2206 – 2580	2250 – 2550	3
8	2631 – 2940	2650 – 2900	1
9	2989 – 3300	3050 – 3250	1
10	3351 – 3660	3400 – 3650	0
11	3670 – 3960	3700 – 3950	0

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	13.29	13.30	0.01	0.3
2	14.00	14.10	0.10	5.0
3	15.59	15.74	0.15	7.3
4	16.19	16.61	0.42	20.8
5	15.87	16.59	0.72	36.2
6	14.24	15.16	0.92	46.2
7	14.78	16.22	1.45	72.3
8	13.95	15.93	1.97	98.7
9	14.29	16.53	2.24	111.8
10	15.58	18.12	2.55	127.3
11	18.33	21.31	2.98	149.0

Plot of turbidity data vs. concentration:

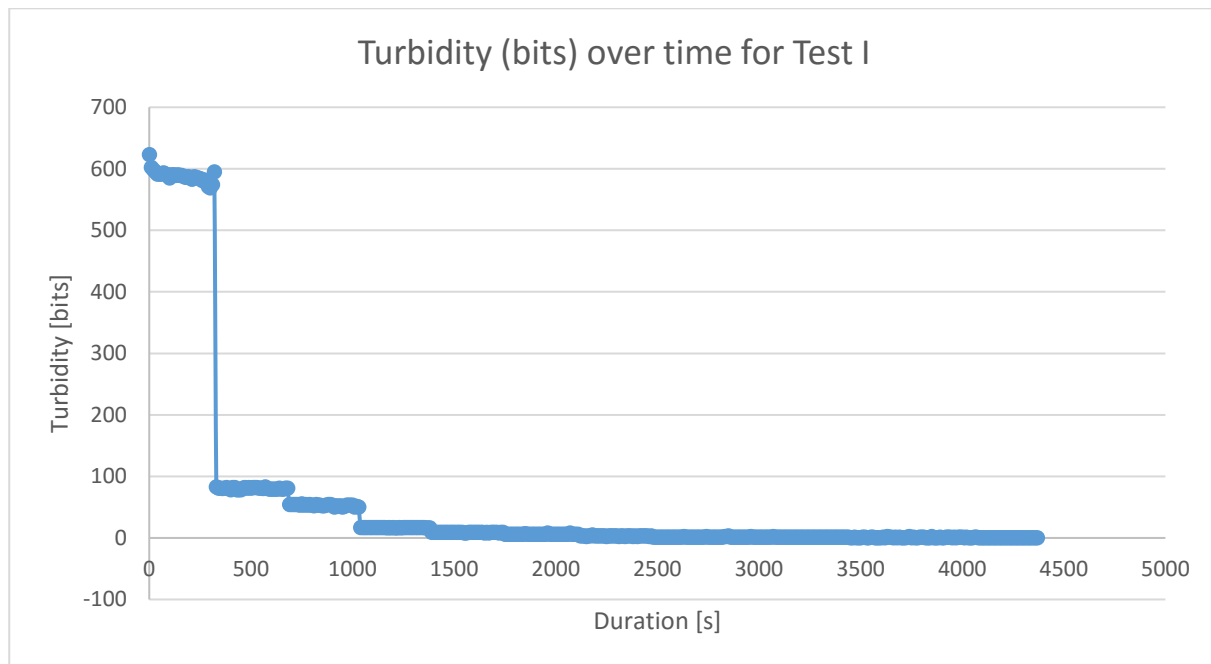


H9: Test I

Test details:

- Date of test: 28/09/2016
- Material being tested: Kaolin in tap water
- Sensor being tested: 5
- Start time of 150g/L test: 3:50pm
- Start time of mixing test: 4:03pm

Raw data measured by turbidity sensor:



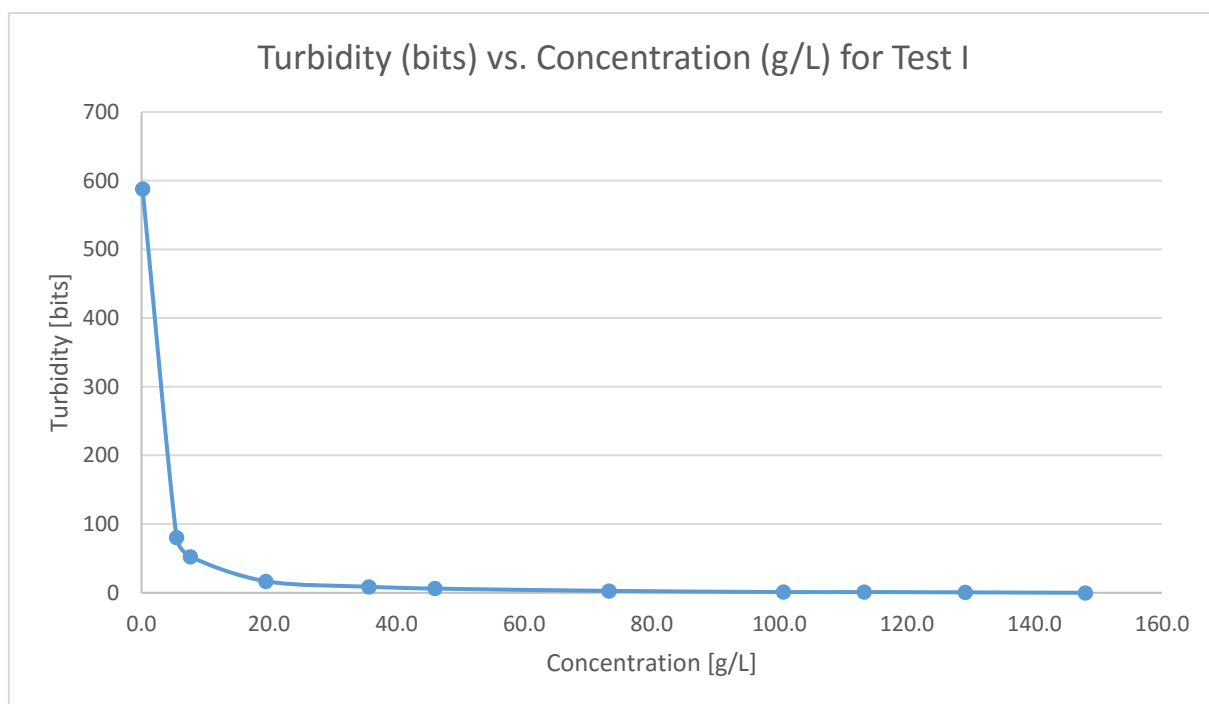
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	588
2	334 – 660	400 – 650	80
3	696 – 1020	750 – 1000	53
4	1048 – 1380	1100 – 1350	17
5	1403 – 1740	1450 – 1700	9
6	1770 – 2100	1800 – 2050	6
7	2142 – 2460	2200 – 2450	3
8	2512 – 2820	2550 – 2800	1
9	2860 – 3180	2900 – 3100	1
10	3231 – 4070	3300 – 4000	1
11	4080 – 4370	4100 – 4350	0

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	15.60	15.60	0.00	0.2
2	15.54	15.65	0.11	5.5
3	15.59	15.75	0.15	7.7
4	13.95	14.34	0.39	19.5
5	18.30	19.02	0.71	35.7
6	15.64	16.56	0.92	46.0
7	15.86	17.33	1.47	73.3
8	14.24	16.25	2.01	100.7
9	14.00	16.27	2.27	113.3
10	13.29	15.87	2.58	129.2
11	14.30	17.26	2.96	148.0

Plot of turbidity data vs. concentration:

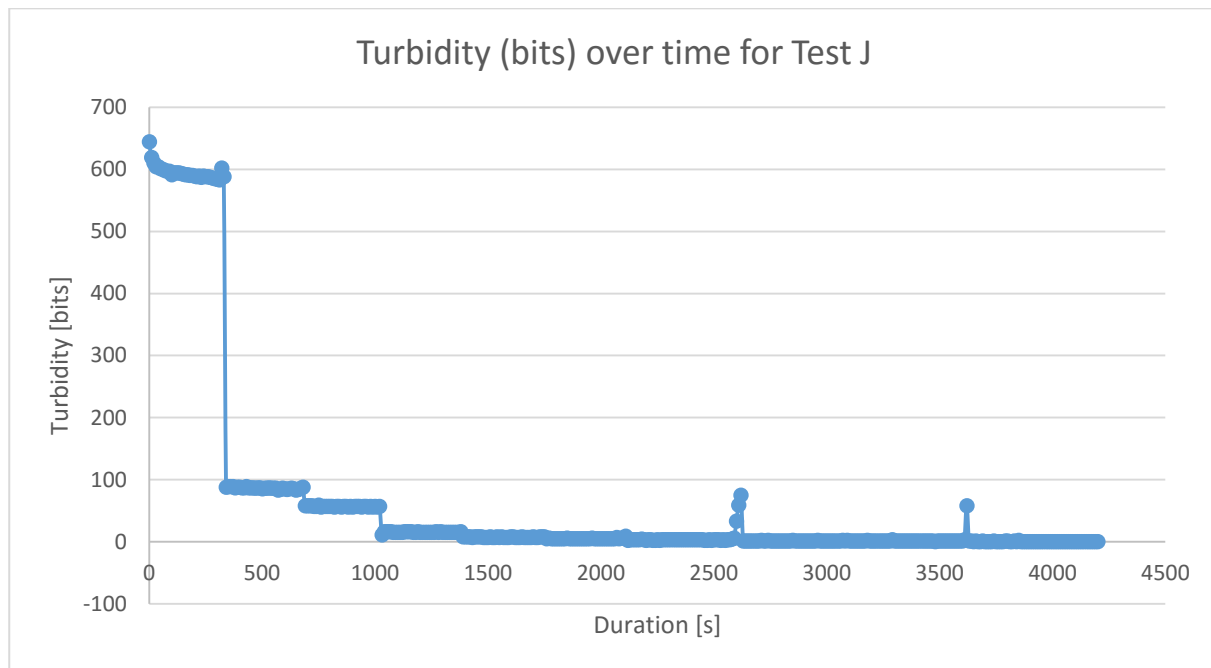


H10: Test J

Test details:

- Date of test: 30/09/2016
- Material being tested: Kaolin in tap water
- Sensor being tested: 5
- Start time of 150g/L test: 2:11pm
- Start time of mixing test: 2:20pm

Raw data measured by turbidity sensor:



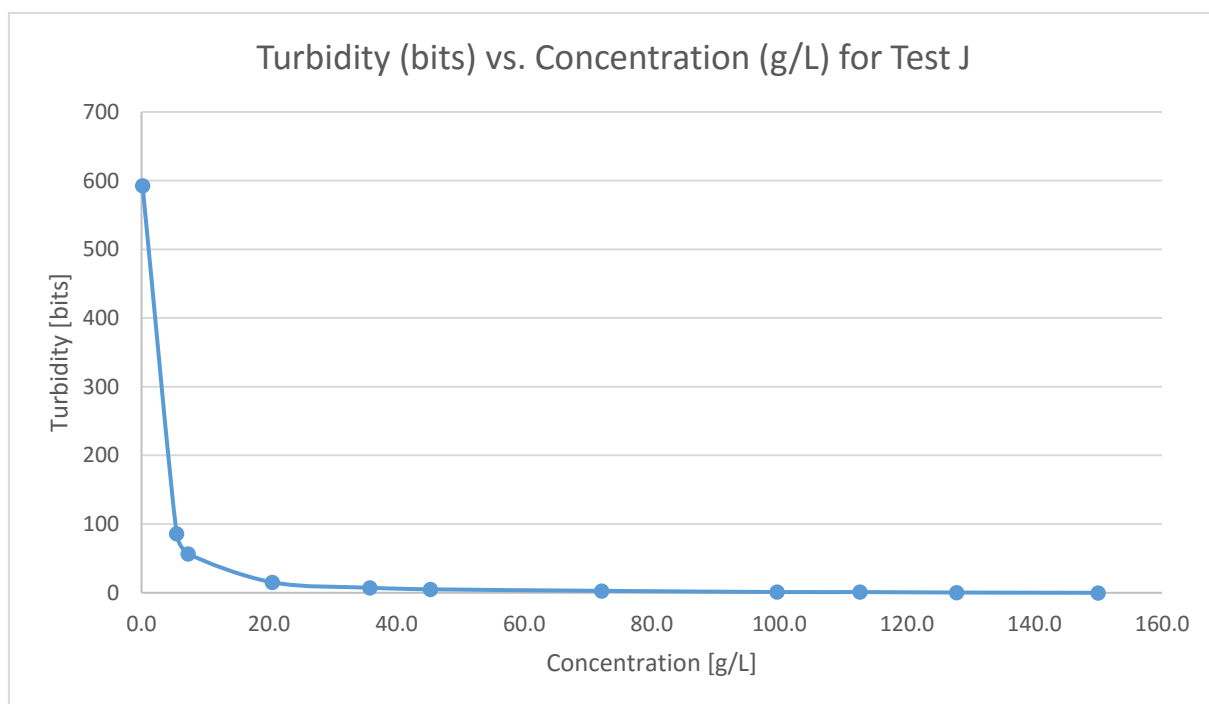
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	593
2	338 – 660	400 – 650	86
3	695 – 1020	750 – 1000	57
4	1044 – 1380	1100 – 1350	15
5	1404 – 1740	1450 – 1700	7
6	1772 – 2100	1800 – 2050	5
7	2138 – 2460	2200 – 2450	3
8	2508 – 2820	2700 – 3050	1
9	2858 – 3180	3150 – 3550	1
10	3231 – 3900	3700 – 3850	0
11	3910 – 4200	3950 – 4150	0

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	15.19	15.19	0.00	0.2
2	14.30	14.41	0.11	5.5
3	15.41	15.55	0.15	7.3
4	17.18	17.59	0.41	20.5
5	14.00	14.71	0.72	35.8
6	16.19	17.09	0.91	45.3
7	14.74	16.18	1.44	72.2
8	13.94	15.93	1.99	99.7
9	16.41	18.66	2.25	112.7
10	14.23	16.78	2.56	127.8
11	13.25	16.25	3.00	150.0

Plot of turbidity data vs. concentration:

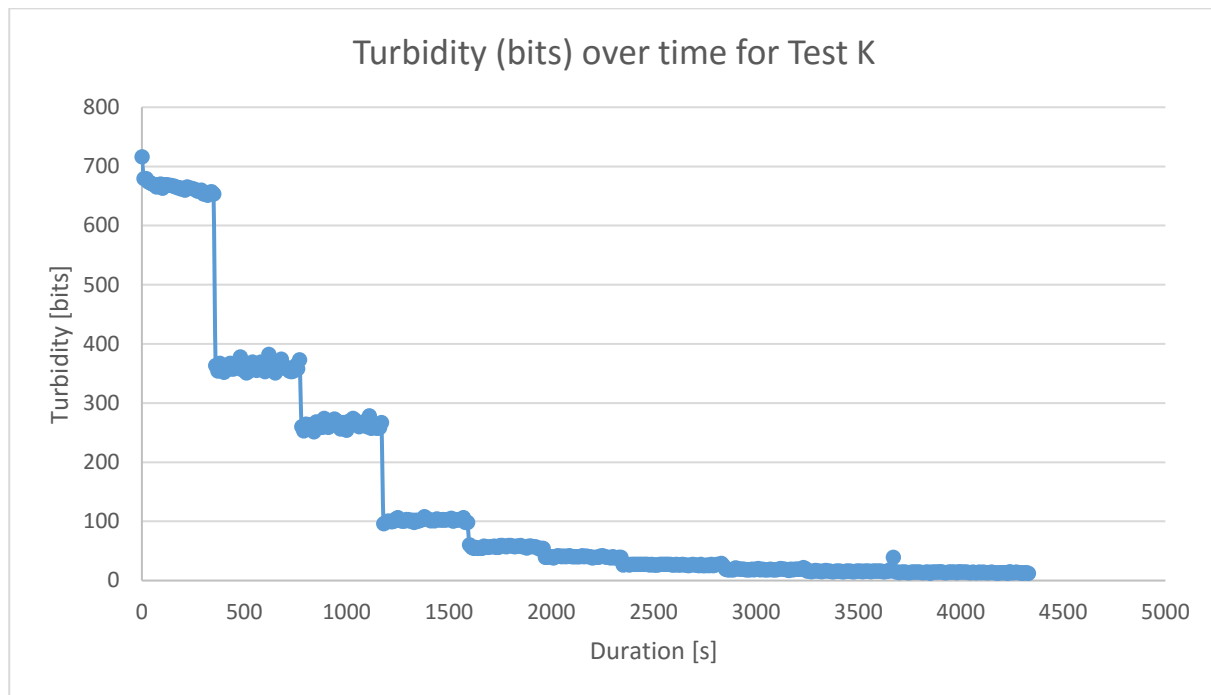


H11: Test K

Test details:

- Date of test: 12/09/2016
- Material being tested: Silica in salt water
- Sensor being tested: 1
- Start time of 150g/L test: 4:08pm
- Start time of mixing test: 4:25pm

Raw data measured by turbidity sensor:



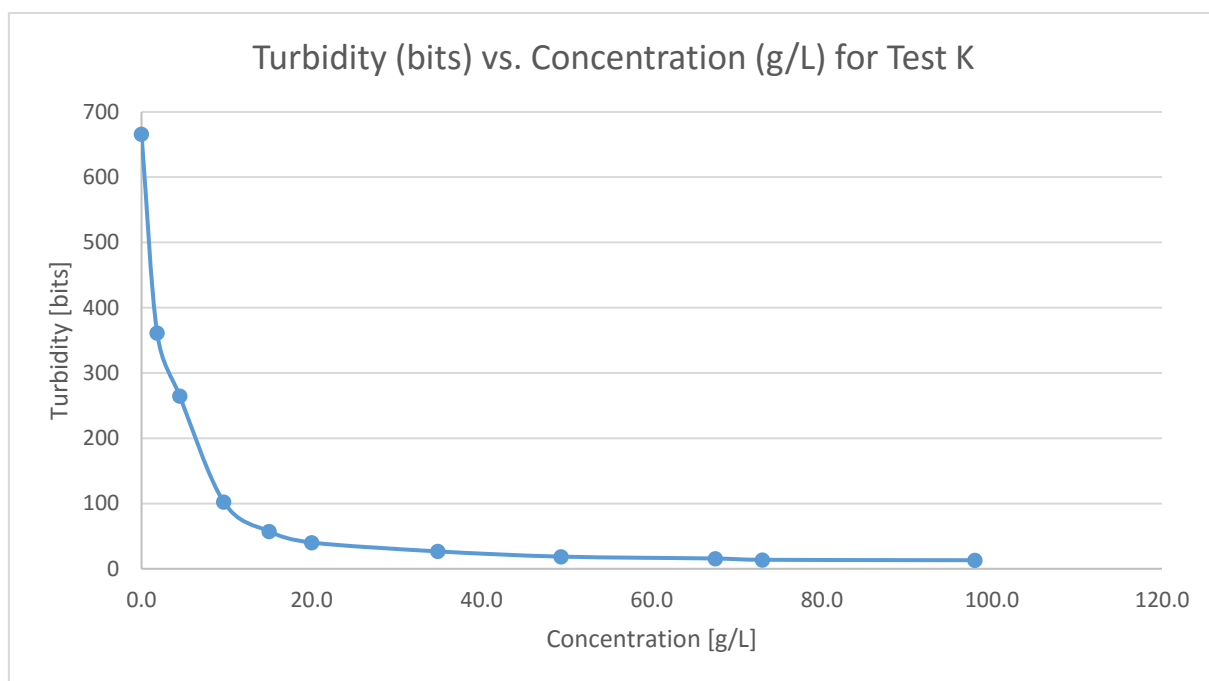
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	666
2	363 – 720	400 - 700	362
3	787 – 1140	800 – 1100	265
4	1192 – 1560	1250 – 1500	102
5	1587 – 1920	1650 – 1900	57
6	1958 – 2280	2050 – 2250	40
7	2335 – 2700	2400 – 2650	27
8	2842 – 3180	2900 – 3100	19
9	3240 – 3600	3300 – 3550	16
10	3695 – 4020	3750 - 4000	14
11	4030 – 4330	4050 – 4300	13

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.47	9.56	0.09	0.10	-0.5
2	9.80	9.93	0.13	0.10	1.5
3	9.50	9.69	0.19	0.10	4.5
4	9.67	9.97	0.30	0.10	10.0
5	9.51	9.91	0.40	0.10	15.0
6	9.76	10.26	0.50	0.10	20.0
7	9.59	10.38	0.79	0.10	34.5
8	9.62	10.70	1.08	0.10	49.0
9	9.69	11.14	1.45	0.10	67.5
10	9.61	11.17	1.56	0.10	73.0
11	9.58	11.64	2.06	0.10	98.0

Plot of turbidity data vs. concentration:

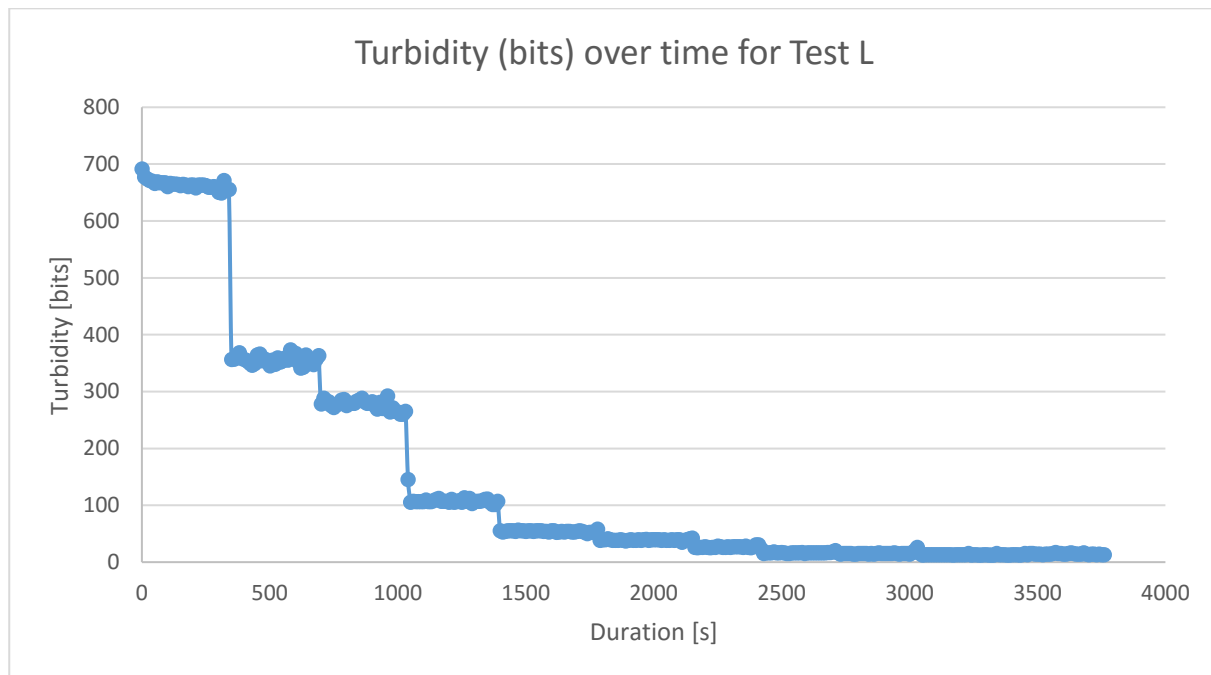


H12: Test L

Test details:

- Date of test: 15/09/2016
- Material being tested: Silica in salt water
- Sensor being tested: 2
- Start time of 150g/L test: 1:43pm
- Start time of mixing test: 1:53pm

Raw data measured by turbidity sensor:



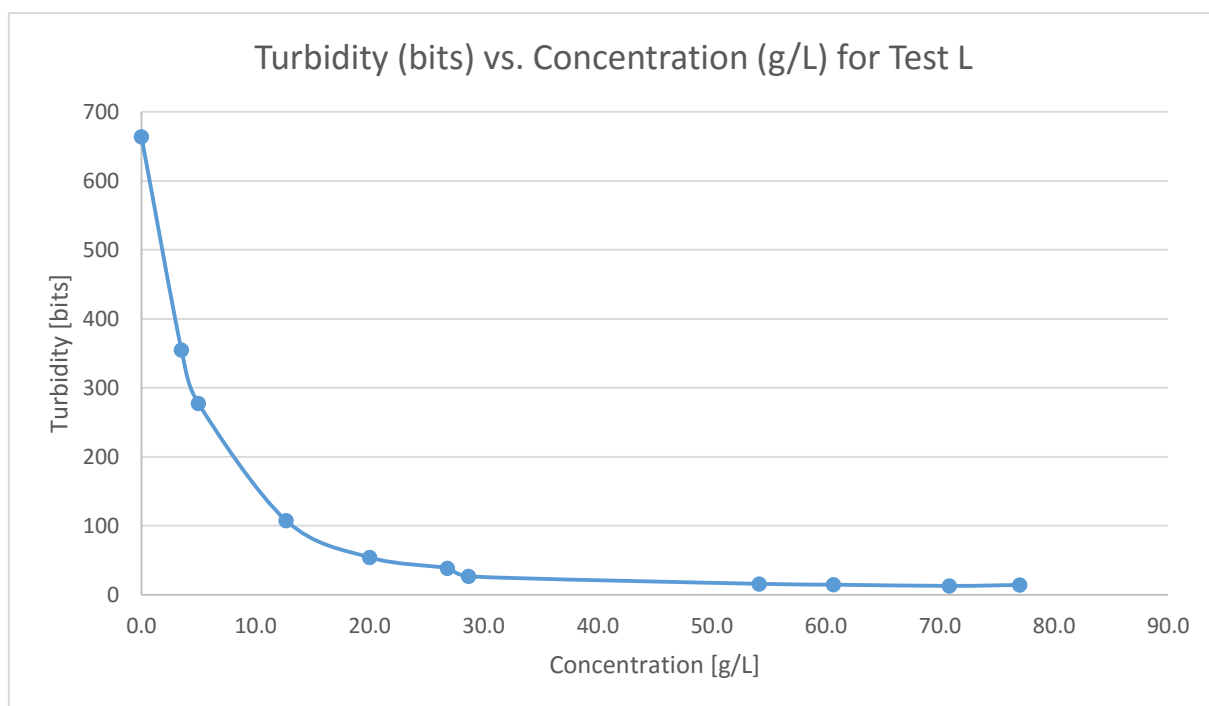
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	664
2	354 – 660	400 – 650	355
3	705 – 1020	750 – 1000	277
4	1061 – 1380	1100 – 1350	108
5	1420 – 1740	1450 – 1700	54
6	1781 – 2100	1800 – 2050	39
7	2153 – 2460	2200 – 2400	27
8	2516 – 2820	2550 – 2800	16
9	2876 – 3180	2950 – 3150	15
10	3248 – 3460	3300 – 3450	13
11	3470 – 3760	3500 – 3750	14

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.46	9.55	0.09	0.10	0.0
2	9.60	9.77	0.17	0.10	3.5
3	9.50	9.70	0.20	0.10	5.0
4	9.59	9.94	0.35	0.10	12.7
5	9.51	10.01	0.50	0.10	20.0
6	9.59	10.22	0.64	0.10	26.8
7	9.58	10.25	0.67	0.10	28.7
8	9.68	10.86	1.18	0.10	54.2
9	9.75	11.06	1.31	0.10	60.7
10	9.76	11.27	1.52	0.10	70.8
11	9.68	11.32	1.64	0.10	77.0

Plot of turbidity data vs. concentration:

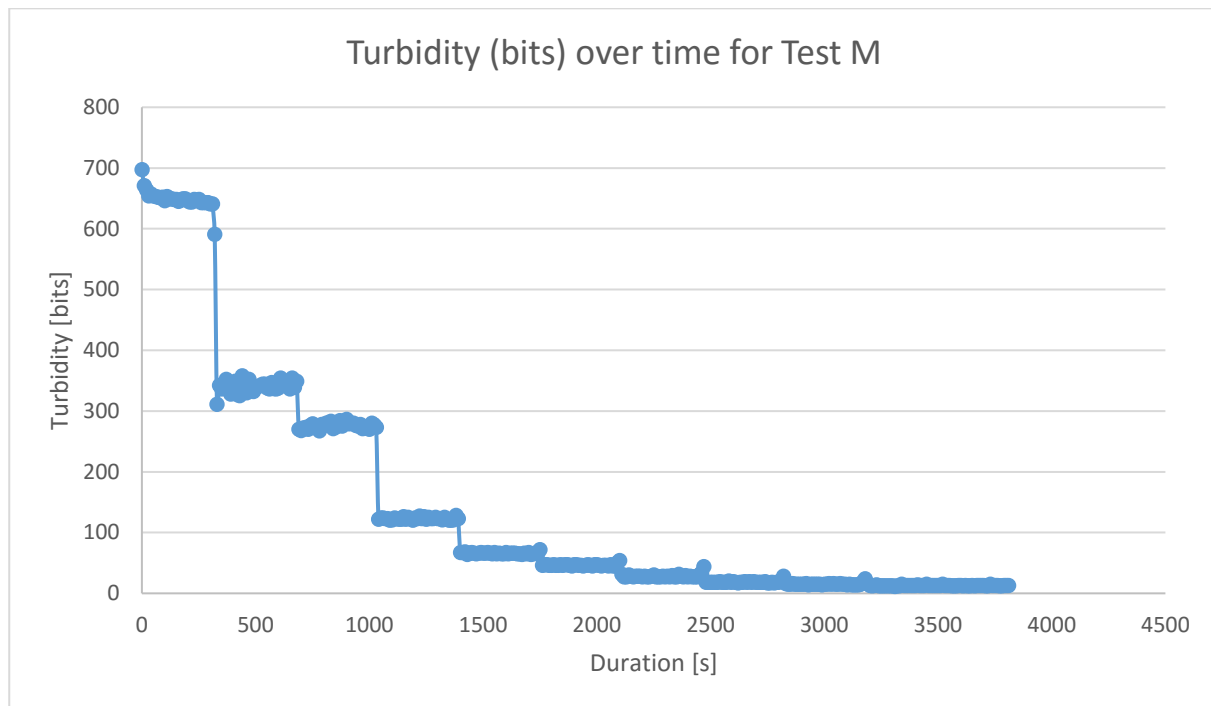


H13: Test M

Test details:

- Date of test: 27/09/2016
- Material being tested: Silica in salt water
- Sensor being tested: 3
- Start time of 150g/L test: 1:51pm
- Start time of mixing test: 2:00pm

Raw data measured by turbidity sensor:



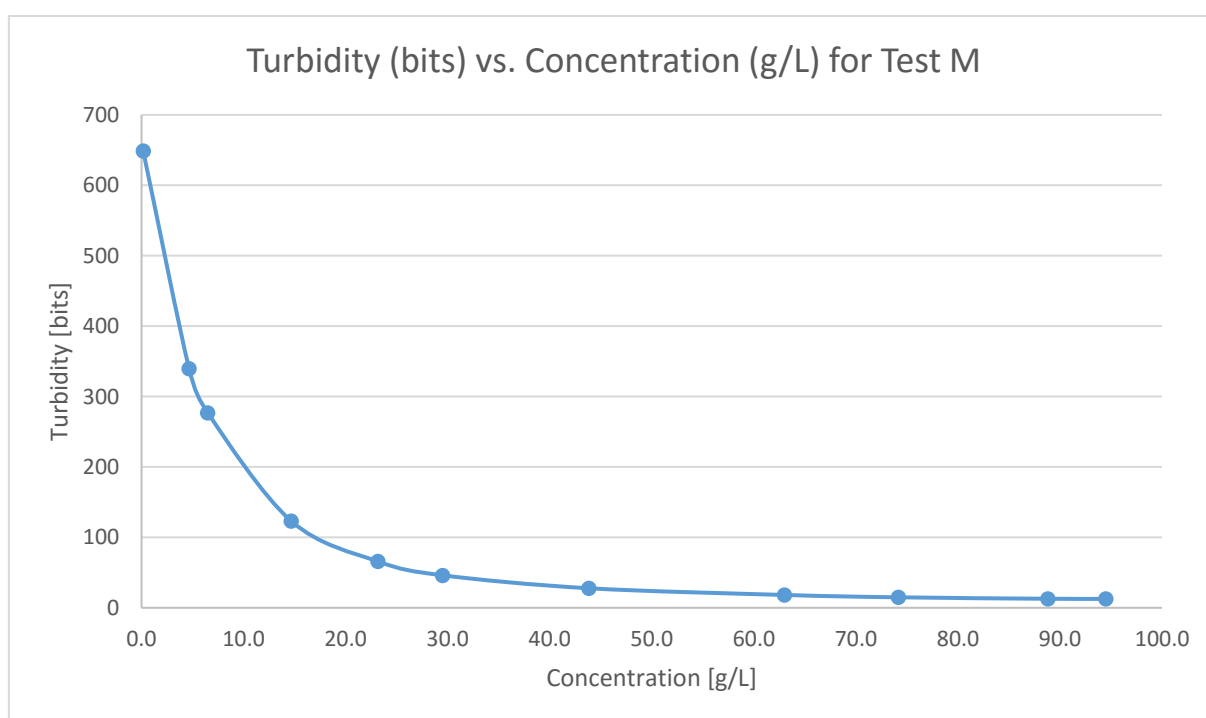
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	649
2	337 – 660	350 – 600	339
3	698 – 1020	750 – 1000	277
4	1050 – 1380	1100 – 1350	123
5	1413 – 1740	1450 – 1700	66
6	1772 – 2100	1800 – 2050	46
7	2139 – 2460	2200 – 2400	28
8	2503 – 2820	2550 – 2750	18
9	2855 – 3180	2900 – 3150	15
10	3226 – 3510	3250 – 3500	13
11	3520 – 3810	3550 – 3800	13

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.76	9.86	0.10	0.10	0.2
2	9.57	9.76	0.19	0.10	4.7
3	9.50	9.73	0.23	0.10	6.5
4	9.67	10.06	0.39	0.10	14.7
5	9.47	10.03	0.56	0.10	23.2
6	9.48	10.17	0.69	0.10	29.5
7	9.74	10.72	0.98	0.10	43.8
8	9.67	11.03	1.36	0.10	63.0
9	9.66	11.25	1.58	0.10	74.2
10	9.55	11.42	1.88	0.10	88.8
11	9.57	11.56	1.99	0.10	94.5

Plot of turbidity data vs. concentration:

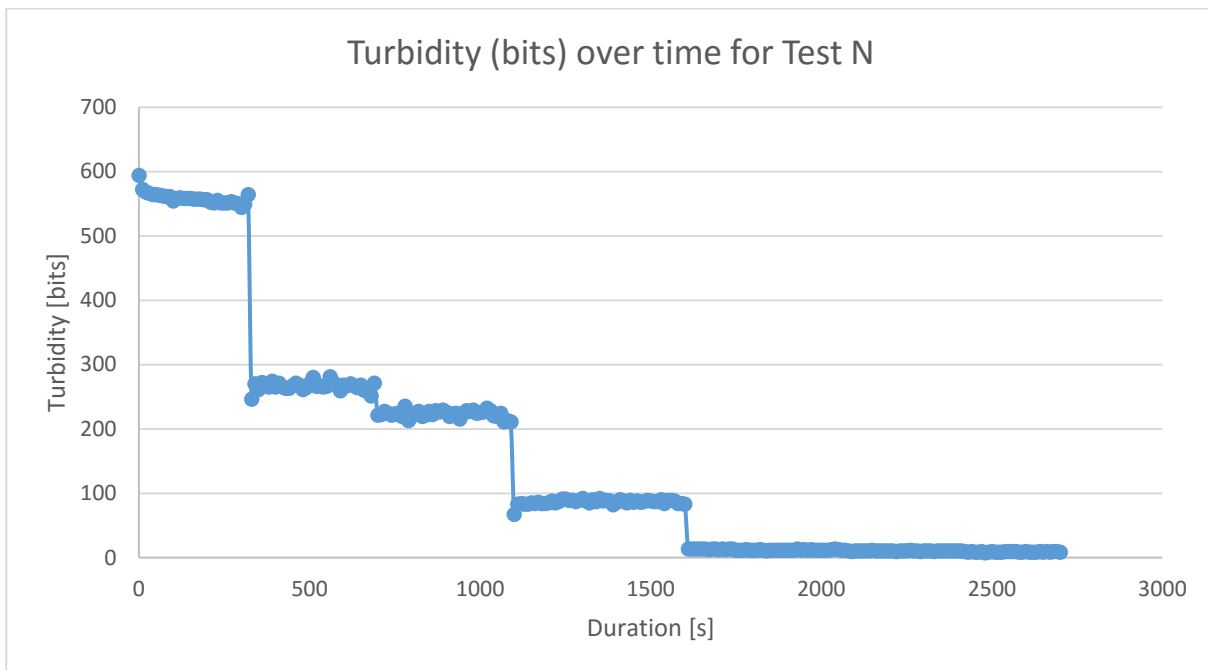


H14: Test N

Test details:

- Date of test: 28/09/2016
- Material being tested: Silica in salt water
- Sensor being tested: 4
- Start time of 150g/L test: 5:25pm
- Start time of mixing test: 5:39pm

Raw data measured by turbidity sensor:



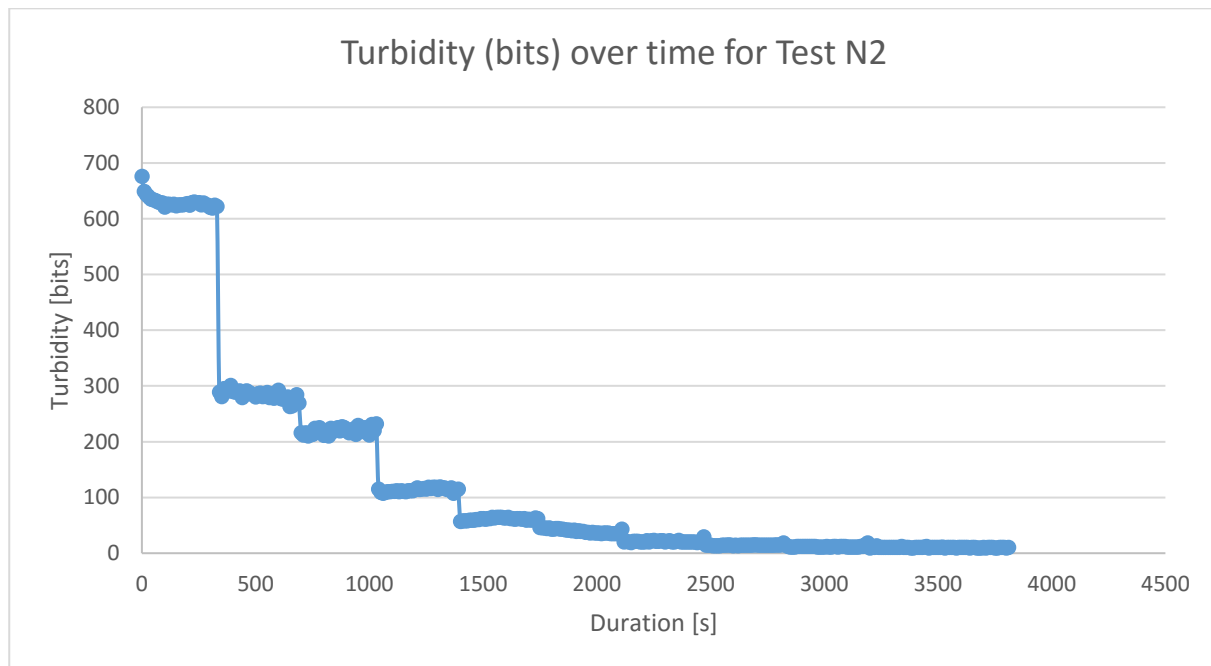
Test abandoned due to significant loss of data observed – only 6 steps in the graph while 11 are expected.

H15: Test N2

Test details:

- Date of test: 29/09/2016
- Material being tested: Silica in salt water
- Sensor being tested: 4
- Start time of 150g/L test: 12:38pm
- Start time of mixing test: 12:48pm

Raw data measured by turbidity sensor:



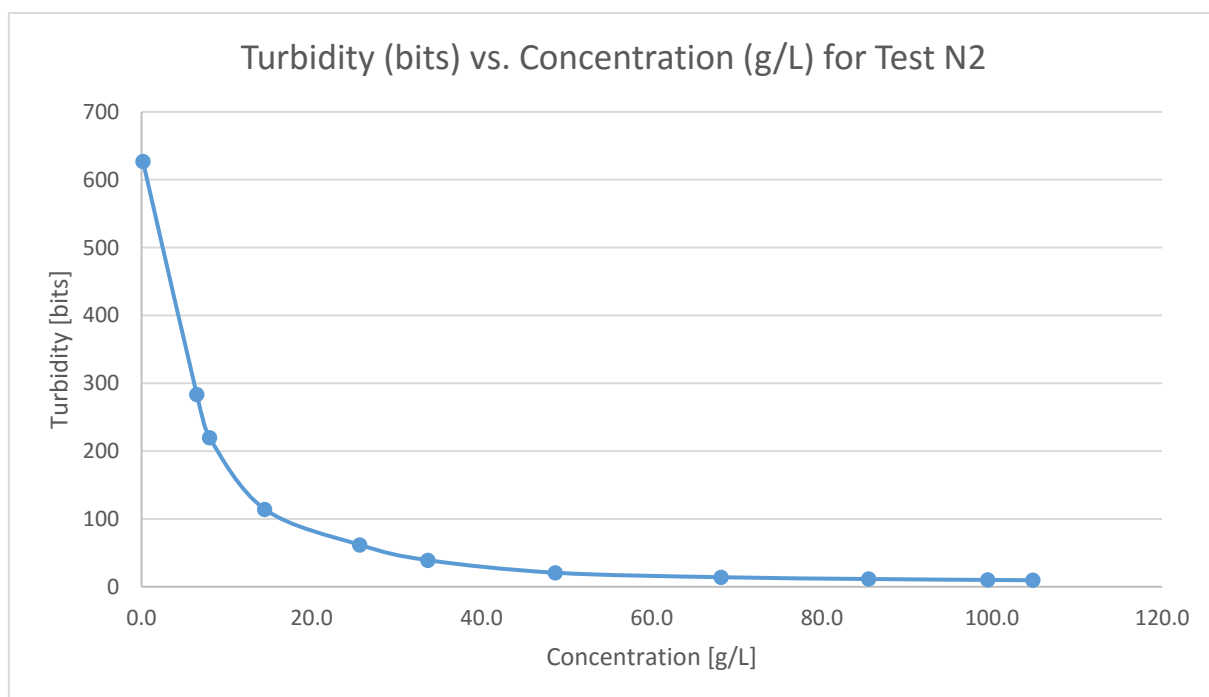
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	627
2	341 – 660	400 – 650	284
3	700 – 1020	750 – 1000	220
4	1054 – 1380	1100 – 1350	114
5	1412 – 1740	1450 – 1700	62
6	1766 – 2100	1800 – 2050	39
7	2136 – 2460	2200 – 2450	21
8	2502 – 2820	2550 – 2800	14
9	2859 – 3180	2900 – 3150	12
10	3229 – 3510	3300 – 3500	10
11	3520 – 3810	3550 – 3800	10

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.68	9.78	0.10	0.10	0.2
2	9.48	9.71	0.23	0.10	6.5
3	9.56	9.82	0.26	0.10	8.0
4	9.74	10.13	0.39	0.10	14.5
5	9.51	10.12	0.61	0.10	25.7
6	9.67	10.44	0.77	0.10	33.7
7	9.75	10.82	1.07	0.10	48.7
8	9.57	11.03	1.46	0.10	68.2
9	9.57	11.38	1.81	0.10	85.5
10	9.67	11.76	2.09	0.10	99.5
11	9.48	11.67	2.20	0.10	104.8

Plot of turbidity data vs. concentration:

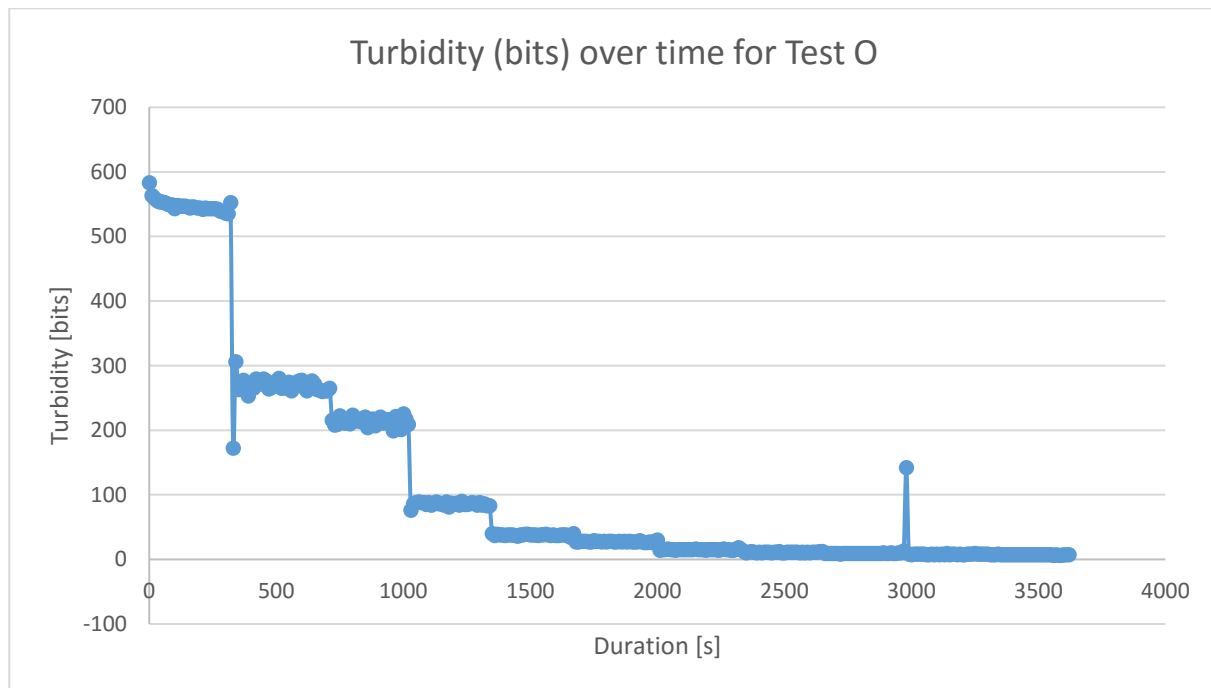


H16: Test O

Test details:

- Date of test: 30/09/2016
- Material being tested: Silica in salt water
- Sensor being tested: 5
- Start time of 150g/L test: 3:44pm
- Start time of mixing test: 3:55pm

Raw data measured by turbidity sensor:



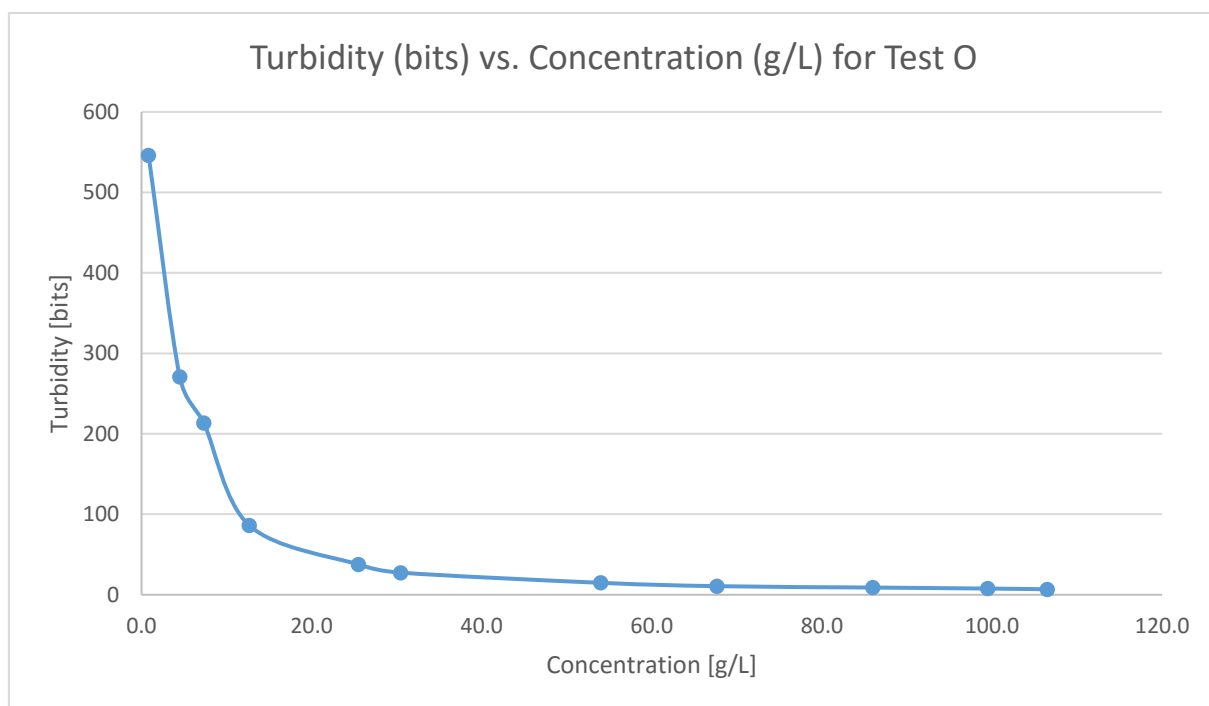
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	546
2	337 – 660	400 – 650	271
3	692 – 1020	800 – 1000	213
4	1042 – 1380	1100 – 1300	86
5	1402 – 1740	1450 – 1650	38
6	1764 – 2100	1750 – 1950	28
7	2137 – 2460	2050 – 2300	15
8	2508 – 2820	2400 – 2600	11
9	2865 – 3180	2700 – 2900	9
10	3234 – 3320	3050 – 3300	8
11	3330 – 3620	3350 – 3600	7

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.48	9.60	0.12	0.10	0.8
2	9.57	9.76	0.19	0.10	4.5
3	9.55	9.80	0.25	0.10	7.3
4	9.42	9.77	0.35	0.10	12.7
5	9.57	10.18	0.61	0.10	25.5
6	9.46	10.17	0.71	0.10	30.5
7	9.72	10.90	1.18	0.10	54.0
8	9.58	11.04	1.45	0.10	67.7
9	9.55	11.37	1.82	0.10	86.0
10	9.72	11.81	2.09	0.10	99.5
11	9.66	11.89	2.23	0.10	106.5

Plot of turbidity data vs. concentration:

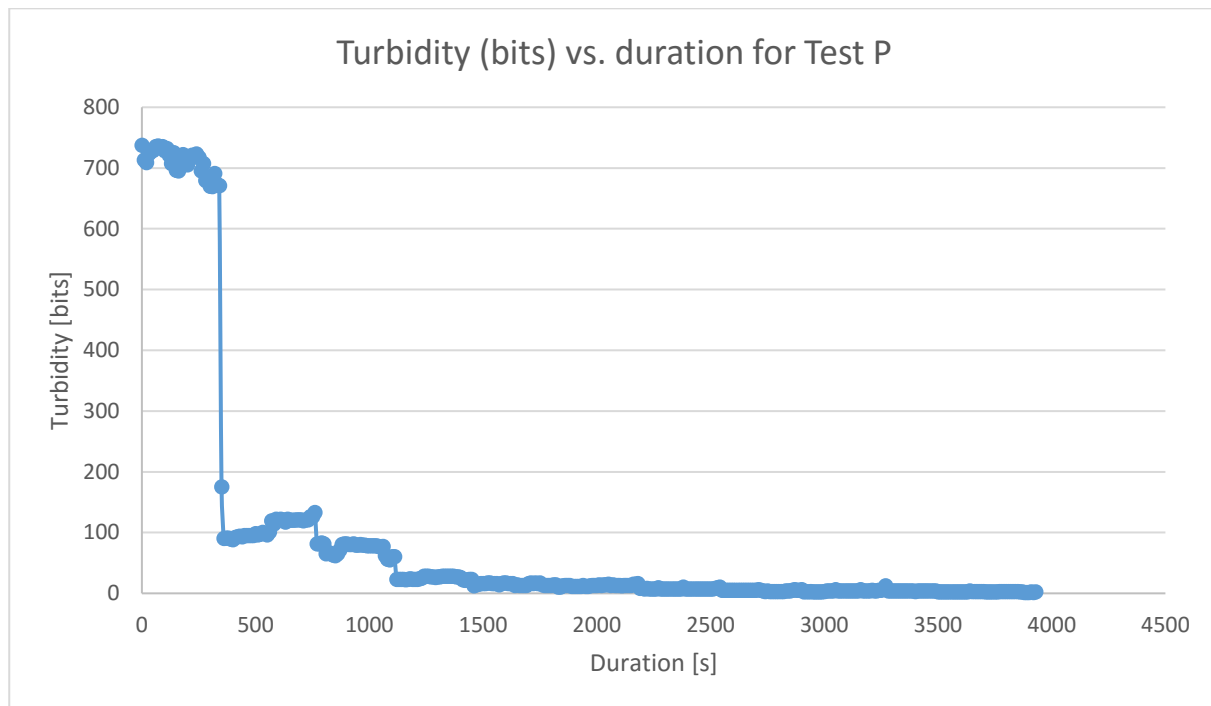


H17: Test P

Test details:

- Date of test: 13/09/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 1
- Start time of 150g/L test: 10:45am
- Start time of mixing test: 11:09am

Raw data measured by turbidity sensor:



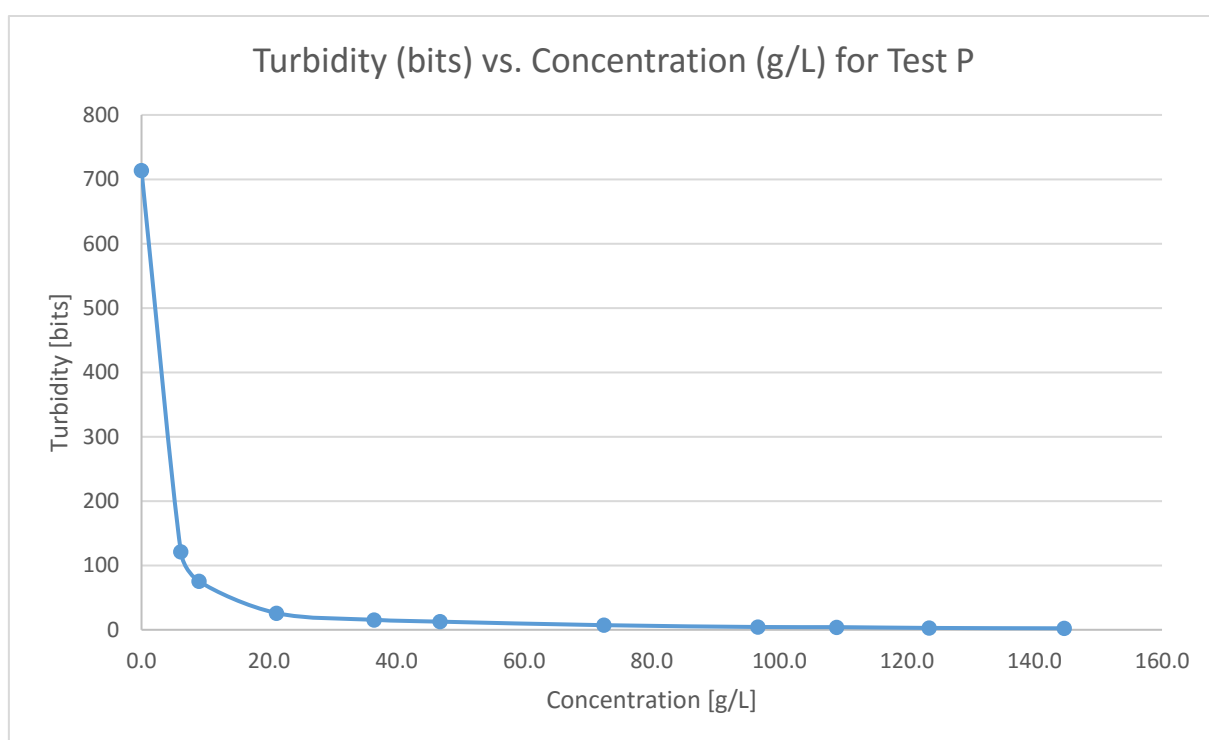
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 300	713
2	364 – 720	600 – 750	121
3	775 – 1080	800 – 1050	75
4	1129 – 1440	1150 – 1400	26
5	1481 – 1800	1500 – 1750	16
6	1844 – 2160	1900 – 2100	13
7	2209 – 2520	2250 – 2500	7
8	2572 – 2880	2600 – 2800	4
9	2929 – 3240	3000 – 3200	4
10	3312 – 3630	3400 – 3600	3
11	3640 – 3930	3700 – 3900	2

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.60	9.70	0.10	0.10	0.0
2	9.51	9.73	0.22	0.10	6.0
3	9.51	9.79	0.28	0.10	9.0
4	9.70	10.23	0.53	0.10	21.5
5	9.56	10.39	0.83	0.10	36.5
6	9.53	10.56	1.03	0.10	46.5
7	9.61	11.16	1.55	0.10	72.5
8	9.49	11.53	2.04	0.10	97.0
9	9.77	12.05	2.28	0.10	109.0
10	9.59	12.16	2.57	0.10	123.5
11	9.53	12.52	2.99	0.10	144.5

Plot of turbidity data vs. concentration:

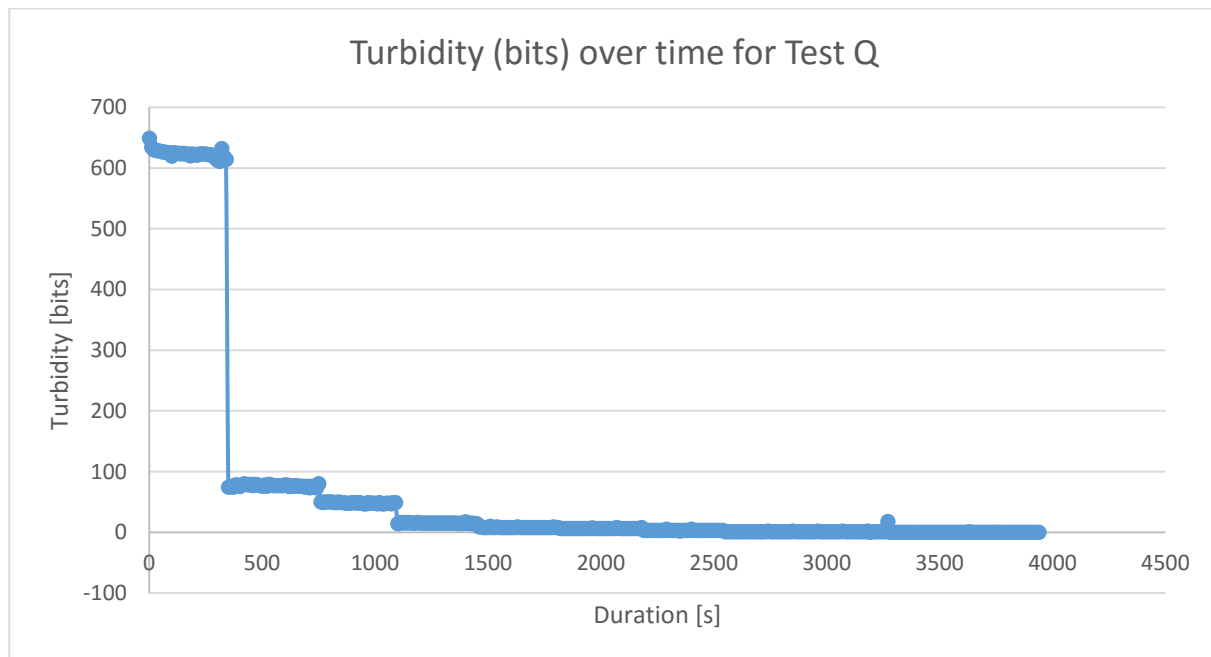


H18: Test Q

Test details:

- Date of test: 15/09/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 2
- Start time of 150g/L test: 3:20pm
- Start time of mixing test: 3:30pm

Raw data measured by turbidity sensor:



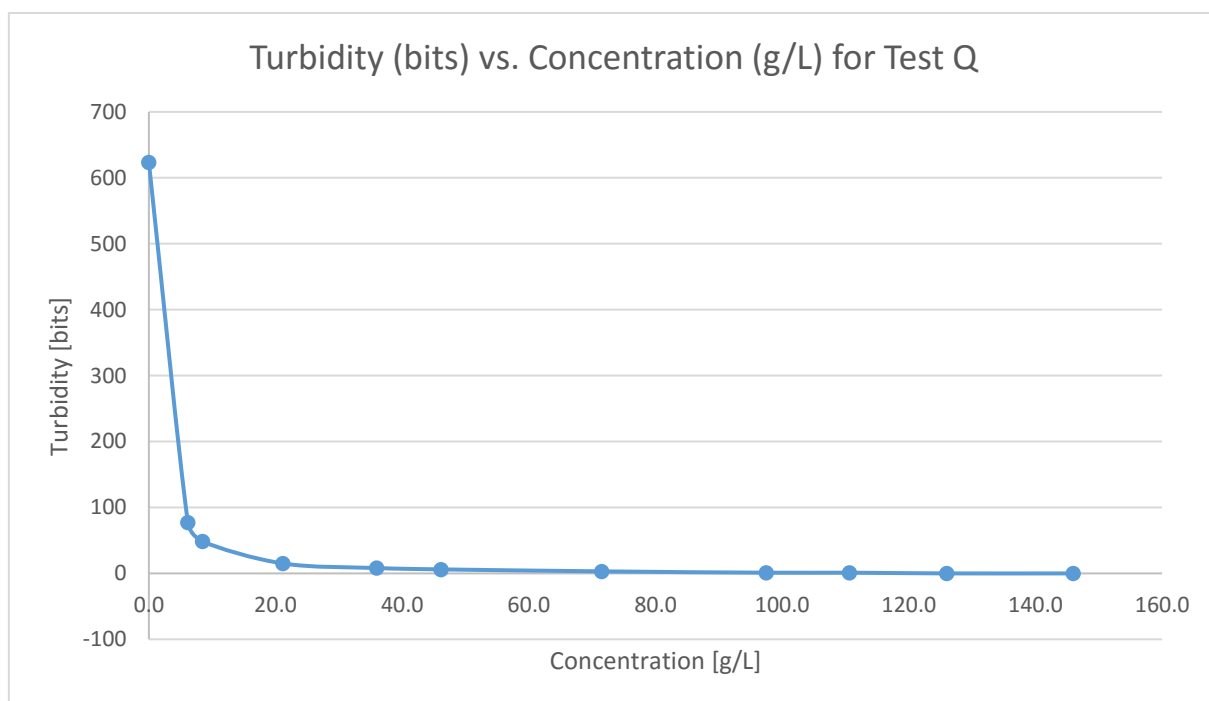
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	623
2	353 – 720	400 – 700	77
3	769 – 1080	800 – 1050	48
4	1114 – 1440	1150 – 1400	15
5	1477 – 1800	1500 – 1750	8
6	1838 – 2160	1850 – 2150	6
7	2215 – 2520	2250 – 2500	3
8	2576 – 2880	2600 – 2850	1
9	2937 – 3240	2950 – 3200	1
10	3313 – 3630	3350 – 3600	0
11	3640 – 3940	3650 – 3900	0

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.50	9.59	0.10	0.10	0.0
2	9.74	9.97	0.22	0.10	6.2
3	9.65	9.92	0.27	0.10	8.5
4	9.78	10.31	0.52	0.10	21.2
5	9.78	10.60	0.82	0.10	36.0
6	9.83	10.85	1.02	0.10	46.2
7	9.60	11.13	1.53	0.10	71.5
8	9.66	11.71	2.05	0.10	97.5
9	9.69	12.00	2.31	0.10	110.7
10	9.77	12.39	2.62	0.10	126.0
11	9.65	12.67	3.02	0.10	146.0

Plot of turbidity data vs. concentration:

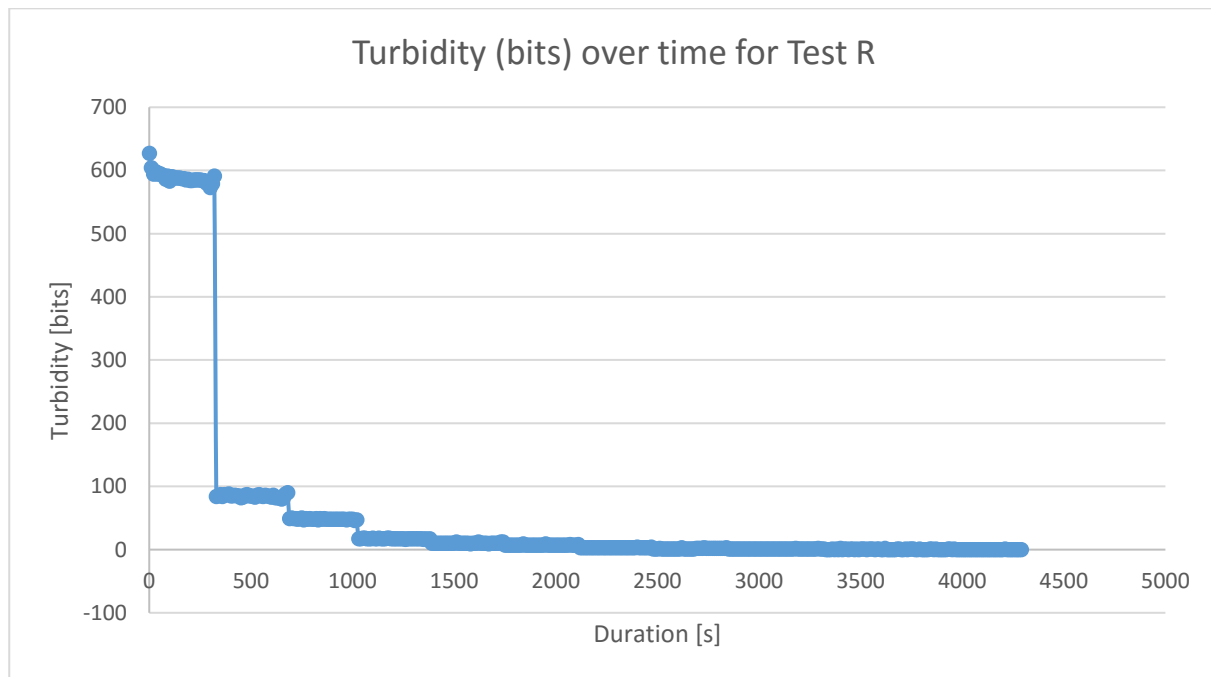


H19: Test R

Test details:

- Date of test: 27/09/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 3
- Start time of 150g/L test: 3:55pm
- Start time of mixing test: 4:05pm

Raw data measured by turbidity sensor:



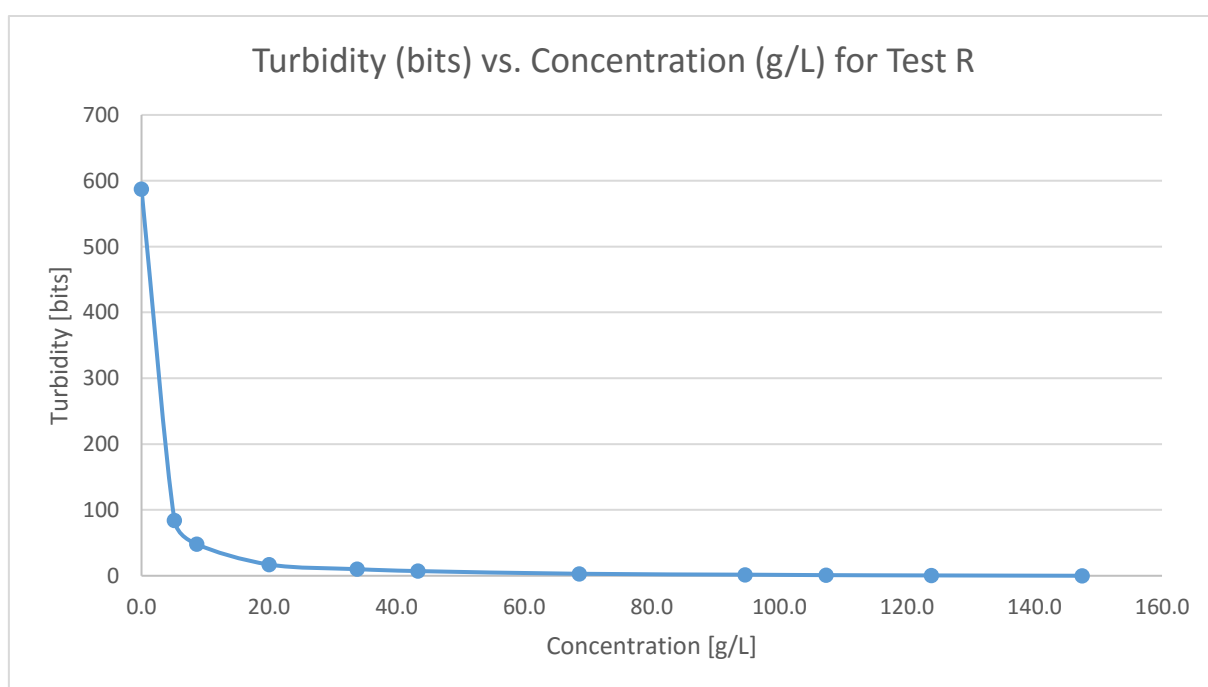
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	587
2	329 – 660	400 – 650	84
3	692 – 1020	750 – 1000	48
4	1041 – 1380	1100 – 1350	17
5	1402 – 1740	1450 – 1700	10
6	1765 – 2100	1800 – 2050	7
7	2133 – 2460	2200 – 2400	3
8	2505 – 2820	2600 – 2800	2
9	2856 – 3180	2900 – 3150	1
10	3227 – 3980	3400 – 3900	1
11	3990 – 4290	4000 – 4250	0

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.59	9.69	0.10	0.10	0.0
2	9.41	9.62	0.20	0.10	5.2
3	9.65	9.92	0.27	0.10	8.7
4	9.59	10.09	0.50	0.10	20.0
5	9.47	10.24	0.78	0.10	33.8
6	9.56	10.53	0.97	0.10	43.3
7	9.56	11.03	1.47	0.10	68.7
8	9.48	11.48	1.99	0.10	94.7
9	9.69	11.94	2.25	0.10	107.3
10	9.49	12.06	2.58	0.10	123.8
11	9.56	12.61	3.05	0.10	147.5

Plot of turbidity data vs. concentration:

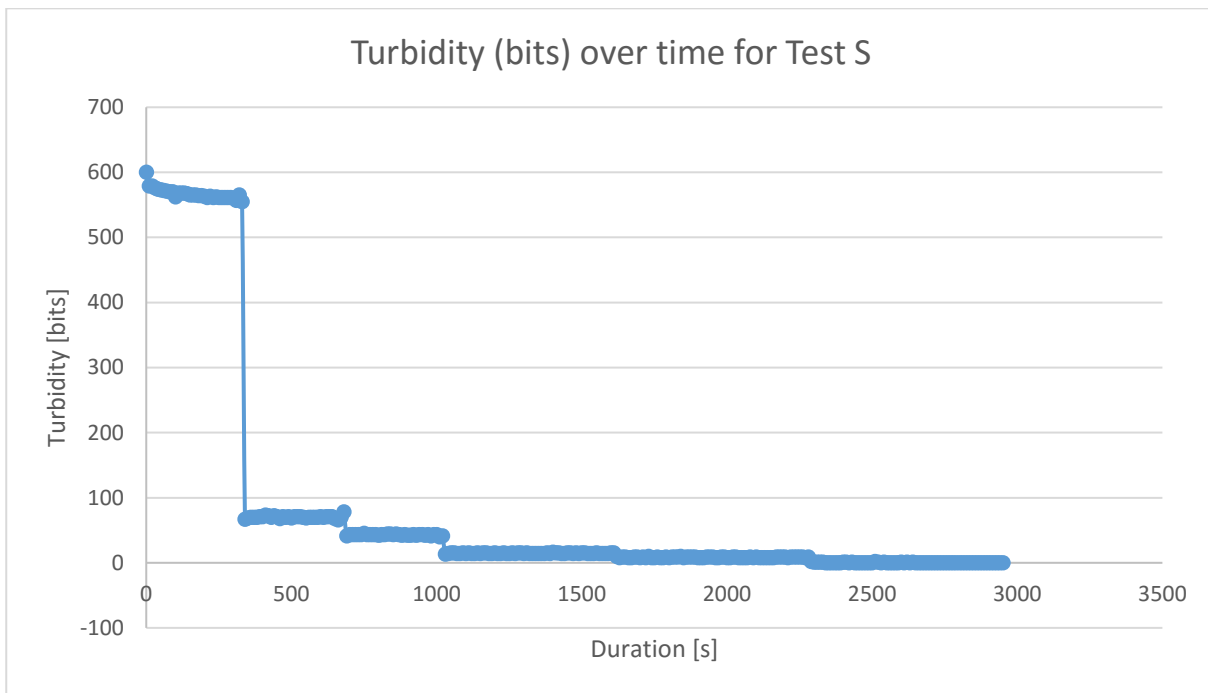


H20: Test S

Test details:

- Date of test: 29/09/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 4
- Start time of 150g/L test: 2:09pm
- Start time of mixing test: 2:20pm

Raw data measured by turbidity sensor:



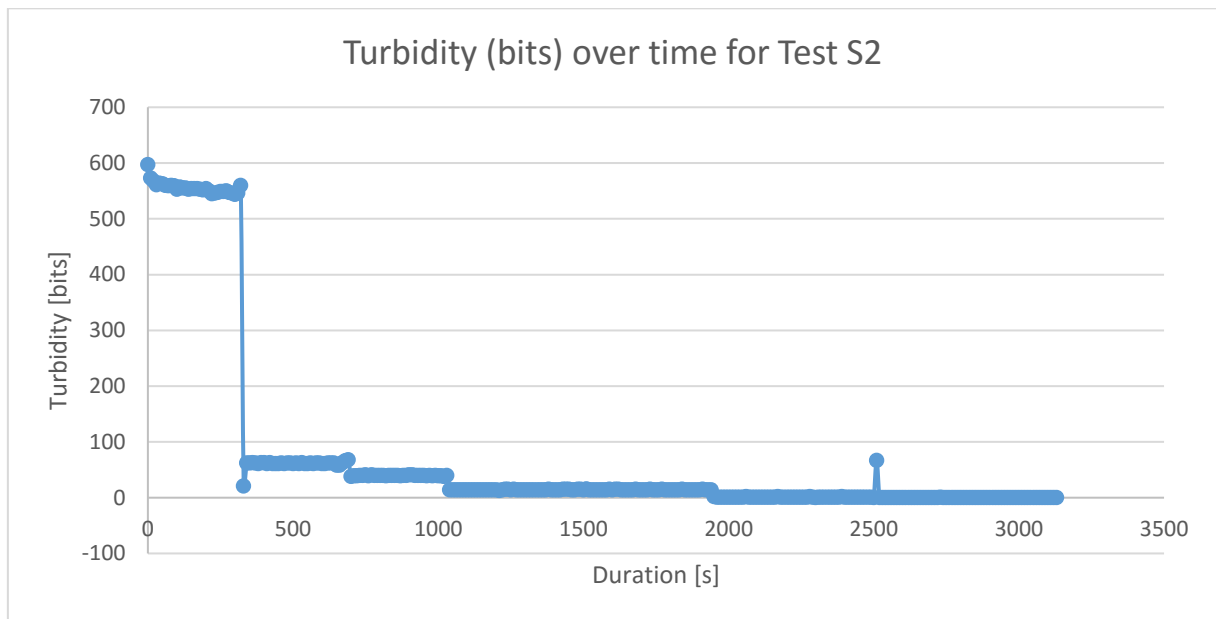
Test abandoned due to significant loss of data observed – only 6 steps in the graph while 11 are expected.

H21: Test S2

Test details:

- Date of test: 29/09/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 4
- Start time of 150g/L test: 4:52pm
- Start time of mixing test: 5:08pm

Raw data measured by turbidity sensor:



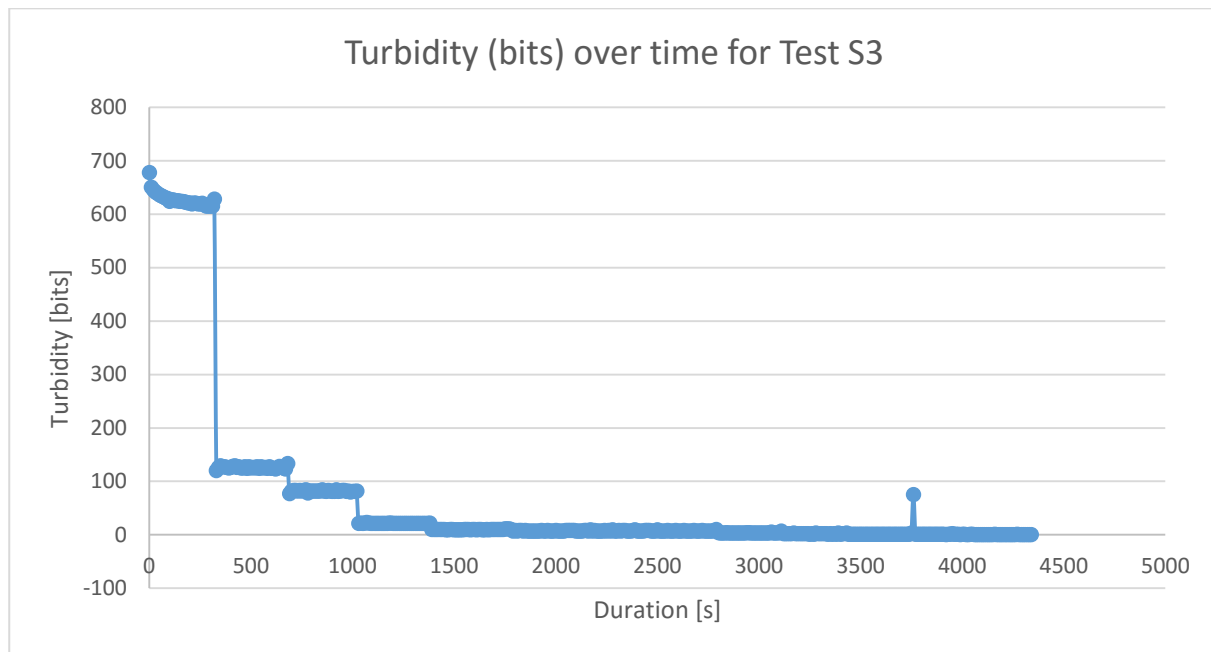
Test abandoned due to significant loss of data observed – only 7 steps in the graph while 11 are expected.

H22: Test S3

Test details:

- Date of test: 01/10/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 4
- Start time of 150g/L test: 1:34pm
- Start time of mixing test: 1:47pm

Raw data measured by turbidity sensor:



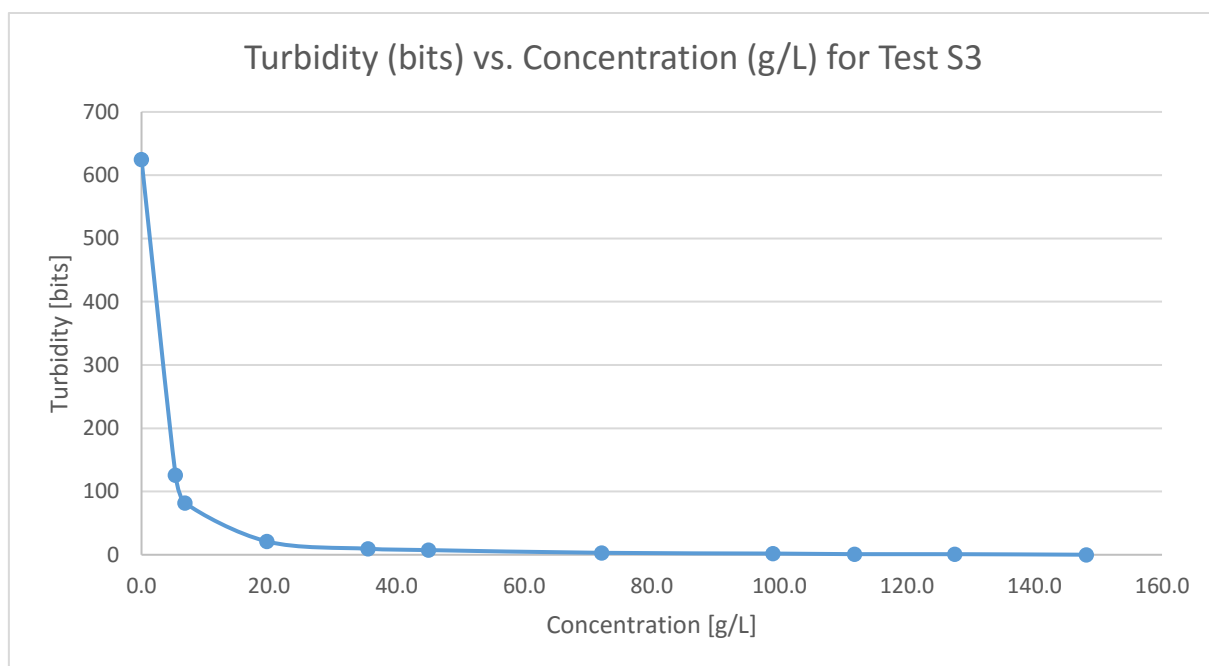
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	625
2	334 – 660	400 – 650	126
3	698 – 1020	750 – 1000	82
4	1042 – 1380	1100 – 1350	21
5	1402 – 1740	1450 – 1700	10
6	1764 – 2100	1850 – 2700	7
7	2141 – 2460	2850 – 3050	3
8	2500 – 2820	3150 – 3350	2
9	2857 – 3180	3450 – 3700	1
10	3222 – 4040	3800 – 4000	1
11	4050 – 4340	4100 – 4300	0

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.50	9.60	0.10	0.10	0.0
2	9.56	9.77	0.21	0.10	5.3
3	9.59	9.83	0.24	0.10	6.8
4	9.56	10.06	0.49	0.10	19.7
5	9.76	10.57	0.81	0.10	35.5
6	9.49	10.49	1.00	0.10	45.0
7	9.68	11.22	1.54	0.10	72.2
8	9.67	11.75	2.08	0.10	99.0
9	9.67	12.01	2.34	0.10	111.8
10	9.49	12.14	2.65	0.10	127.5
11	9.75	12.81	3.06	0.10	148.2

Plot of turbidity data vs. concentration:

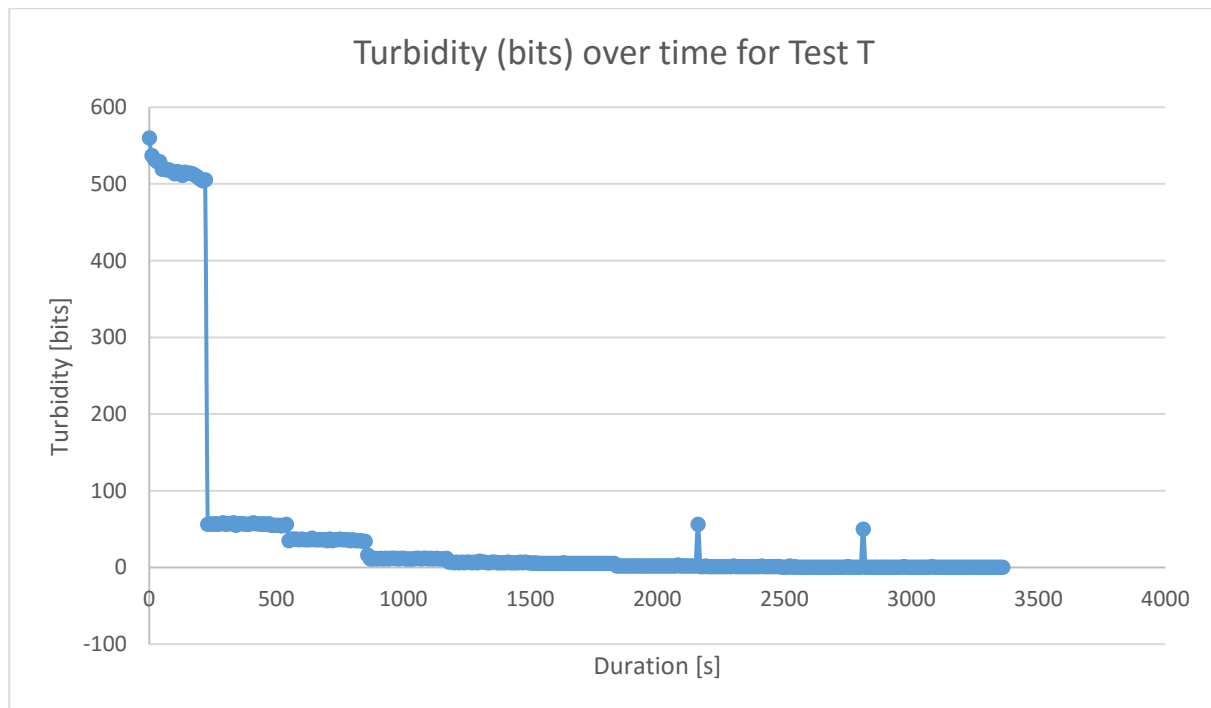


H23: Test T

Test details:

- Date of test: 30/09/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 5
- Start time of 150g/L test: 5:03pm
- Start time of mixing test: 5:14pm

Raw data measured by turbidity sensor:



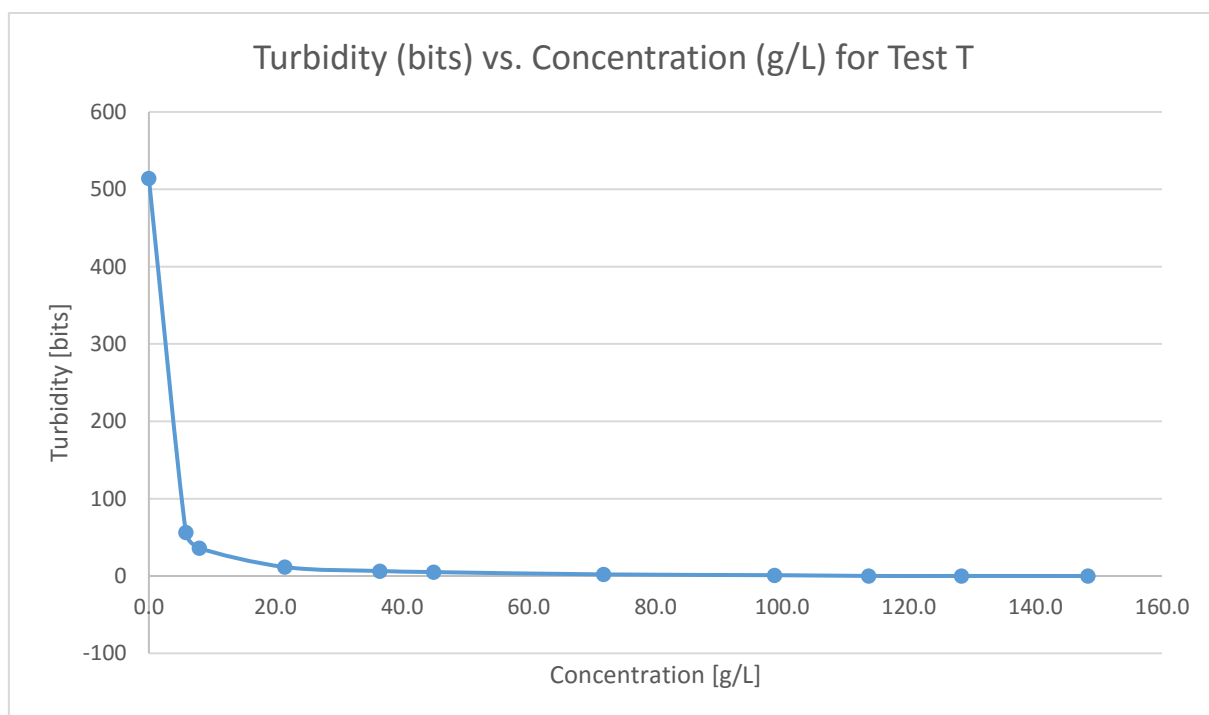
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 200	514
2	333 – 660	250 – 500	57
3	689 - 1020	600 – 800	36
4	1046 – 1380	900 – 1150	12
5	1401 – 1740	1200 – 1450	6
6	1760 – 2100	1550 – 1800	5
7	2132 – 2460	1900 – 2100	2
8	2502 – 2820	2200 – 2450	1
9	2859 – 3180	2550 – 2750	0
10	3230 – 3090	2850 – 3050	0
11	3100 – 3360	3150 – 3350	0

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.57	9.66	0.09	0.10	0.0
2	9.69	9.91	0.22	0.10	5.8
3	9.49	9.75	0.26	0.10	8.0
4	9.43	9.96	0.53	0.10	21.5
5	9.66	10.49	0.83	0.10	36.5
6	9.59	10.59	1.00	0.10	45.0
7	9.55	11.09	1.54	0.10	71.8
8	9.49	11.56	2.08	0.10	98.8
9	9.58	11.95	2.37	0.10	113.7
10	9.60	12.27	2.67	0.10	128.3
11	9.47	12.54	3.07	0.10	148.3

Plot of turbidity data vs. concentration:

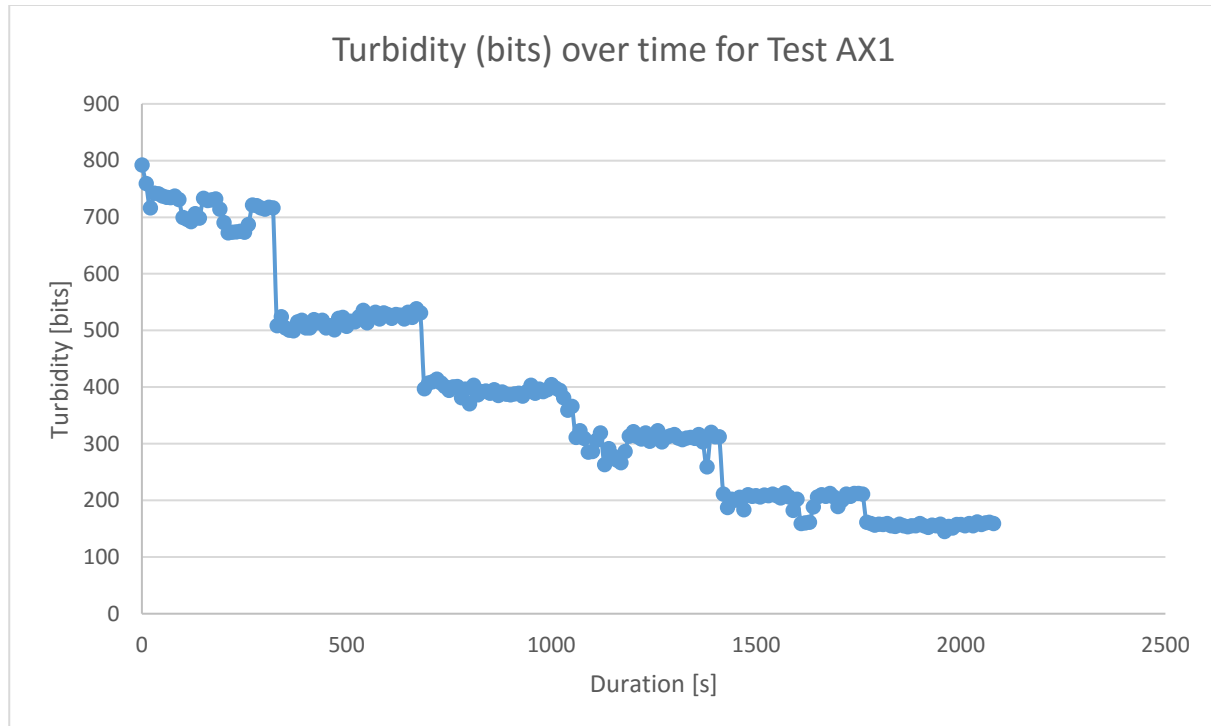


H24: Test AX1

Test details:

- Date of test: 22/09/2016
- Material being tested: Silica in tap water
- Sensor being tested: 1
- Start time of mixing test: 11:56am

Raw data measured by turbidity sensor:



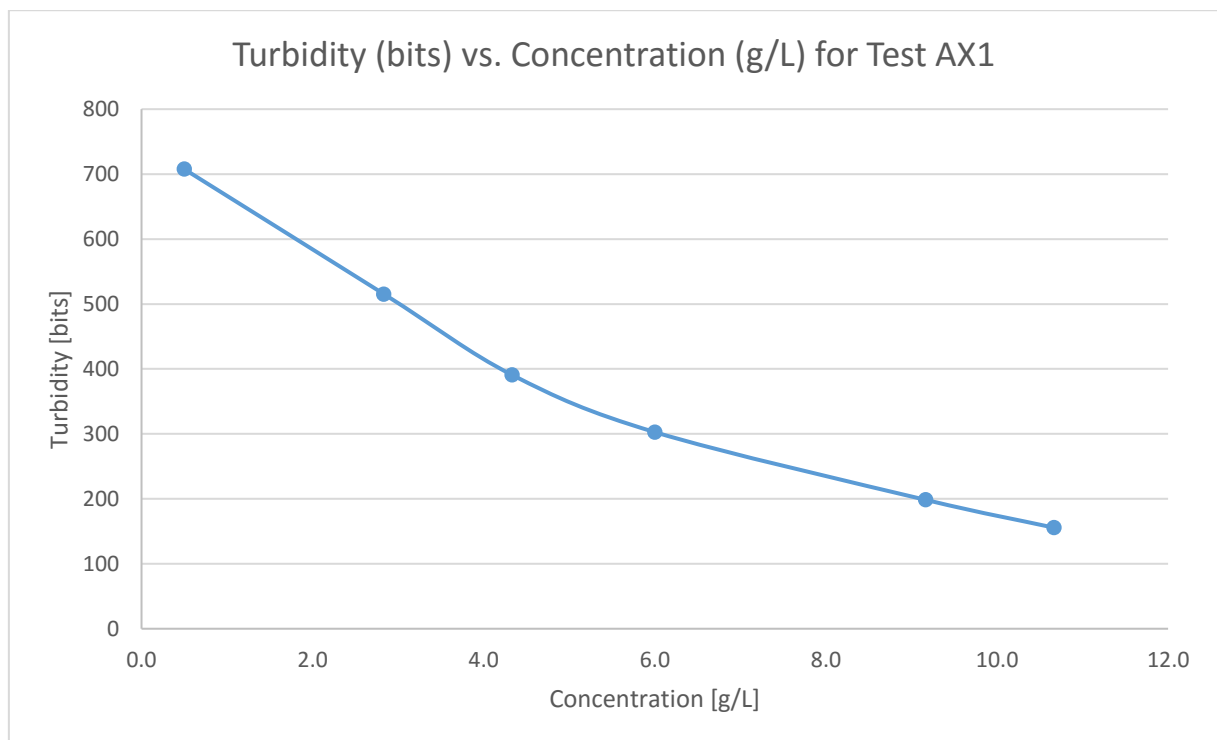
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	708
2	334 – 660	350 – 600	515
3	693 – 1020	750 – 950	391
4	1065 – 1380	1100 – 1350	303
5	1429 – 1740	1450 – 1700	198
6	1788 – 2080	1800 – 2050	156

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	15.93	15.94	0.01	0.5
2	15.66	15.72	0.06	2.8
3	14.02	14.11	0.09	4.3
4	14.30	14.42	0.12	6.0
5	15.66	15.84	0.18	9.2
6	16.27	16.48	0.21	10.7

Plot of turbidity data vs. concentration:

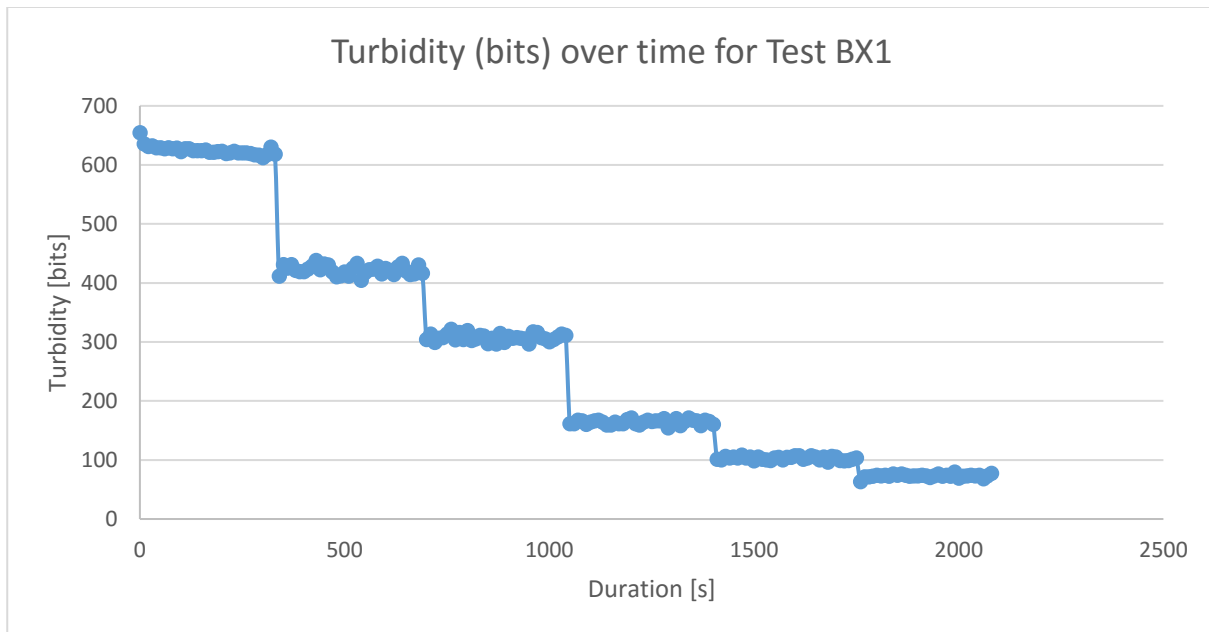


H25: Test BX1

Test details:

- Date of test: 22/09/2016
- Material being tested: Silica in tap water
- Sensor being tested: 2
- Start time of mixing test: 5:02pm

Raw data measured by turbidity sensor:



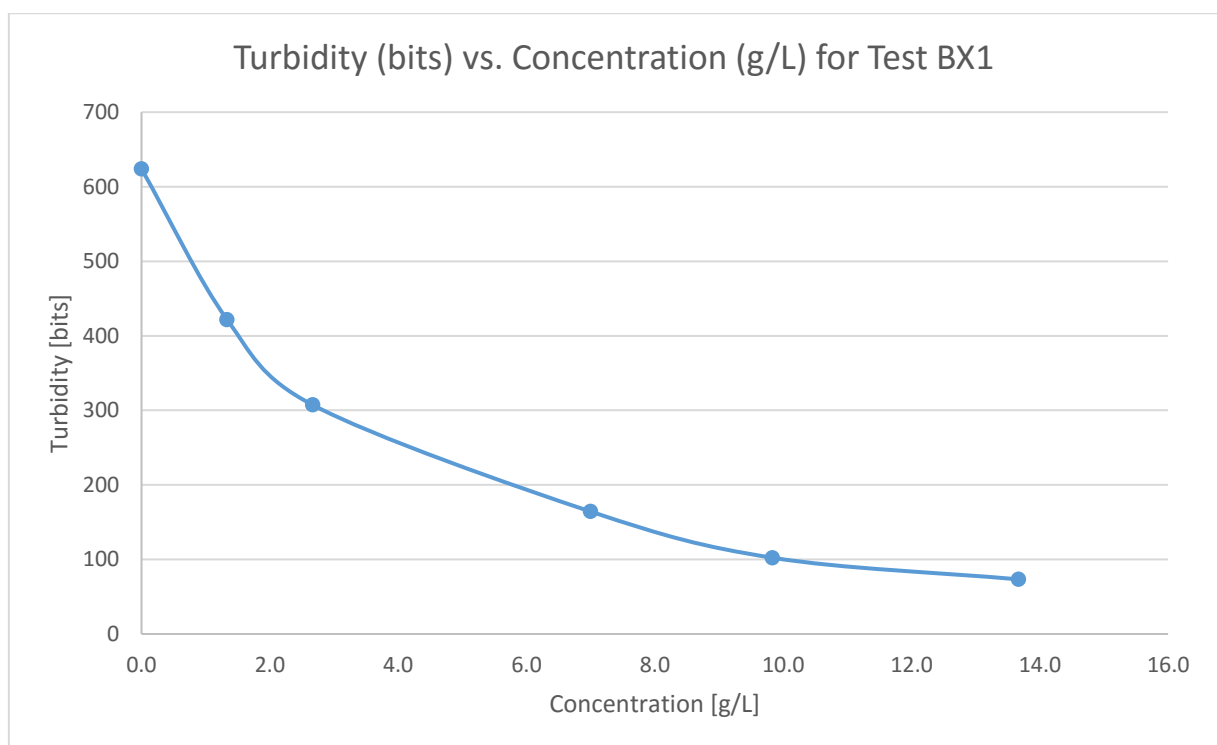
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	624
2	342 – 660	400 – 650	422
3	699 – 1020	750 – 1000	307
4	1055 – 1380	1100 – 1350	164
5	1417 – 1760	1500 – 1750	102
6	1802 – 2080	1850 – 2050	73

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	13.36	13.36	0.00	0.0
2	14.90	14.93	0.03	1.3
3	14.36	14.41	0.05	2.7
4	20.96	21.09	0.14	7.0
5	13.44	13.64	0.20	9.8
6	15.49	15.75	0.27	13.7

Plot of turbidity data vs. concentration:

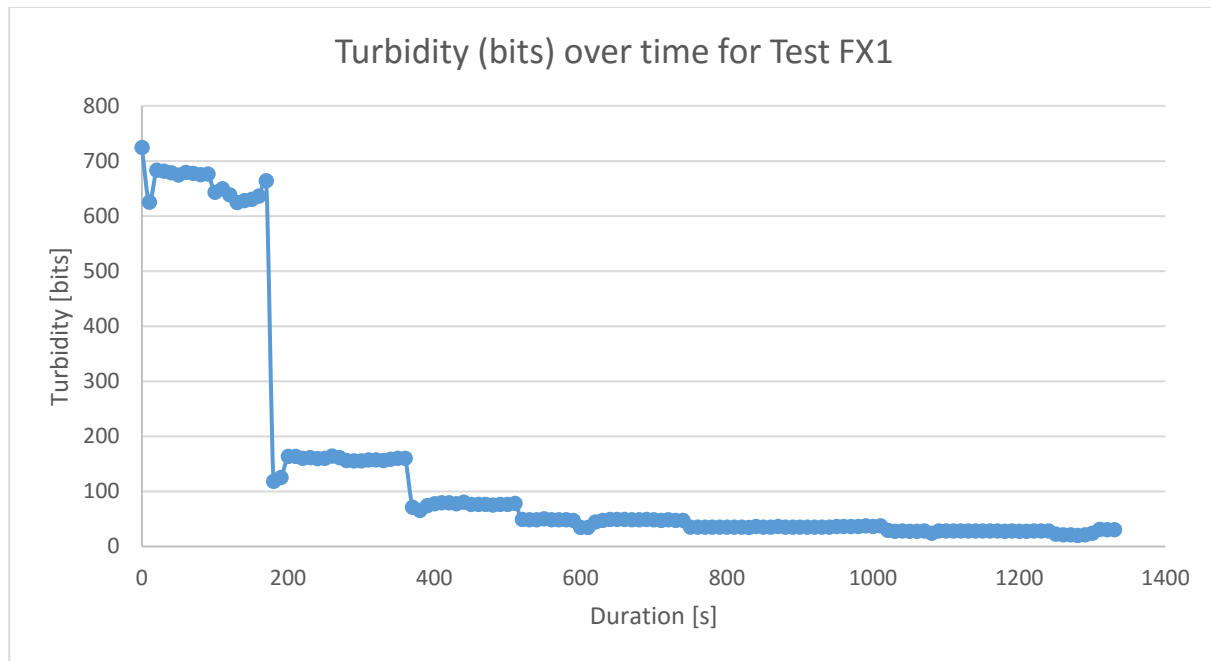


H26: Test FX1

Test details:

- Date of test: 22/09/2016
- Material being tested: Kaolin in tap water
- Sensor being tested: 1
- Start time of mixing test: 12:40pm

Raw data measured by turbidity sensor:



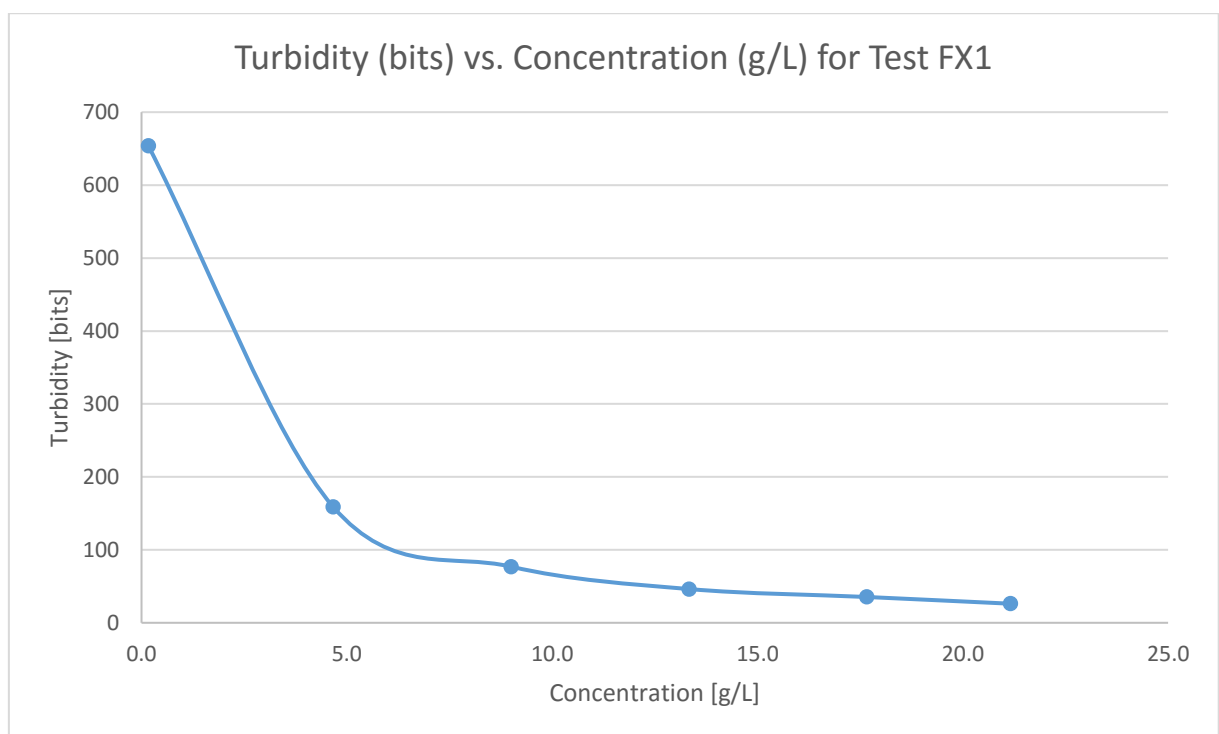
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 150	654
2	342 – 660	200 – 350	159
3	701 – 1020	400 – 500	77
4	1057 – 1380	550 – 700	46
5	1419 – 1740	800 – 1000	35
6	1780 – 2100	1050 – 1300	26

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	15.91	15.90	0.00	0.2
2	14.13	14.21	0.09	4.7
3	18.38	18.56	0.18	9.0
4	15.26	15.53	0.27	13.3
5	16.49	16.84	0.35	17.7
6	14.85	15.28	0.42	21.2

Plot of turbidity data vs. concentration:

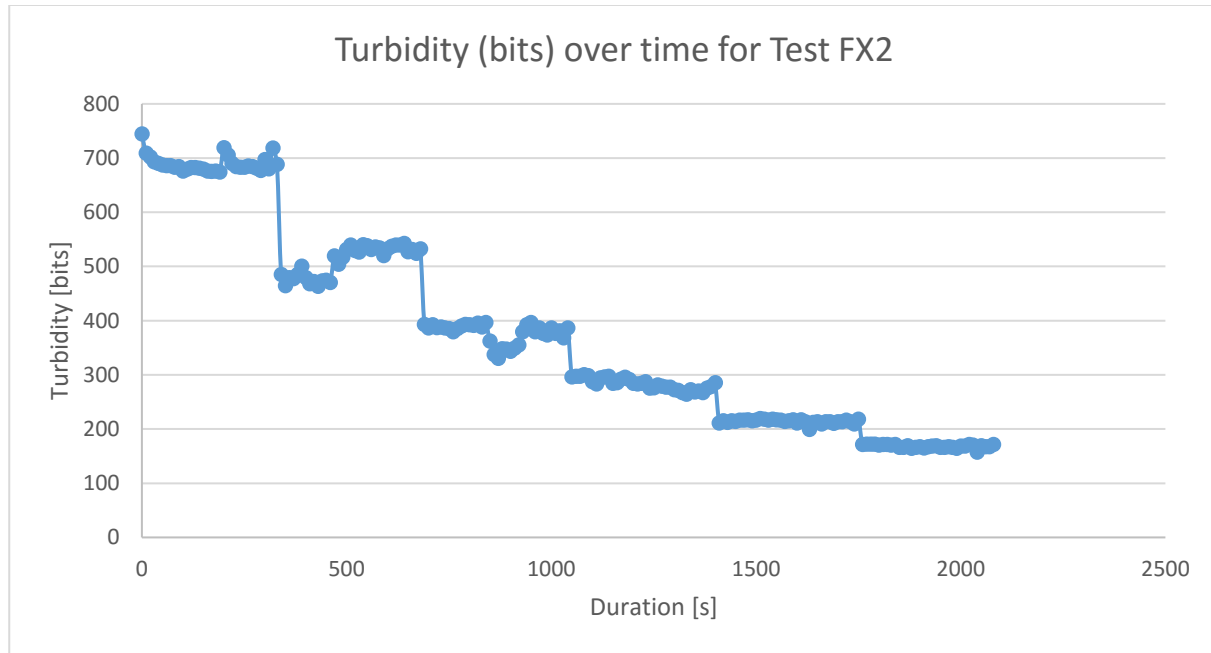


H27: Test FX2

Test details:

- Date of test: 25/09/2016
- Material being tested: Kaolin in tap water
- Sensor being tested: 1
- Start time of mixing test: 1:19pm

Raw data measured by turbidity sensor:



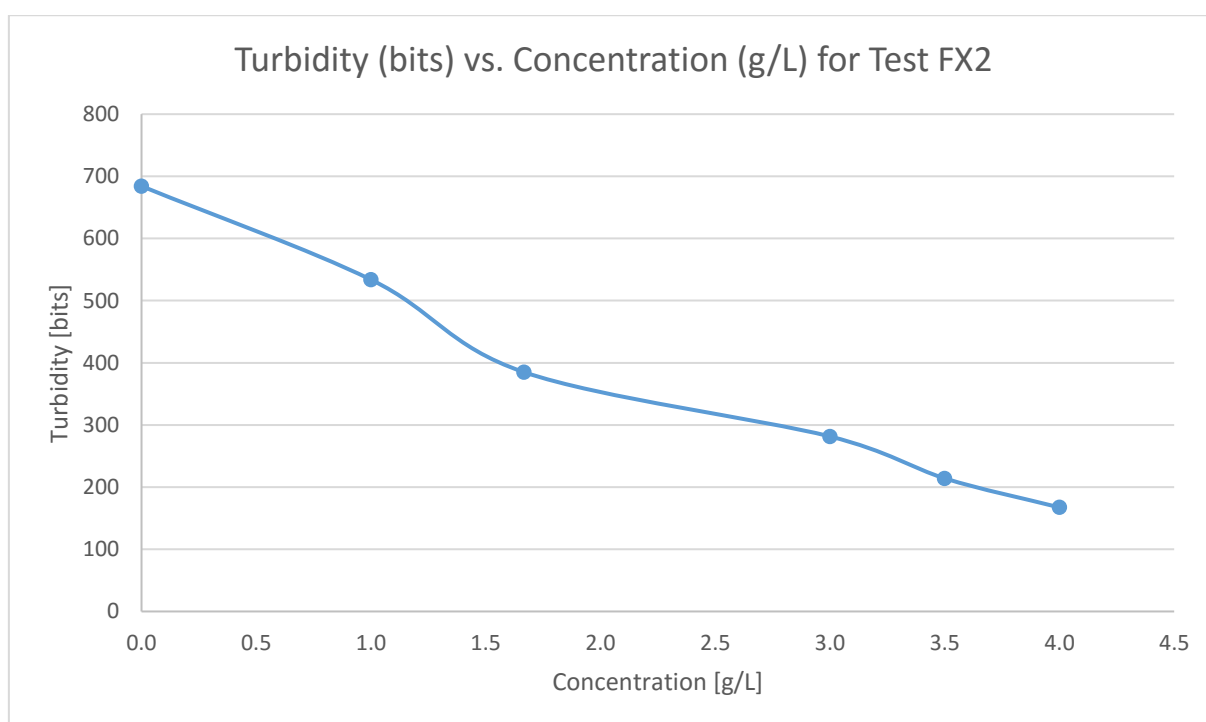
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	684
2	337 – 660	500 – 650	534
3	694 – 1020	750 – 850, 950 – 1000	385
4	1055 – 1380	1100 – 1350	282
5	1418 – 1740	1450 – 1700	214
6	1772 – 2080	1800 – 2050	167

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	14.77	14.78	-0.01	0.0
2	15.89	15.87	0.02	1.0
3	15.22	15.19	0.03	1.7
4	15.48	15.42	0.06	3.0
5	16.50	16.43	0.07	3.5
6	20.98	20.90	0.08	4.0

Plot of turbidity data vs. concentration:

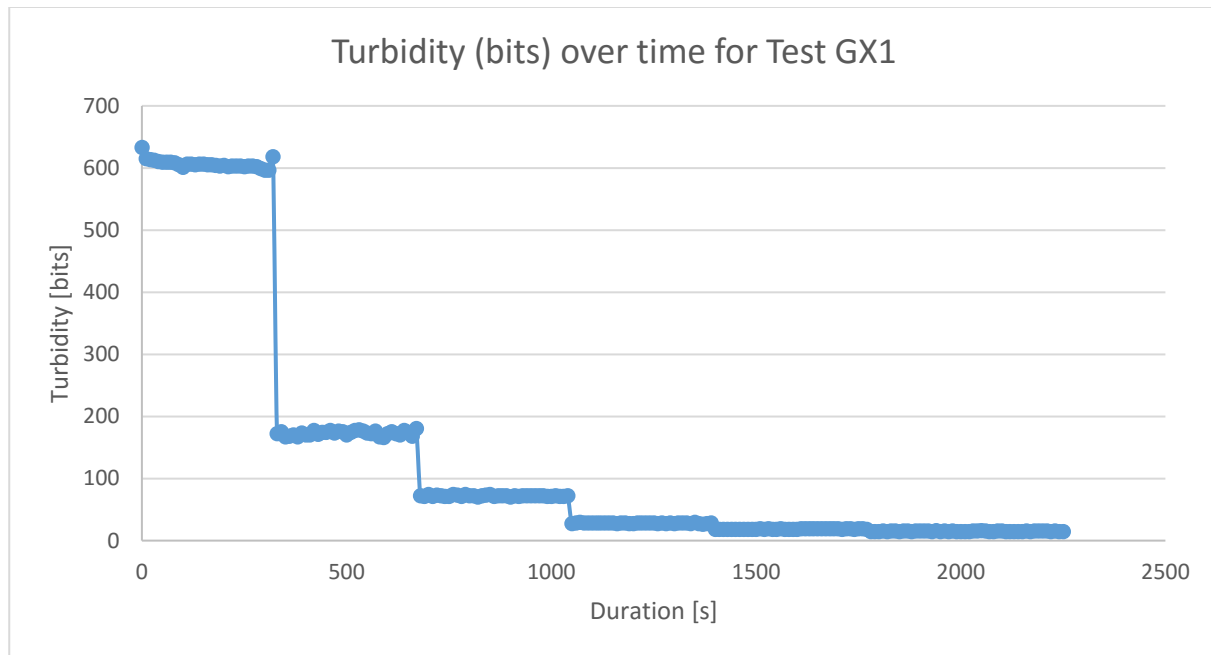


H28: Test GX1

Test details:

- Date of test: 22/09/2016
- Material being tested: Kaolin in tap water
- Sensor being tested: 2
- Start time of mixing test: 5:41pm

Raw data measured by turbidity sensor:



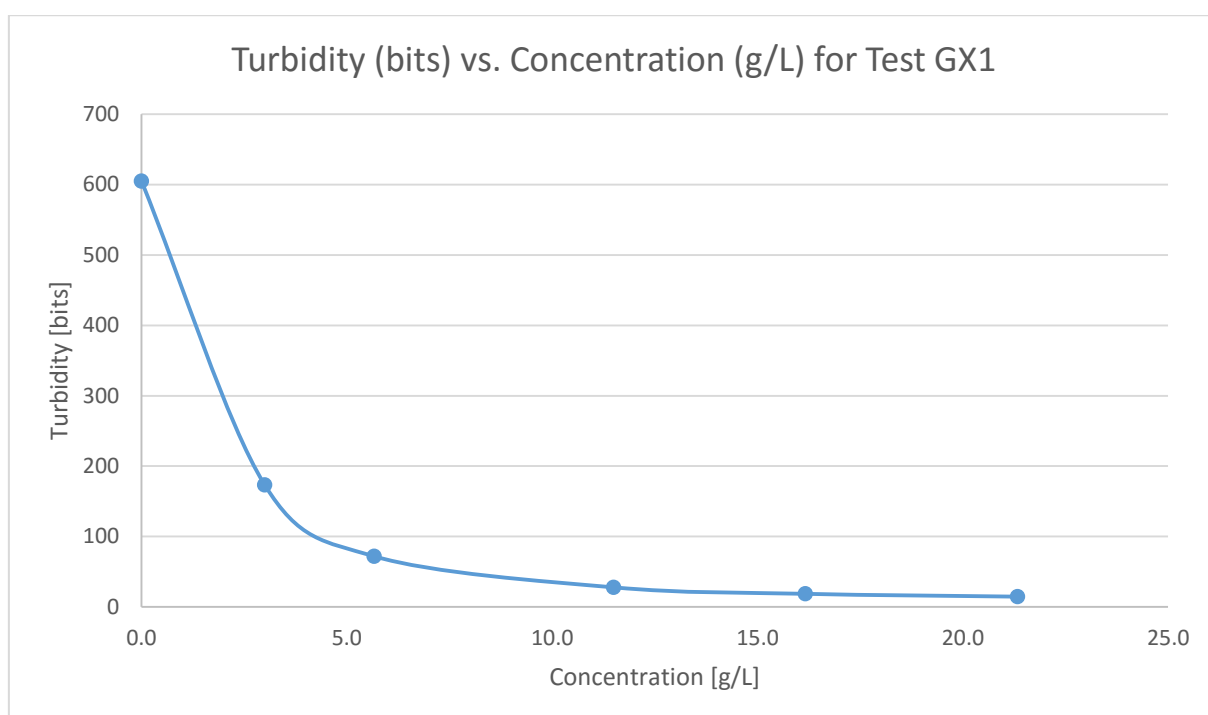
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	605
2	336 – 660	400 – 650	173
3	688 – 1020	750 – 1000	72
4	1058 – 1380	1100 – 1350	28
5	1412 – 1740	1500 – 1700	19
6	1781 – 2250	1850 – 2200	15

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	15.77	15.76	-0.01	0.0
2	17.20	17.25	0.06	3.0
3	15.08	15.18	0.11	5.7
4	18.77	18.99	0.23	11.5
5	13.52	13.84	0.32	16.2
6	15.86	16.28	0.43	21.3

Plot of turbidity data vs. concentration:

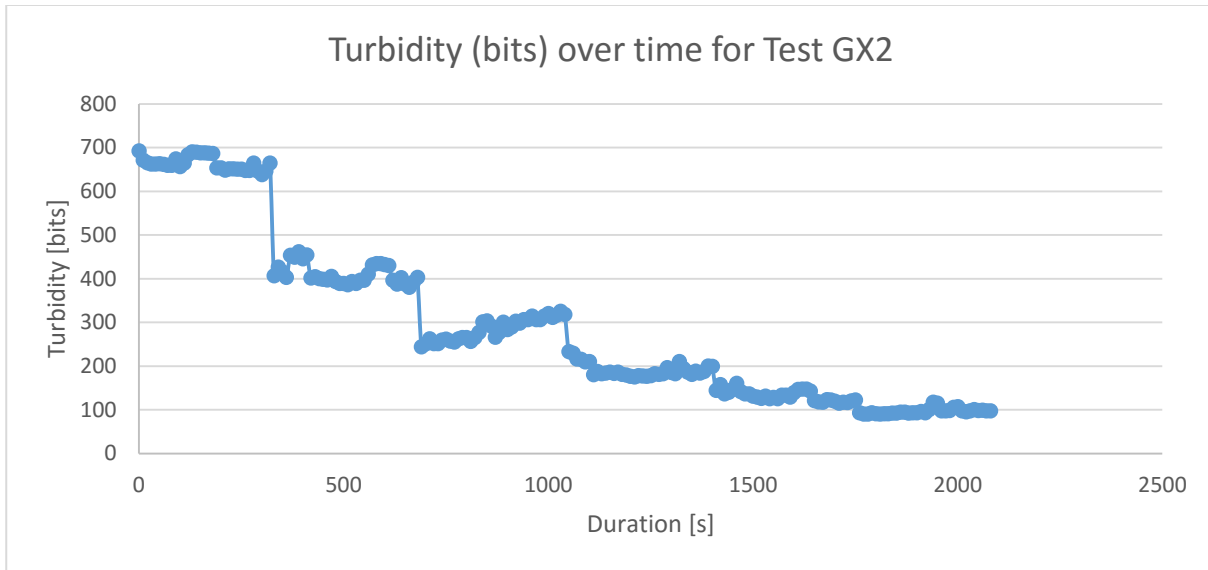


H29: Test GX2

Test details:

- Date of test: 25/09/2016
- Material being tested: Kaolin in tap water
- Sensor being tested: 2
- Start time of mixing test: 1:59pm

Raw data measured by turbidity sensor:



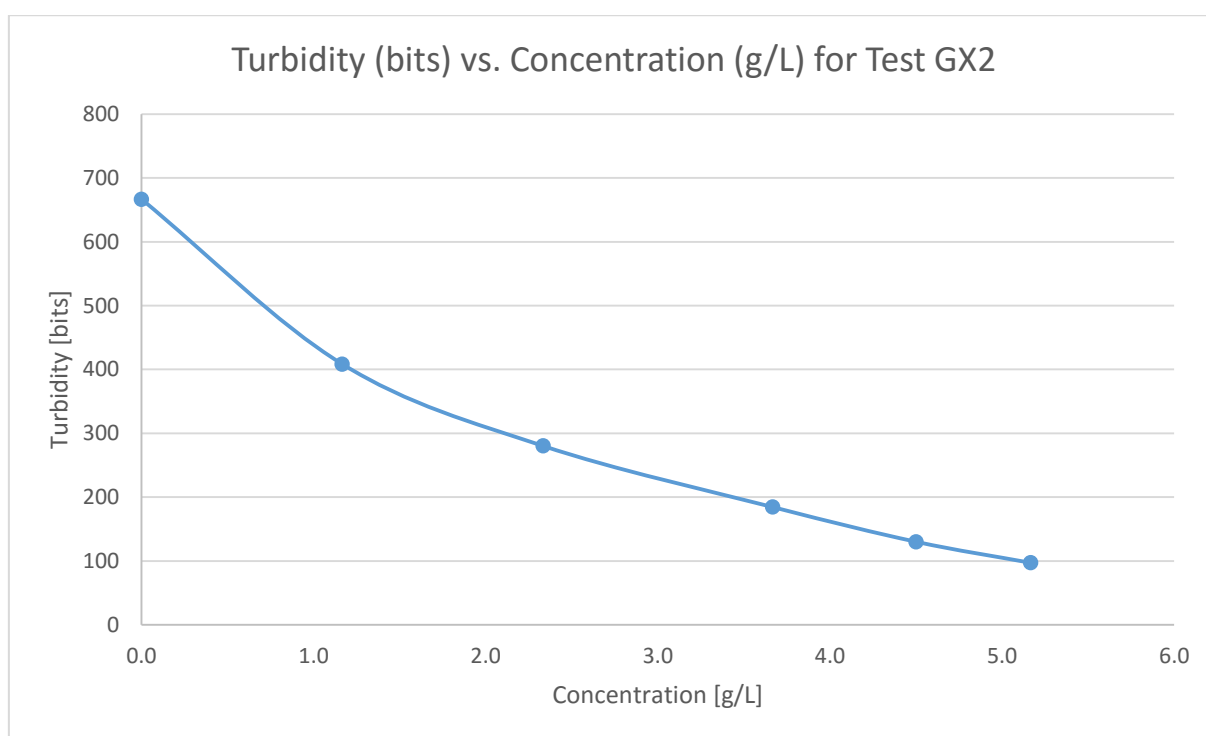
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	667
2	337 – 660	400 – 600	408
3	690 – 1020	750 – 950	280
4	1058 – 1380	1100 – 1350	185
5	1418 – 1740	1500 – 1700	130
6	1777 – 2080	1800 – 2050	97

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	True concentration [g/L]
1	15.75	15.75	0.00	0.0
2	17.20	17.22	0.02	1.2
3	13.28	13.33	0.05	2.3
4	18.74	18.82	0.07	3.7
5	15.86	15.95	0.09	4.5
6	15.07	15.17	0.10	5.2

Plot of turbidity data vs. concentration:

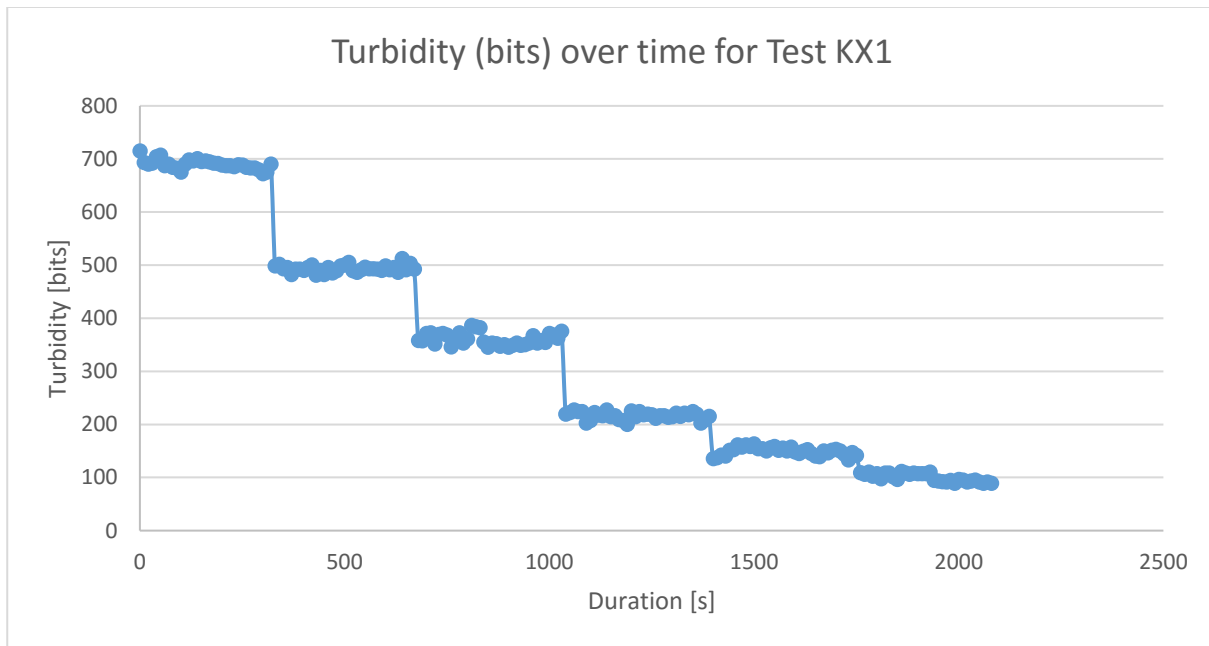


H30: Test KX1

Test details:

- Date of test: 22/09/2016
- Material being tested: Silica in salt water
- Sensor being tested: 1
- Start time of mixing test: 2:42pm

Raw data measured by turbidity sensor:



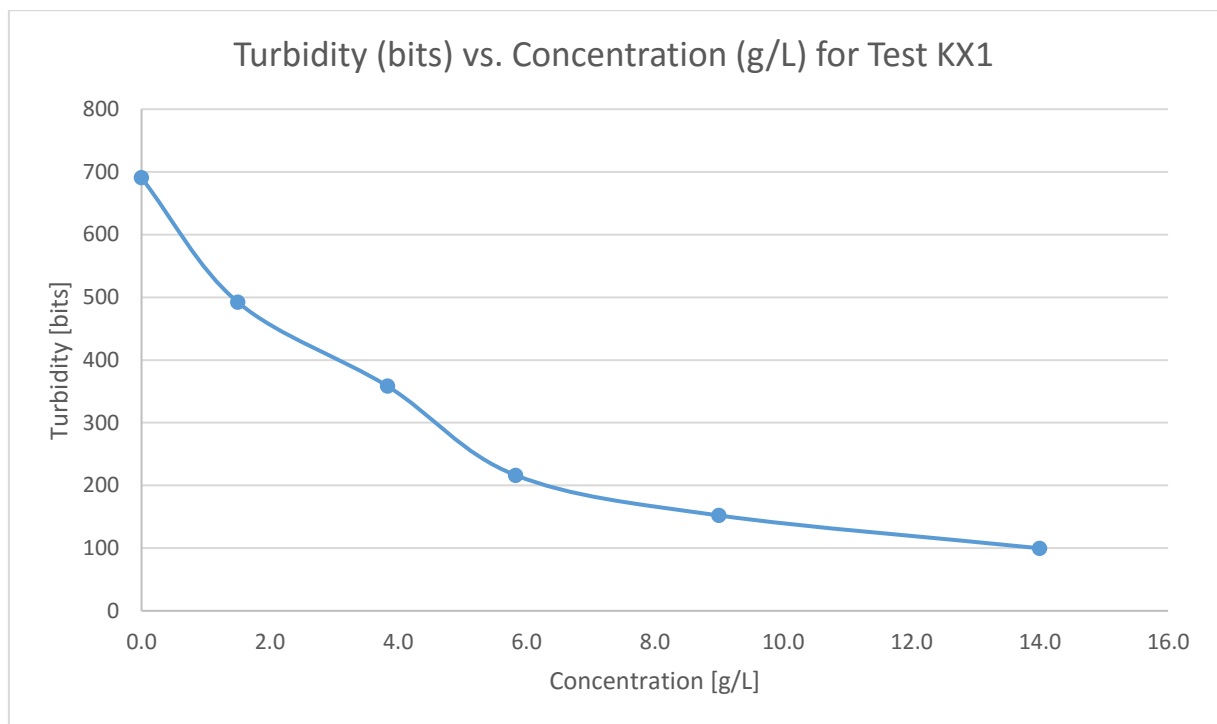
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	691
2	335 – 660	400 – 600	492
3	689 – 1020	750 – 1000	358
4	1047 – 1380	1100 – 1350	216
5	1408 – 1740	1450 – 1700	152
6	1774 – 2080	1800 – 2050	100

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.60	9.70	0.10	0.10	0.0
2	9.72	9.85	0.13	0.10	1.5
3	9.52	9.70	0.18	0.10	3.8
4	9.63	9.85	0.22	0.10	5.8
5	9.80	10.08	0.28	0.10	9.0
6	9.56	9.94	0.38	0.10	14.0

Plot of turbidity data vs. concentration:

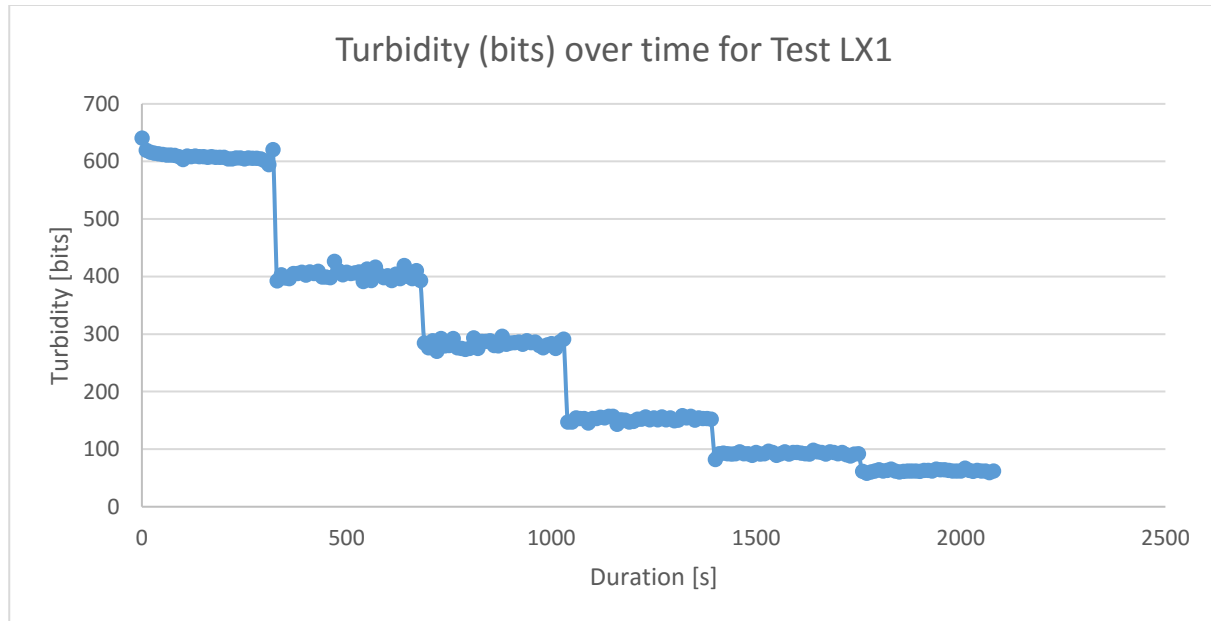


H31: Test LX1

Test details:

- Date of test: 22/09/2016
- Material being tested: Silica in salt water
- Sensor being tested: 2
- Start time of mixing test: 6:32pm

Raw data measured by turbidity sensor:



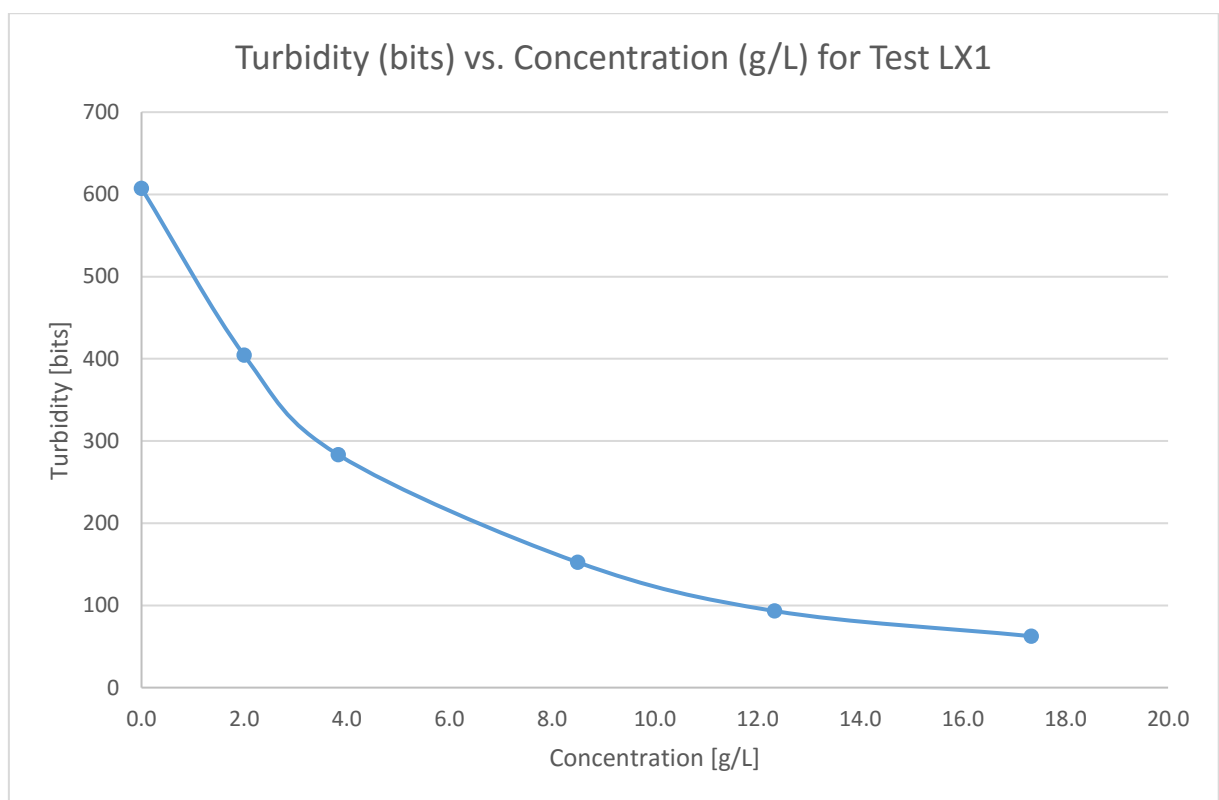
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	607
2	331 – 660	400 – 650	404
3	695 – 1020	750 – 950	283
4	1046 – 1380	1100 – 1350	152
5	1414 – 1740	1500 – 1700	93
6	1771 – 2080	1850 – 2050	63

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.64	9.73	0.09	0.10	0.0
2	9.55	9.69	0.14	0.10	2.0
3	9.64	9.82	0.18	0.10	3.8
4	9.62	9.89	0.27	0.10	8.5
5	9.73	10.08	0.35	0.10	12.3
6	9.55	9.99	0.45	0.10	17.3

Plot of turbidity data vs. concentration:

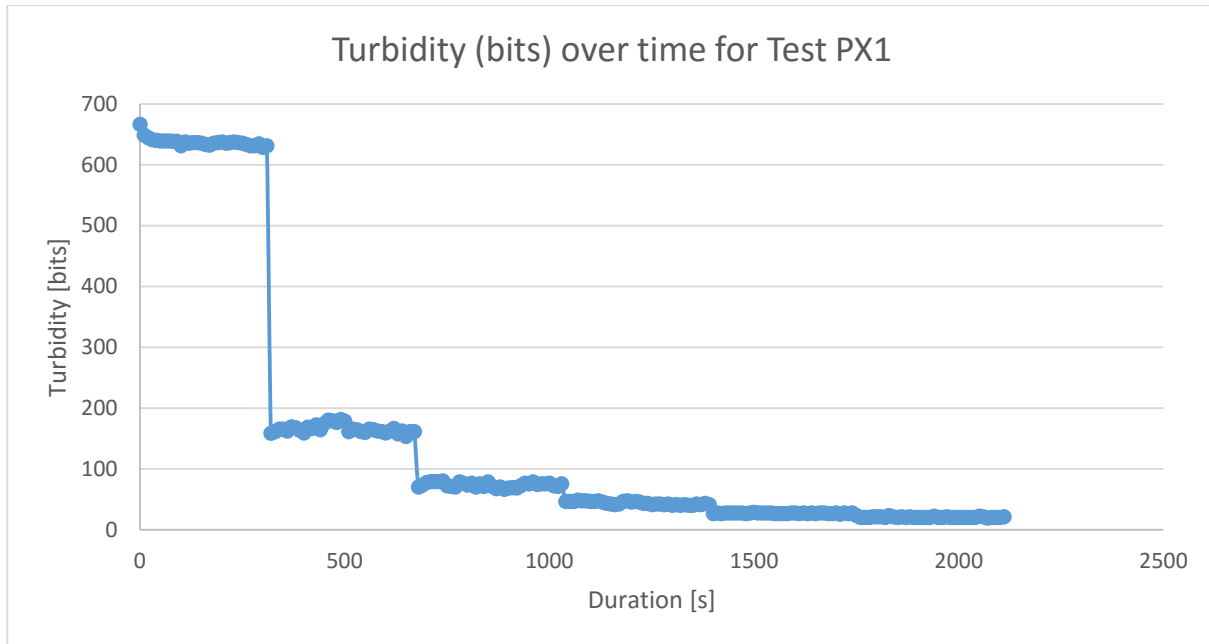


H32: Test PX1

Test details:

- Date of test: 22/09/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 1
- Start time of mixing test: 3:23pm

Raw data measured by turbidity sensor:



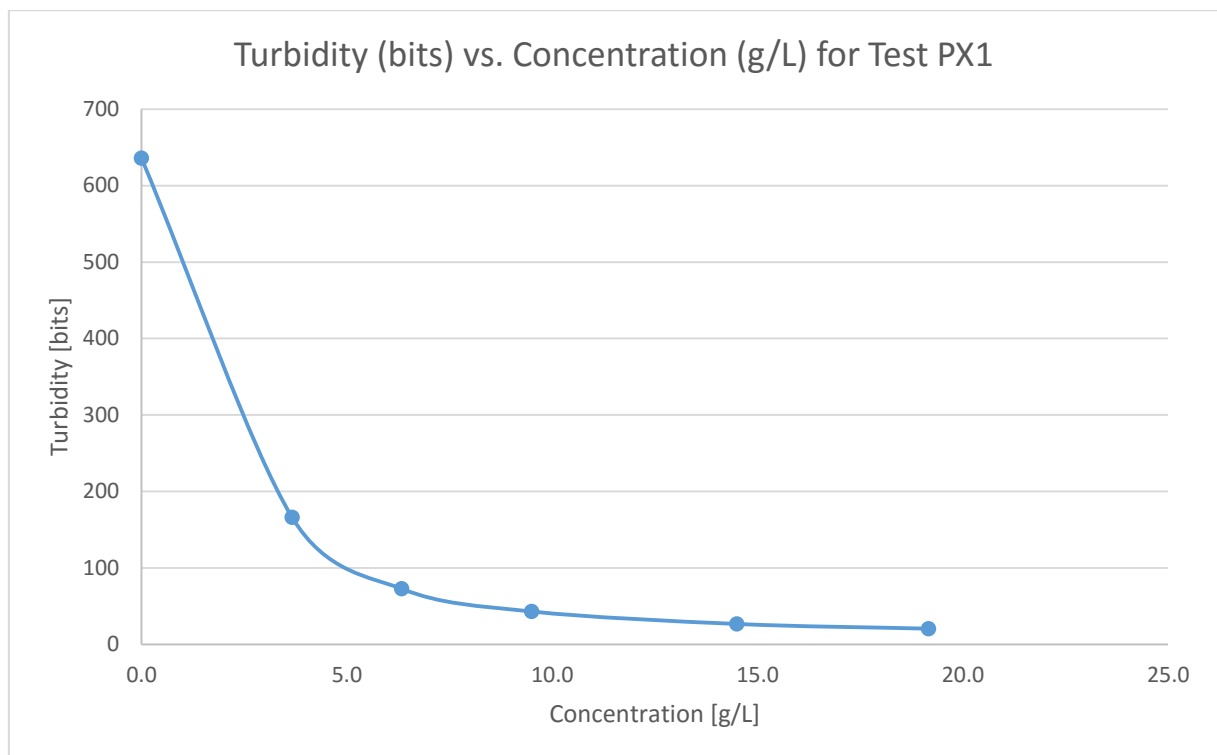
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	636
2	325 – 660	400 – 650	166
3	688 – 1020	750 – 1000	73
4	1042 – 1380	1100 – 1350	43
5	1417 – 1740	1450 – 1700	27
6	1774 – 2110	1800 – 2050	21

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.73	9.83	0.10	0.10	0.0
2	9.53	9.70	0.17	0.10	3.7
3	9.78	10.01	0.23	0.10	6.3
4	9.66	9.95	0.29	0.10	9.5
5	9.61	10.00	0.39	0.10	14.5
6	9.48	9.97	0.48	0.10	19.2

Plot of turbidity data vs. concentration:

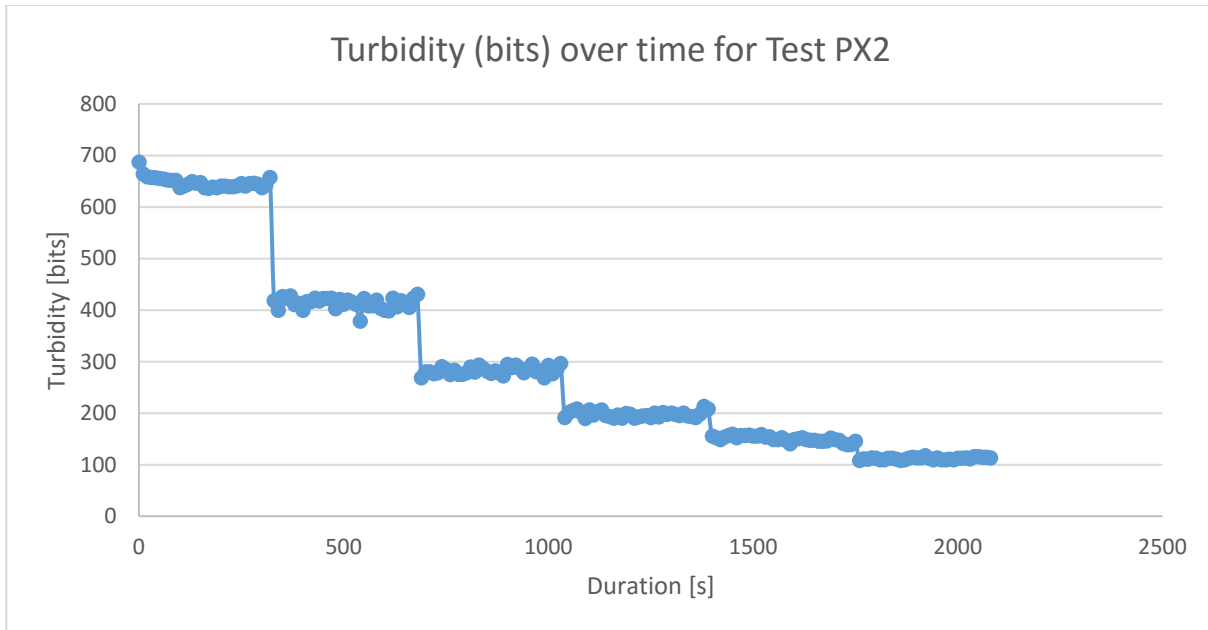


H33: Test PX2

Test details:

- Date of test: 25/09/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 1
- Start time of mixing test: 3:40pm

Raw data measured by turbidity sensor:



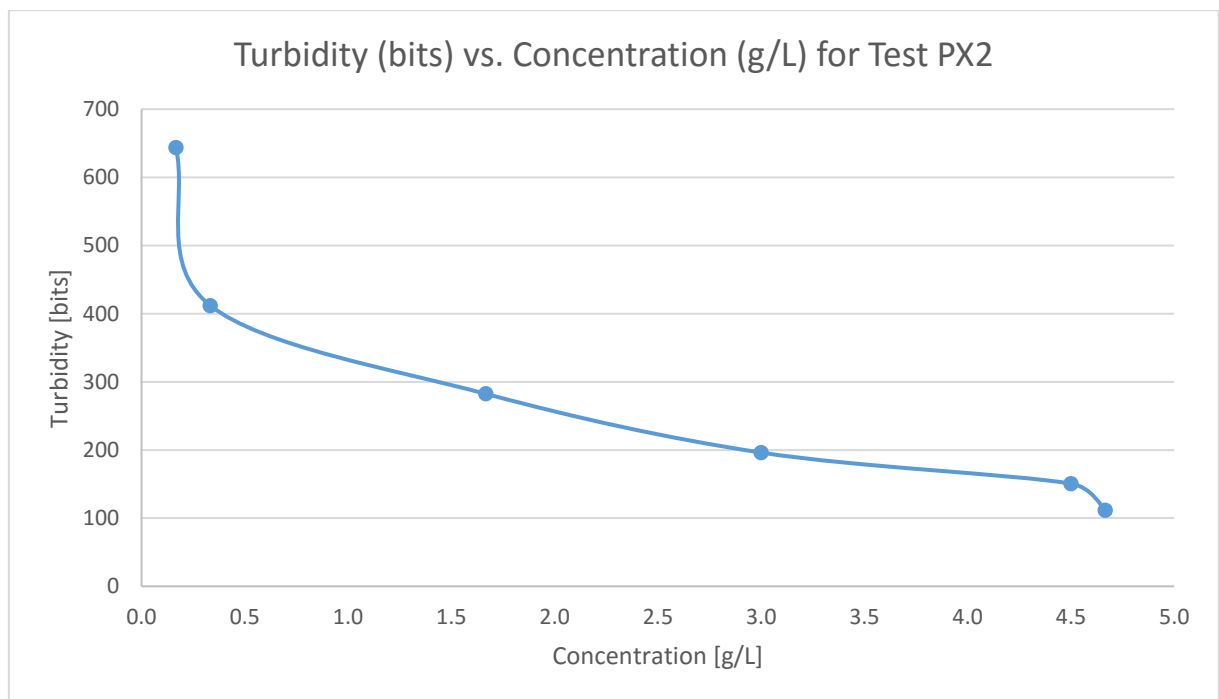
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	644
2	329 – 660	400 – 650	412
3	689 – 1020	750 – 950	282
4	1051 – 1380	1100 – 1350	196
5	1406 – 1740	1450 – 1700	151
6	1770 – 2080	1850 – 2050	112

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.48	9.59	0.10	0.10	0.2
2	9.49	9.60	0.11	0.10	0.3
3	9.58	9.72	0.13	0.10	1.7
4	9.73	9.89	0.16	0.10	3.0
5	9.56	9.75	0.19	0.10	4.5
6	9.49	9.69	0.19	0.10	4.7

Plot of turbidity data vs. concentration:

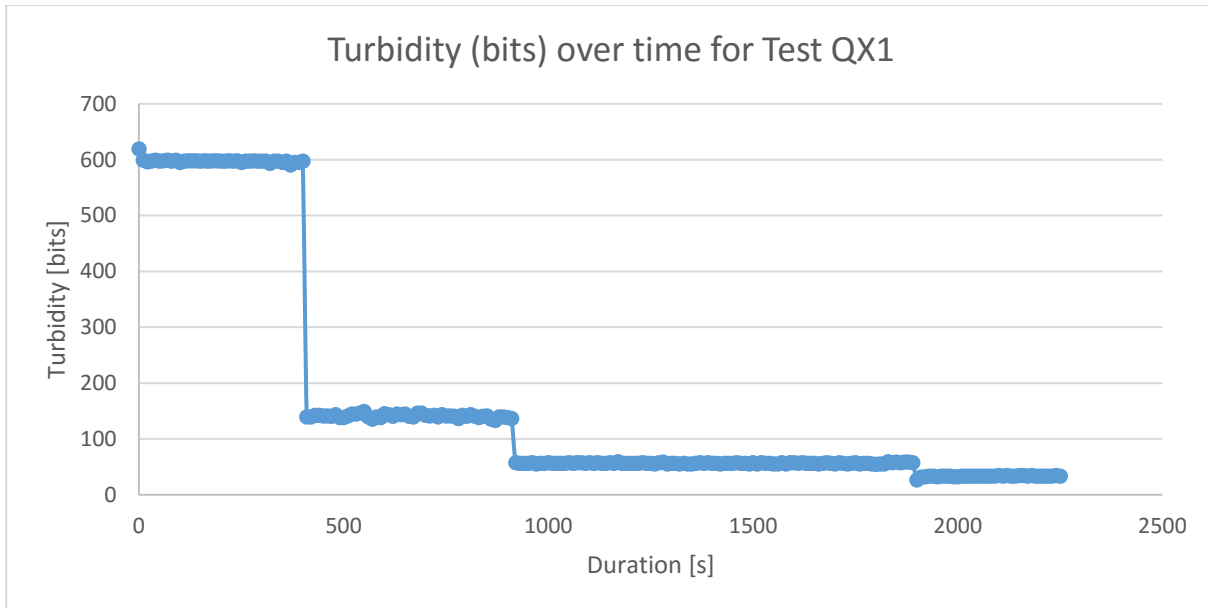


H34: Test QX1

Test details:

- Date of test: 22/09/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 2
- Start time of mixing test: 7:12pm

Raw data measured by turbidity sensor:



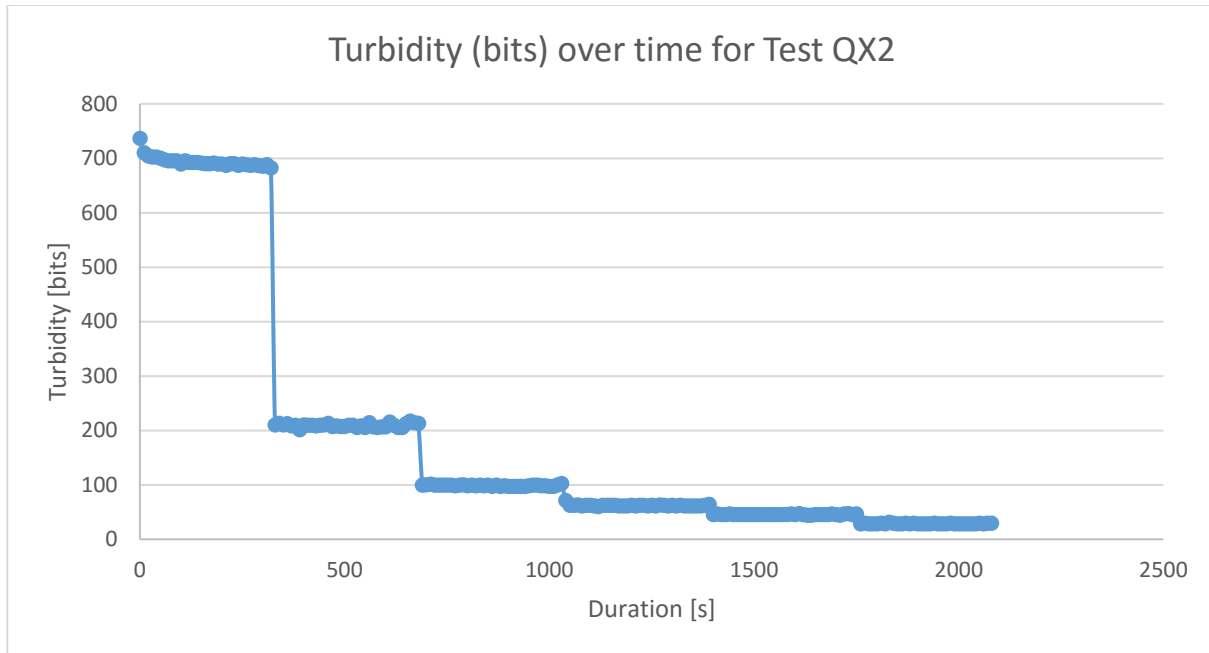
Test abandoned due to significant loss of data observed – only 4 steps in the graph while 6 are expected.

H35: Test QX2

Test details:

- Date of test: 23/09/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 2
- Start time of mixing test: 10:53am

Raw data measured by turbidity sensor:



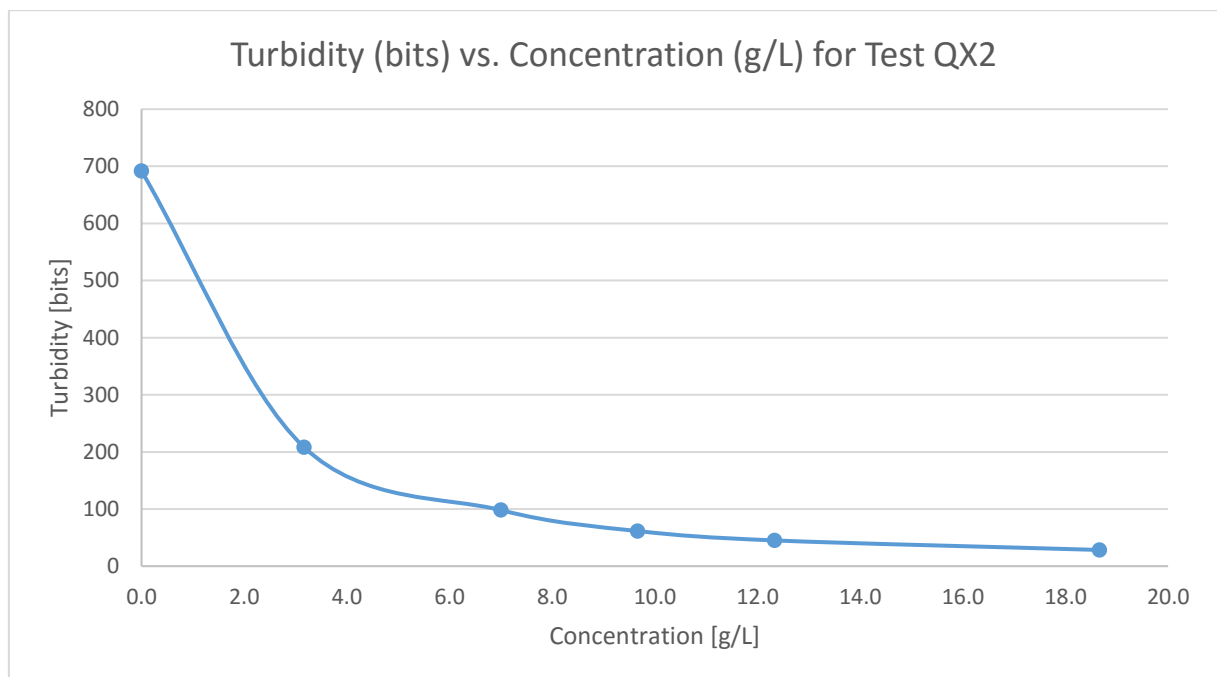
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	692
2	326 – 660	400 – 650	208
3	693 – 1020	750 – 1000	98
4	1054 – 1380	1100 – 1350	62
5	1411 – 1740	1450 – 1700	45
6	1772 – 2080	1800 – 2050	28

Mass measurements from oven drying:

Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.56	9.66	0.10	0.10	0.0
2	9.42	9.59	0.16	0.10	3.2
3	9.54	9.78	0.24	0.10	7.0
4	9.49	9.79	0.29	0.10	9.7
5	9.68	10.03	0.35	0.10	12.3
6	9.74	10.21	0.47	0.10	18.7

Plot of turbidity data vs. concentration:

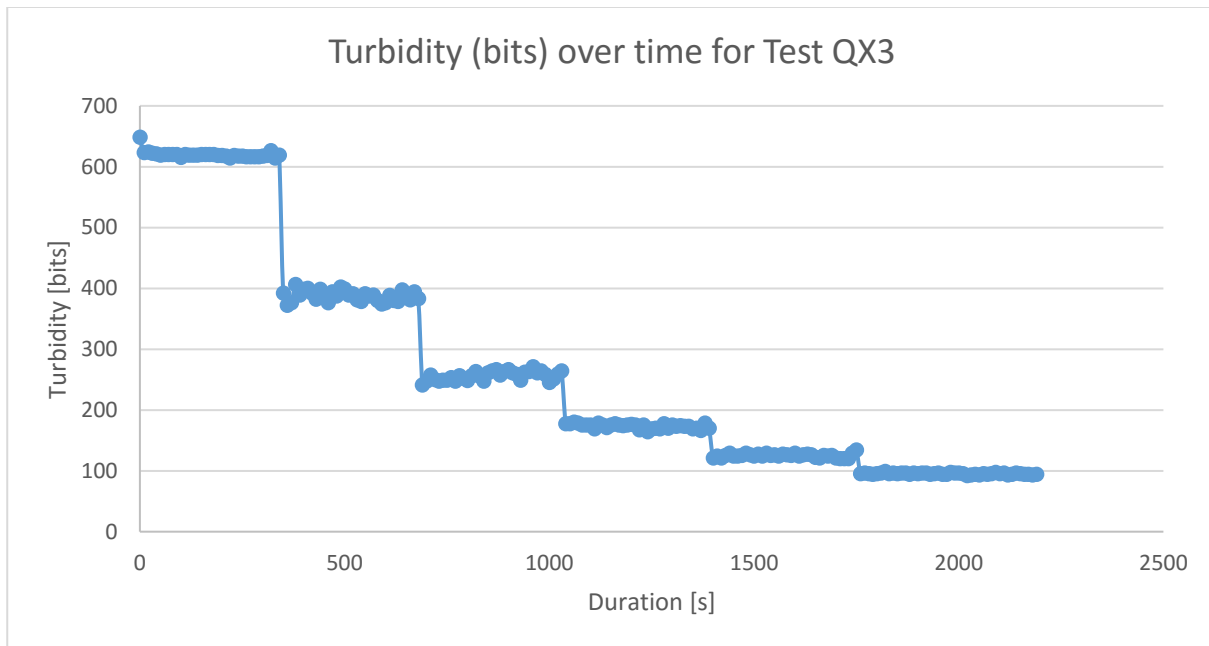


H36: Test QX3

Test details:

- Date of test: 25/09/2016
- Material being tested: Kaolin in salt water
- Sensor being tested: 2
- Start time of mixing test: 4:18pm

Raw data measured by turbidity sensor:



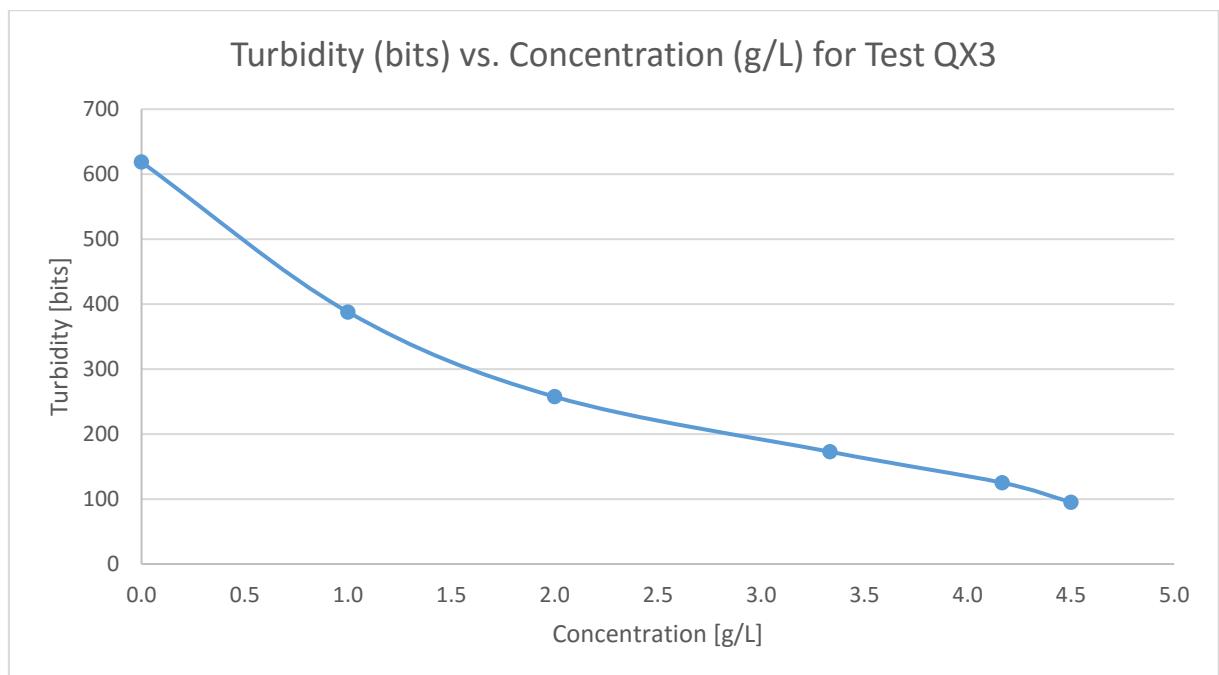
Selected data from raw turbidity sensor data:

Mix:	Relevant duration [s]	Range of data selected (durations)	Average Turbidity [bits]
1	0 – 300	50 – 250	619
2	346 – 660	400 – 650	388
3	689 – 1020	750 – 1000	258
4	1050 – 1380	1100 – 1350	173
5	1407 – 1740	1450 – 1700	125
6	1766 – 2190	1800 – 2100	95

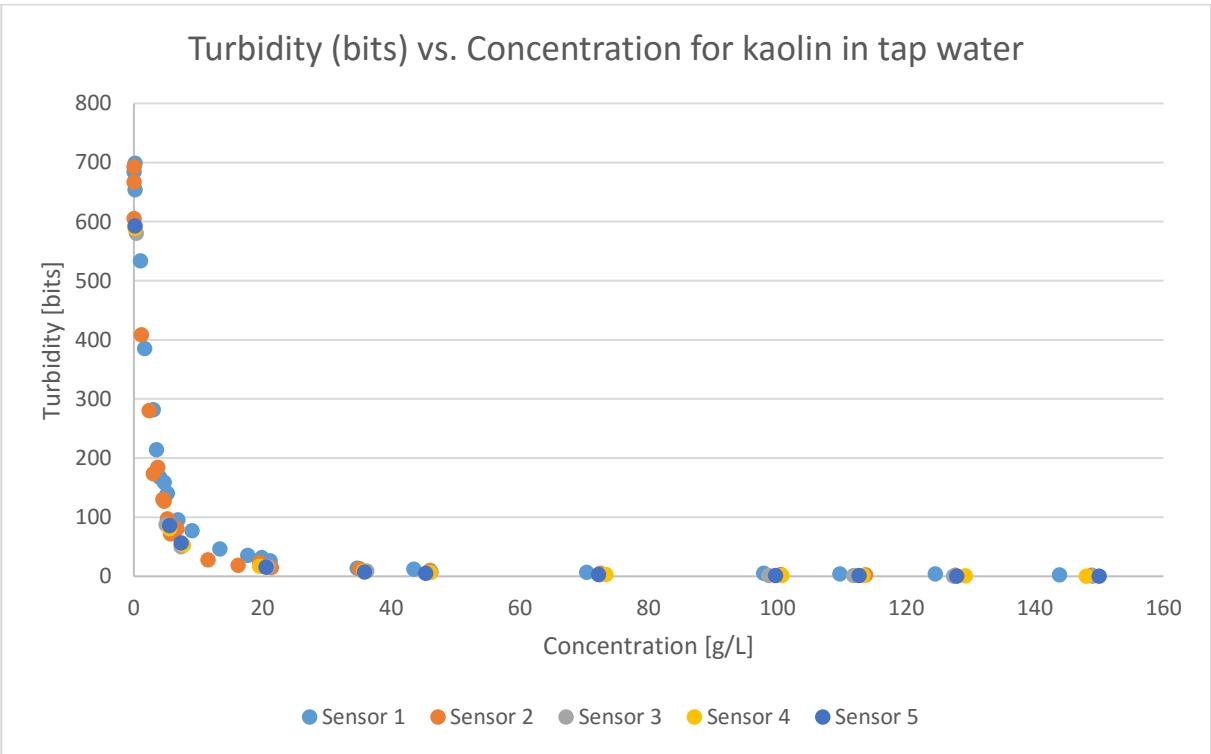
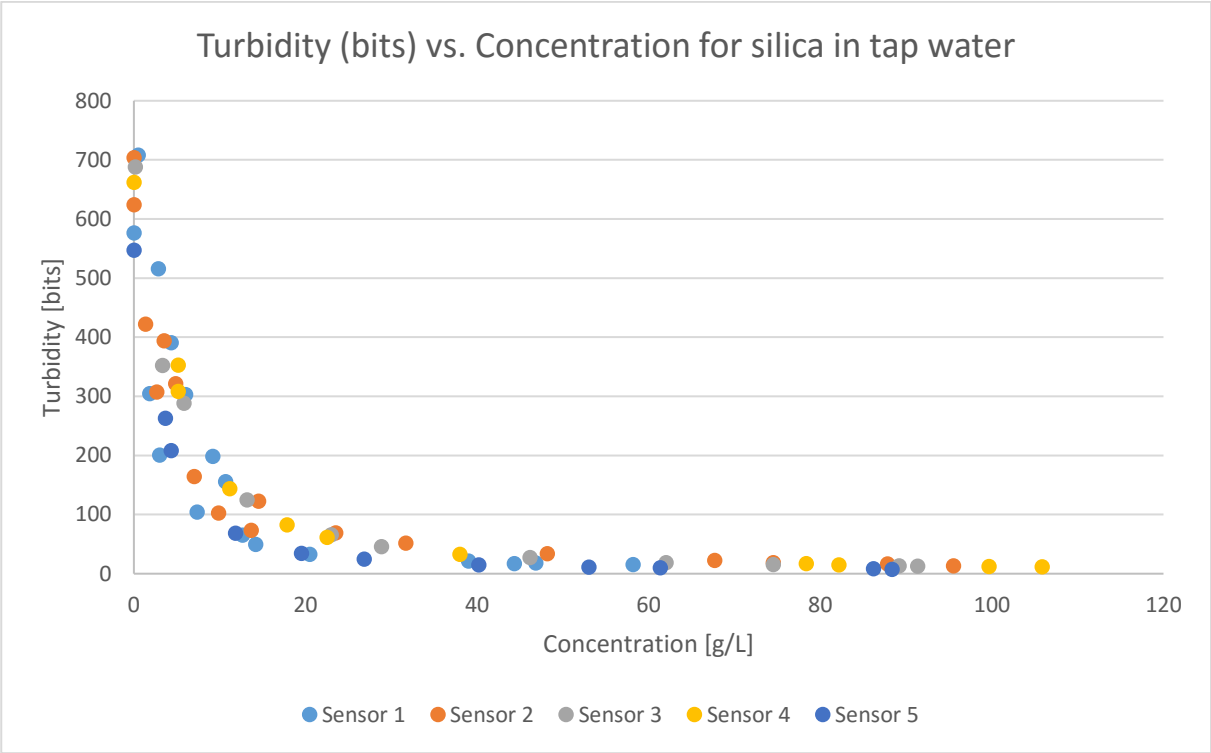
Mass measurements from oven drying:

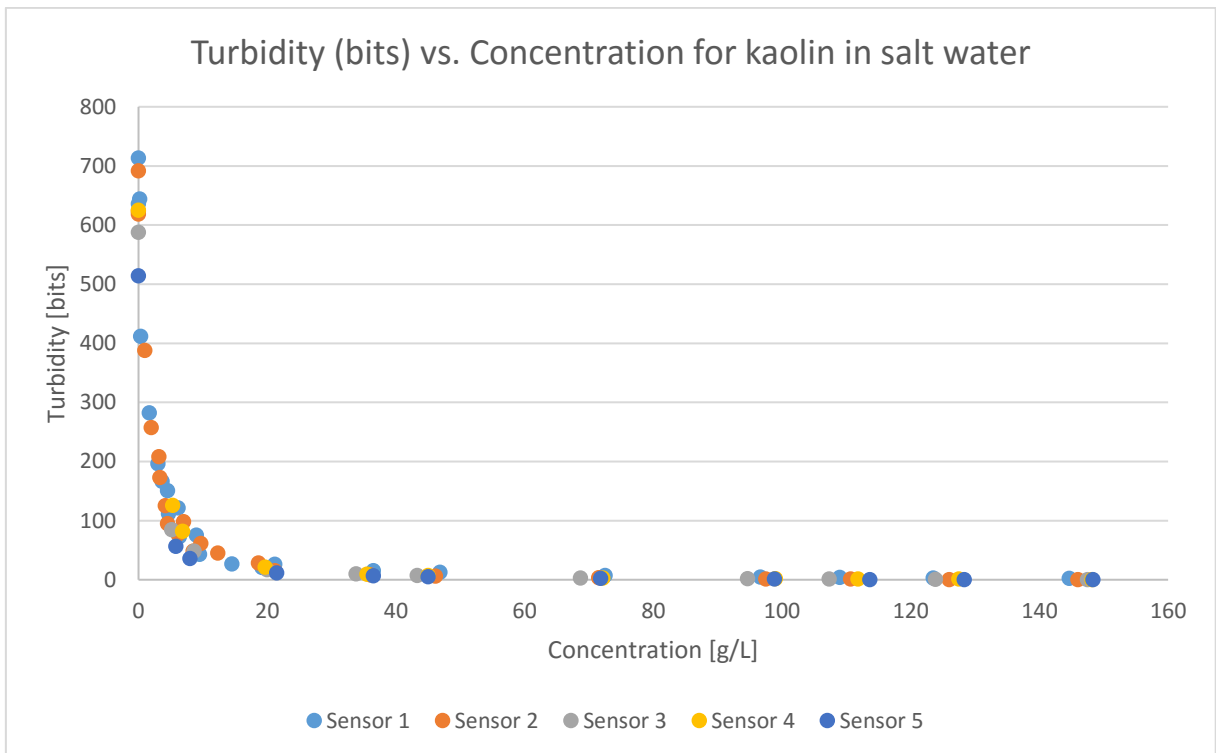
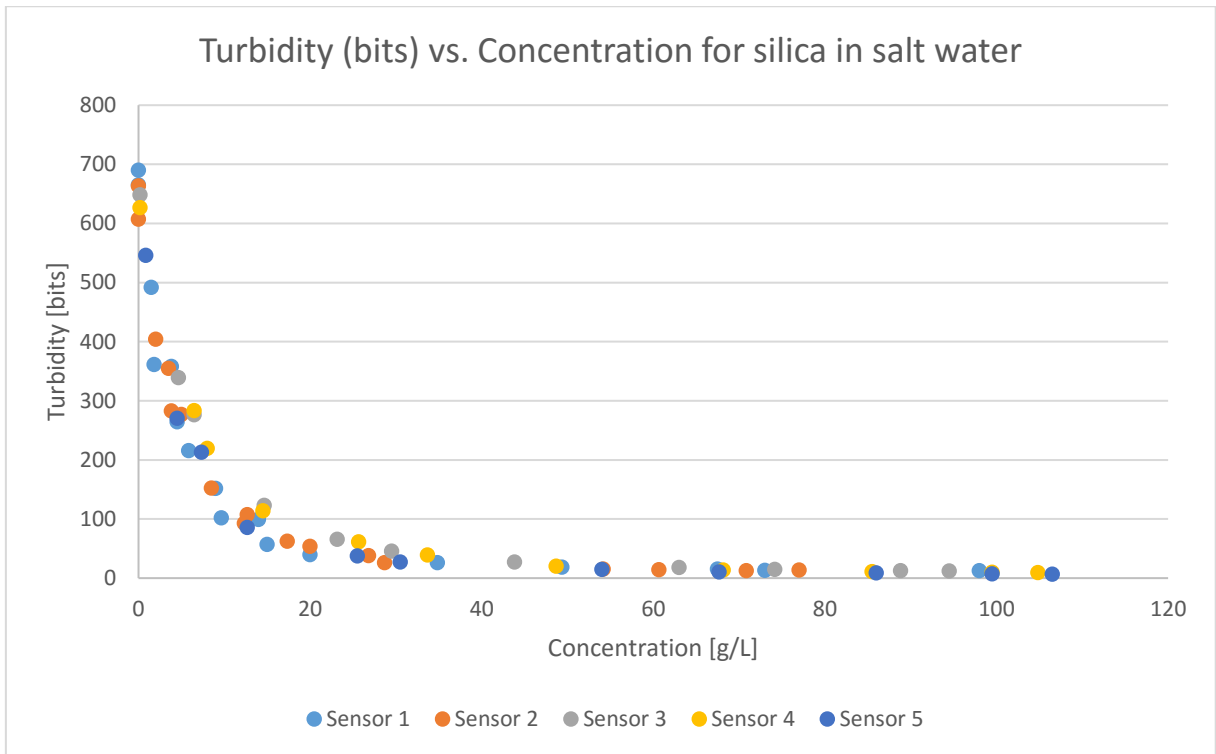
Mix:	Average tin mass [g]	Average tin + sample mass [g]	Sample mass [g]	Salt mass [g]	True concentration [g/L]
1	9.66	9.76	0.10	0.10	0.0
2	9.73	9.85	0.12	0.10	1.0
3	9.56	9.70	0.14	0.10	2.0
4	9.44	9.61	0.17	0.10	3.3
5	9.57	9.75	0.18	0.10	4.2
6	9.51	9.70	0.19	0.10	4.5

Plot of turbidity data vs. concentration:



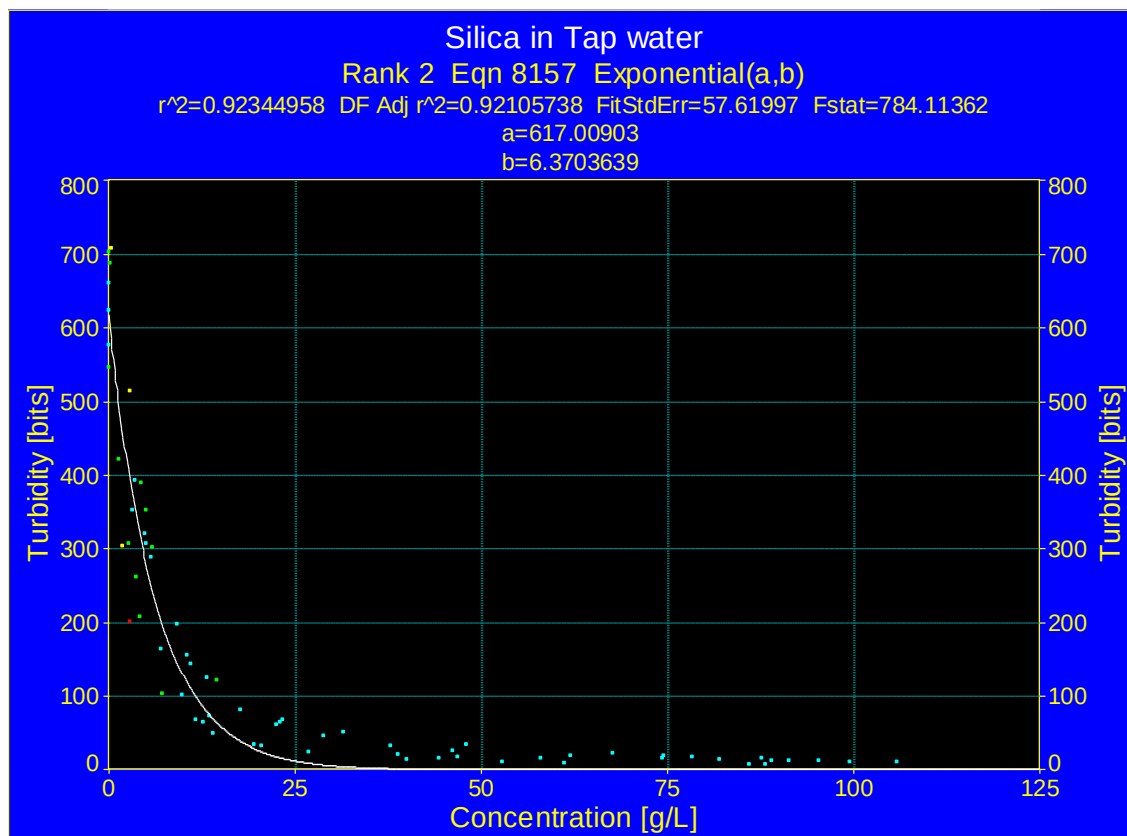
Appendix I: Comparisons of output from different sensors



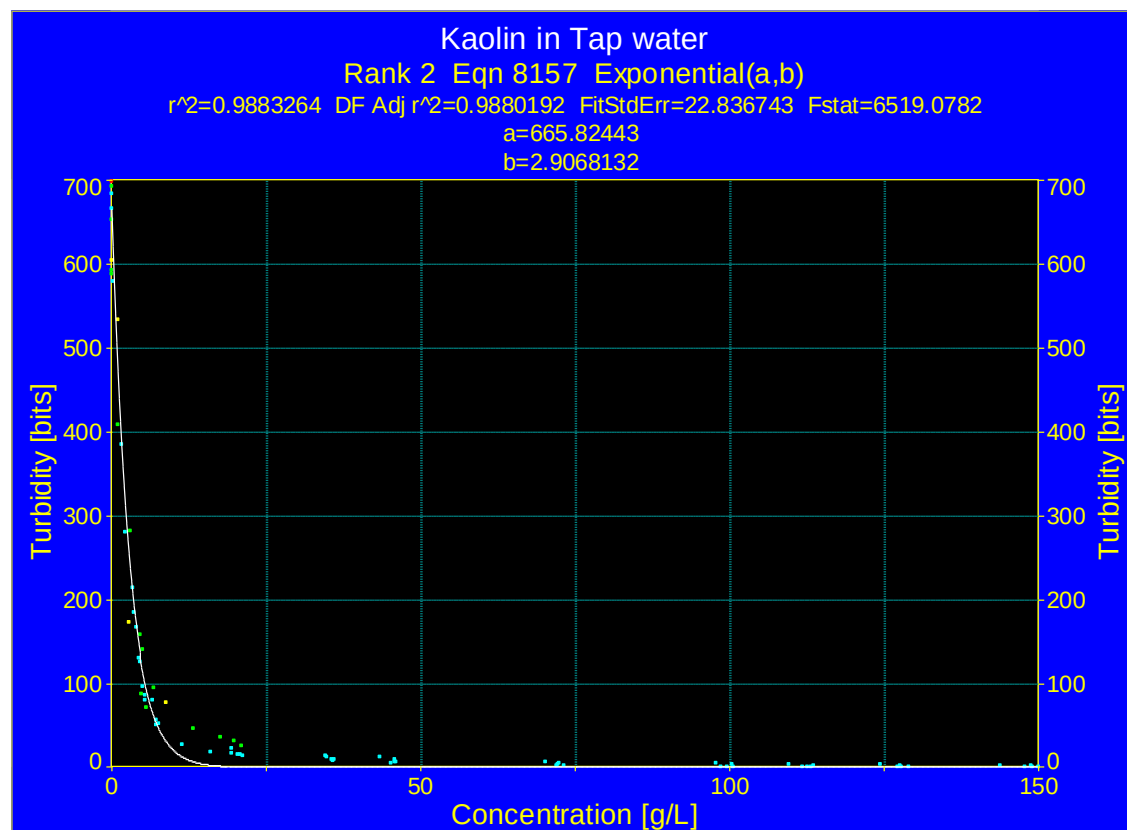


Appendix J: TableCurve 2D outputs

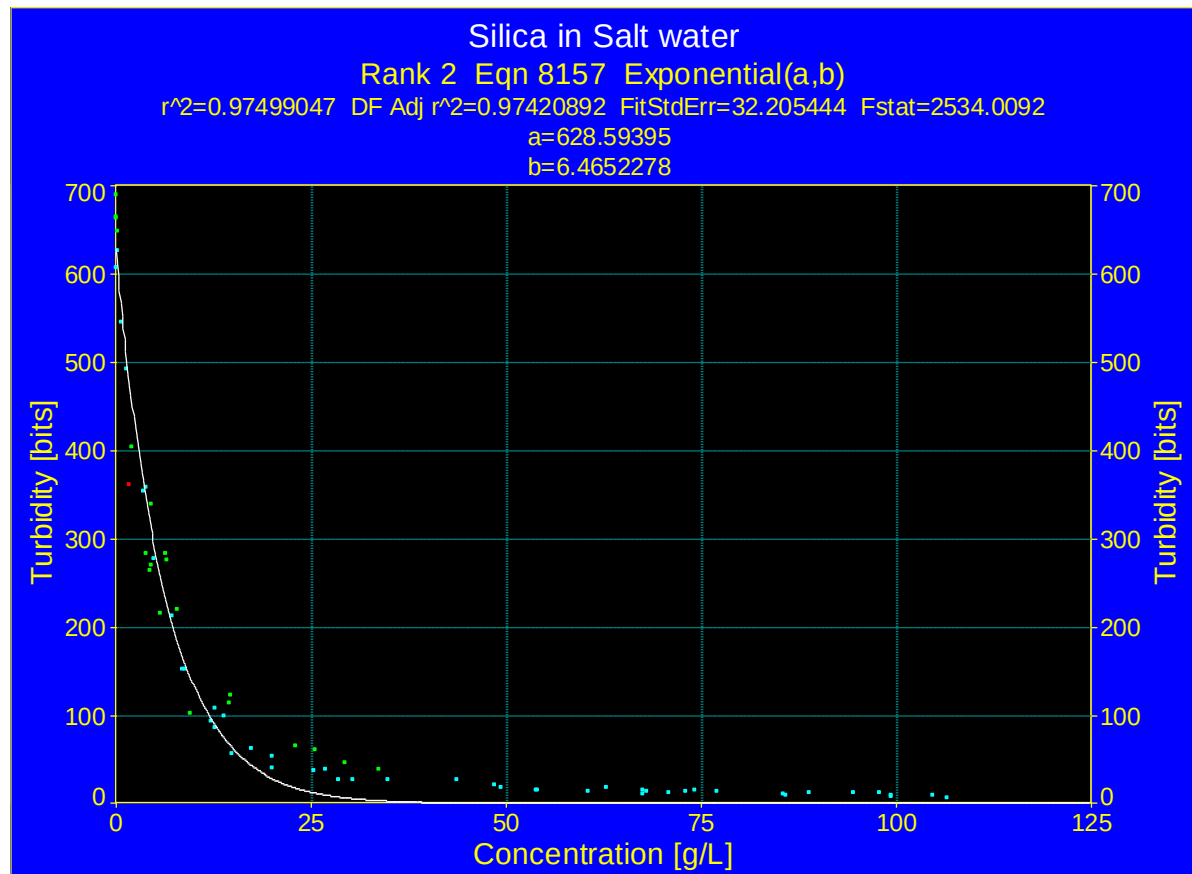
Silica in Tap water, negative exponential function



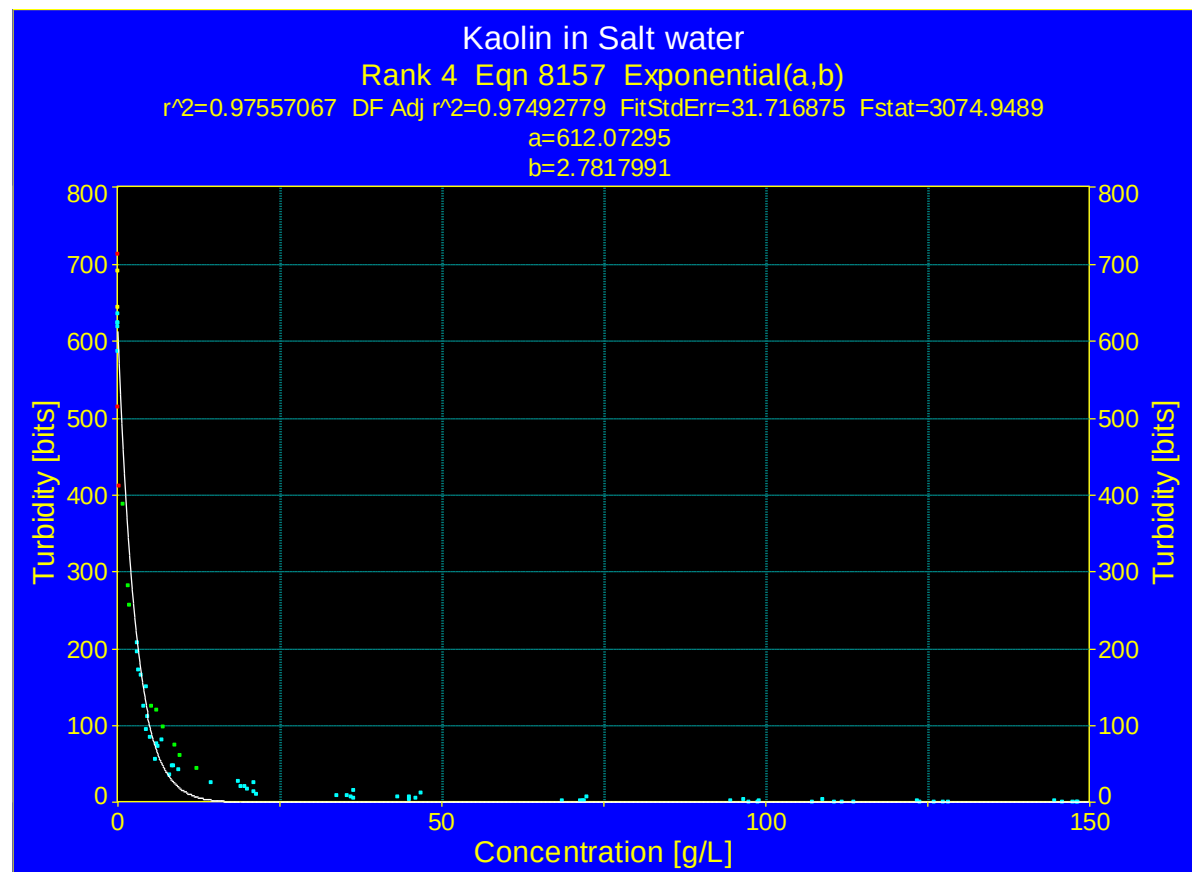
Kaolin in Tap water, negative exponential function



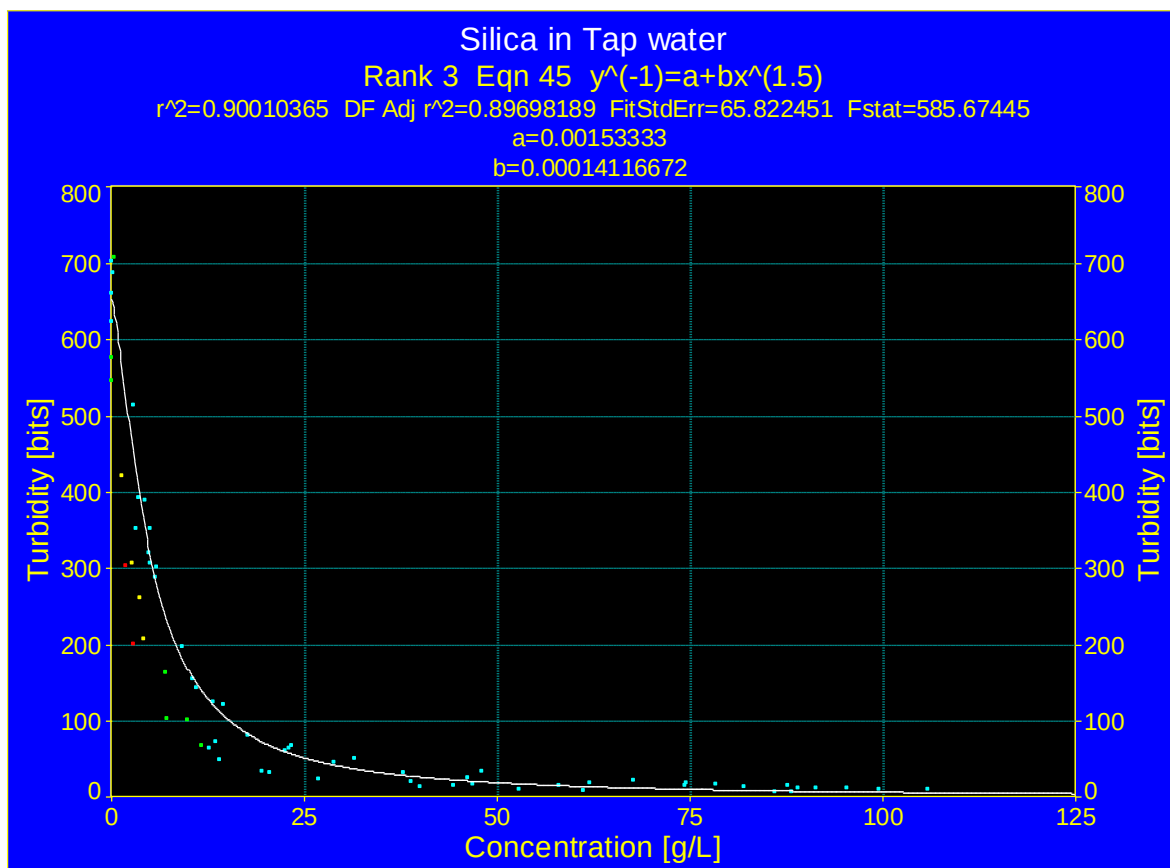
Silica in Salt water, negative exponential function



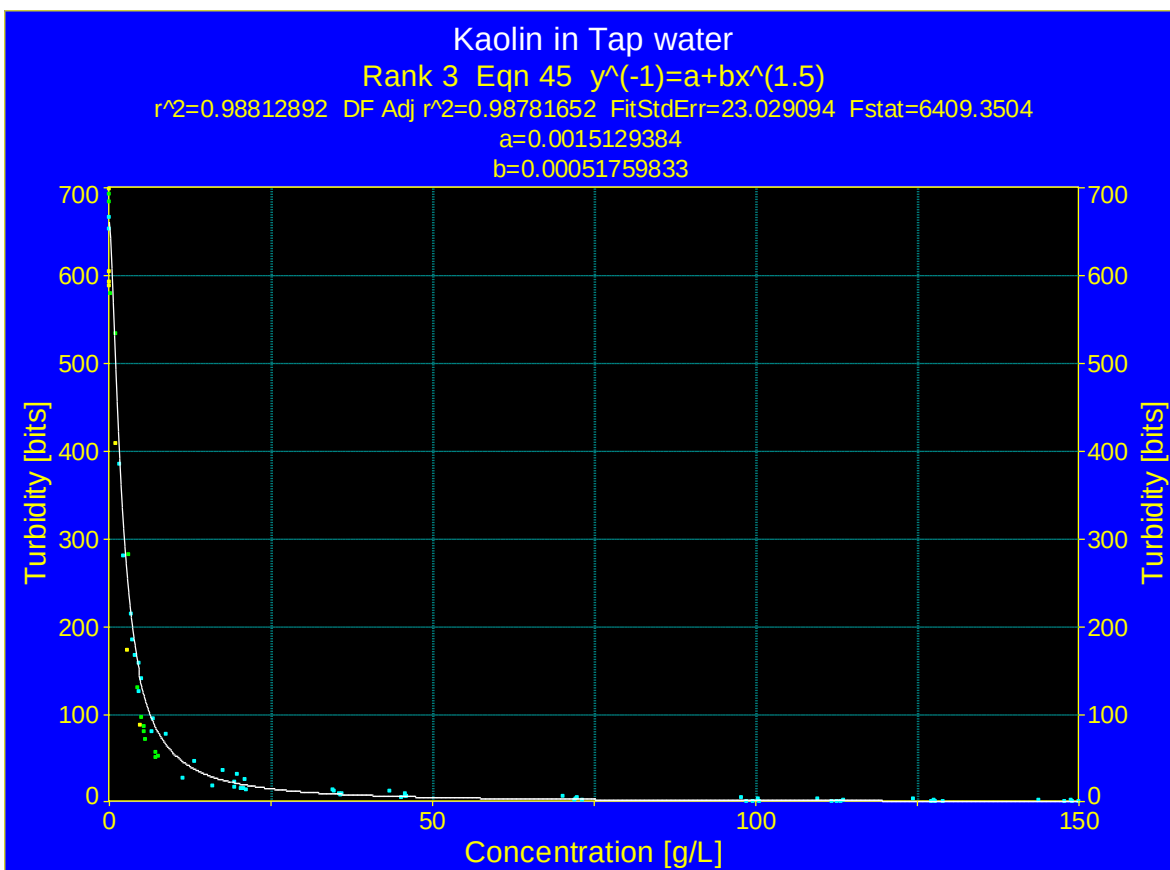
Kaolin in Salt water, negative exponential function



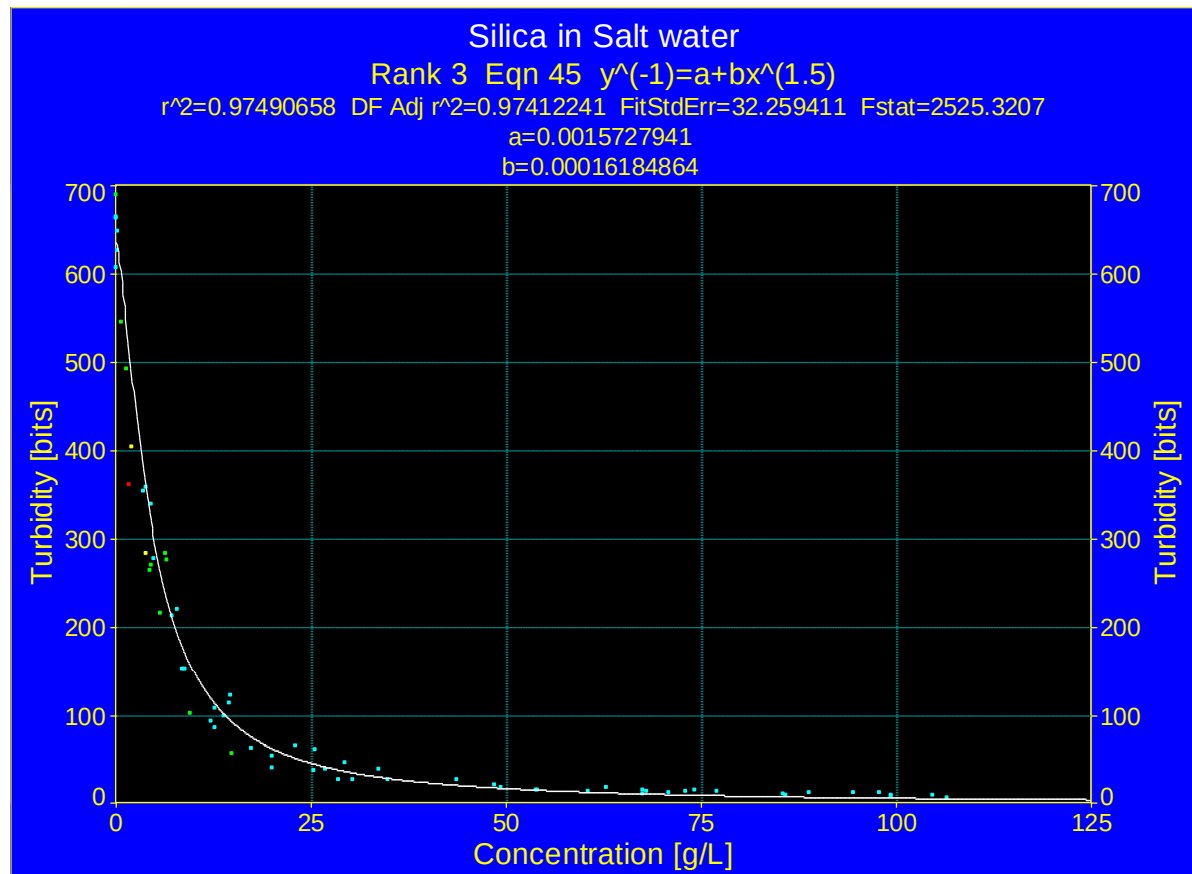
Silica in Tap water, inverse function relation



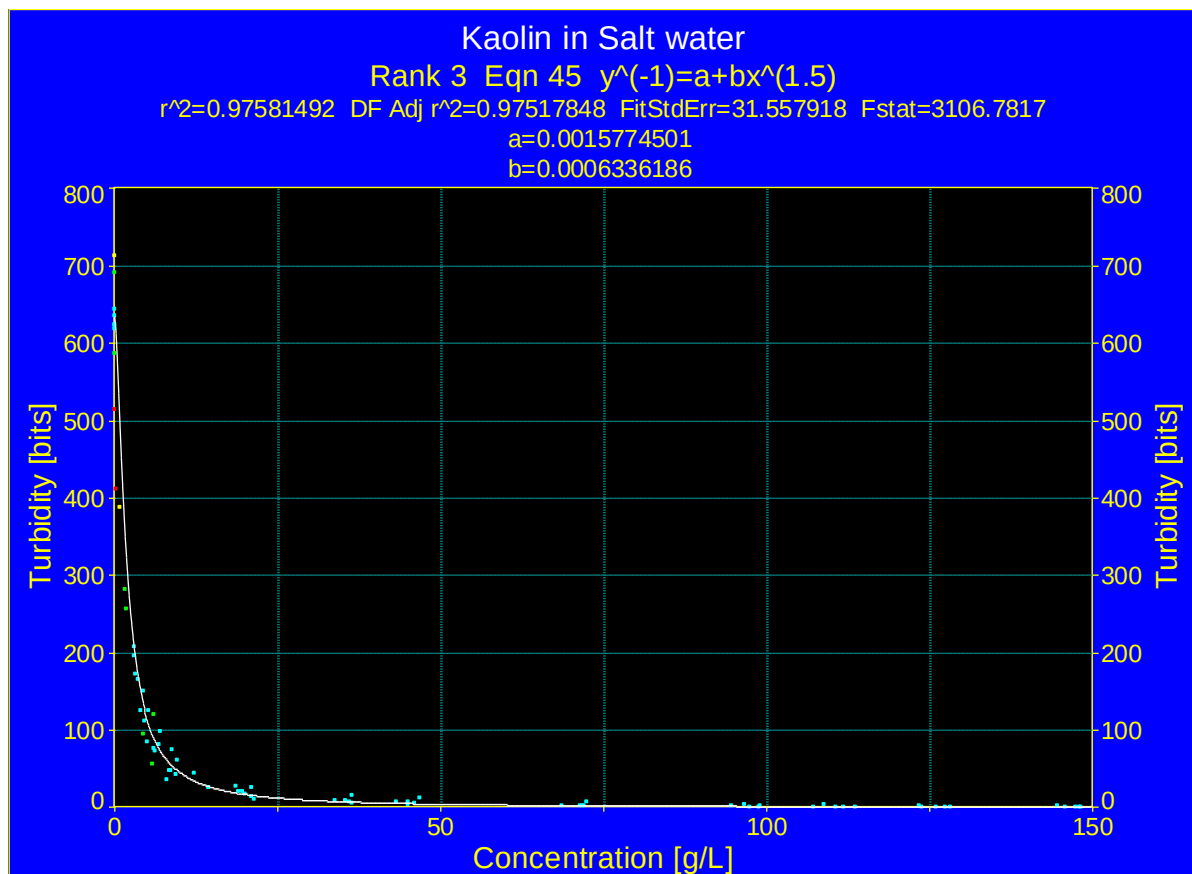
Kaolin in Tap water, inverse function relation



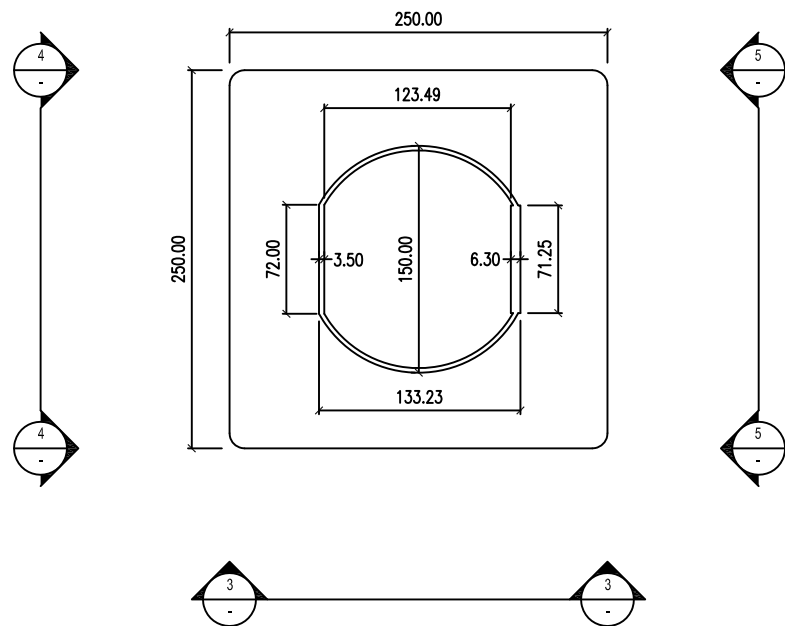
Silica in Salt water, inverse function relation



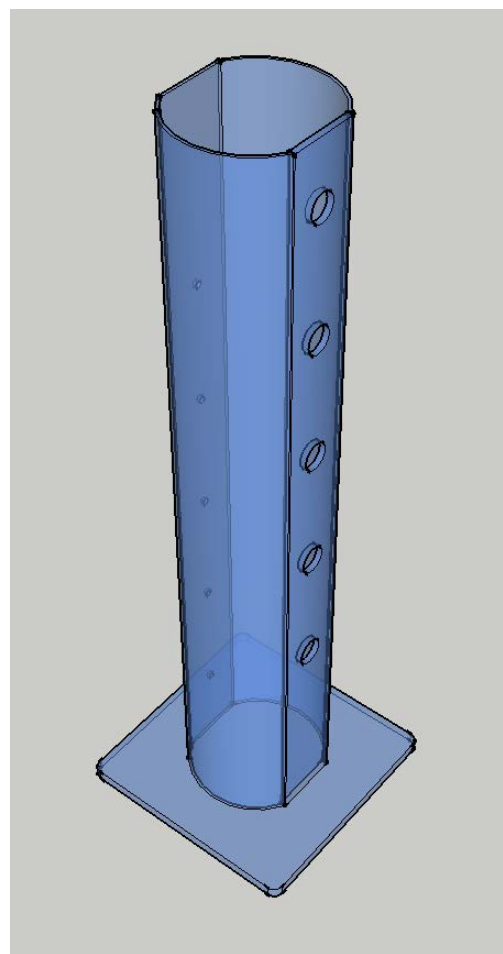
Kaolin in Salt water, inverse function relation



Appendix K: As-built drawing of the model column

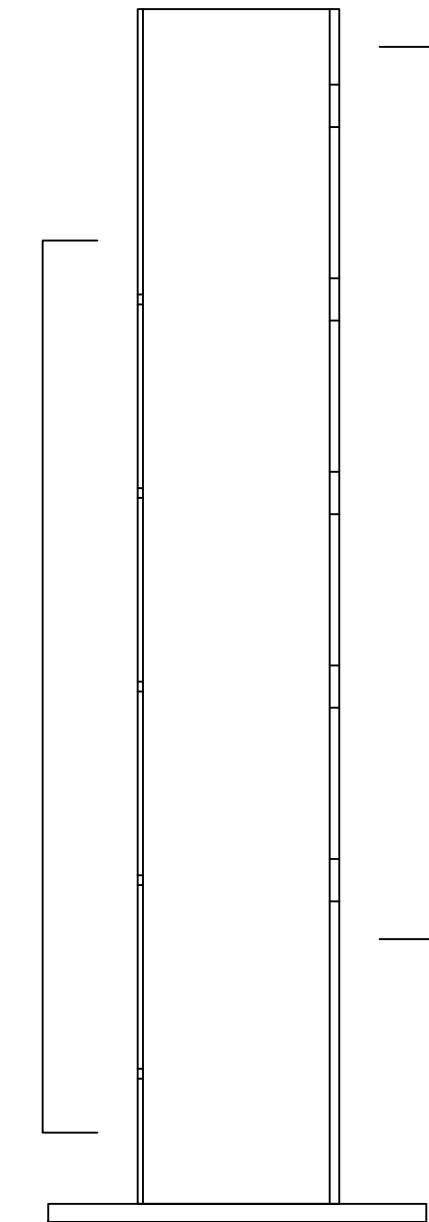


1 PLAN VIEW
SCALE 1:5



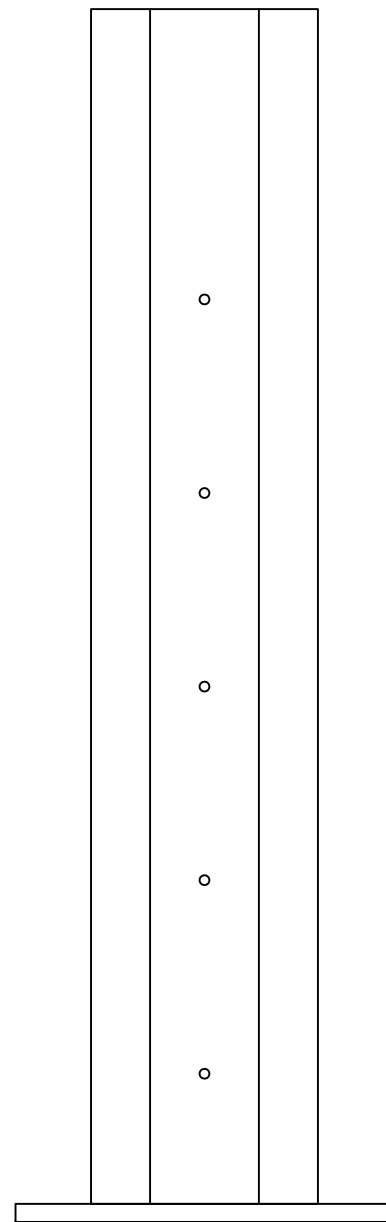
2 MODEL COLUMN PERSPECTIVE
NOT TO SCALE

5 X DIELECTRIC
SENSORS

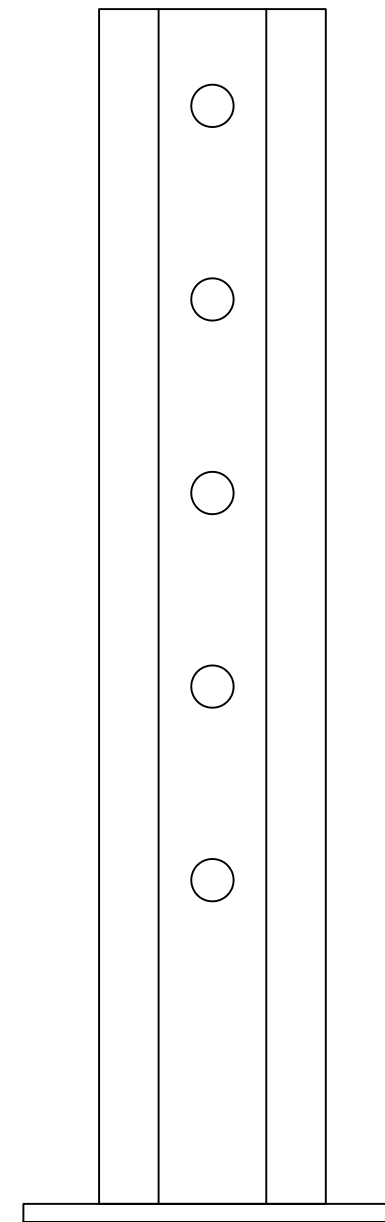


3 FRONT ELEVATION
SCALE 1:5

5 X TURBIDITY
SENSORS



4 DIELECTRIC ELEVATION
SCALE 1:5



5 TURBIDITY ELEVATION
SCALE 1:5

THE UNIVERSITY OF QUEENSLAND - EAIT FACULTY, SCHOOL OF CIVIL ENGINEERING					
GENERAL NOTES: ALL DIMENSIONS IN MM UNLESS OTHERWISE NOTED DO NOT SCALE	TITLE: MODEL COLUMN FOR SEDIMENTATION TESTING - AS BUILT				
	DATE: 05/10/2016	DRAWN: JG	DRAWING No: DWG 2-0		
	SCALE: AS NOTED	SHEET SIZE: A3	SHEET No: SHEET 1 OF 1	REV: 1	

Appendix L: Example of model column turbidity test data processing

Having used the methodology outlined in Section 5.2.5, four model column tests were undertaken to determine the methods by which the turbidity measurements could be used to interpret sedimentation processes. This appendix outlines the approach taken towards the processing of the raw data from these tests, using the example of Test i.

Initially, the mass of the empty tins (with labels applied) was found by measuring the mass of each tin three time and averaging these measurements. This process was adopted in an attempt to minimise random errors associated with these measurements. Three tins were also used for this same purpose. These are presented in Table L1.

Table L1: Mass measurements of empty tins

	Item:	Measurement	Measurement	Measurement	Average [g]
		1 [g]	2 [g]	3 [g]	
Measured, 11/10/16	Tin mass (1)	18.38	18.38	18.38	18.38
	Tin mass (2)	13.28	13.29	13.28	13.28
	Tin mass (3)	18.29	18.30	18.30	18.30

Once the model column test had concluded, data from the Arduino data loggers were collected. As the clocks on these data loggers had been configured, the data from each logger was collated and plotted over the duration of the test. This can be seen in Figure L1.

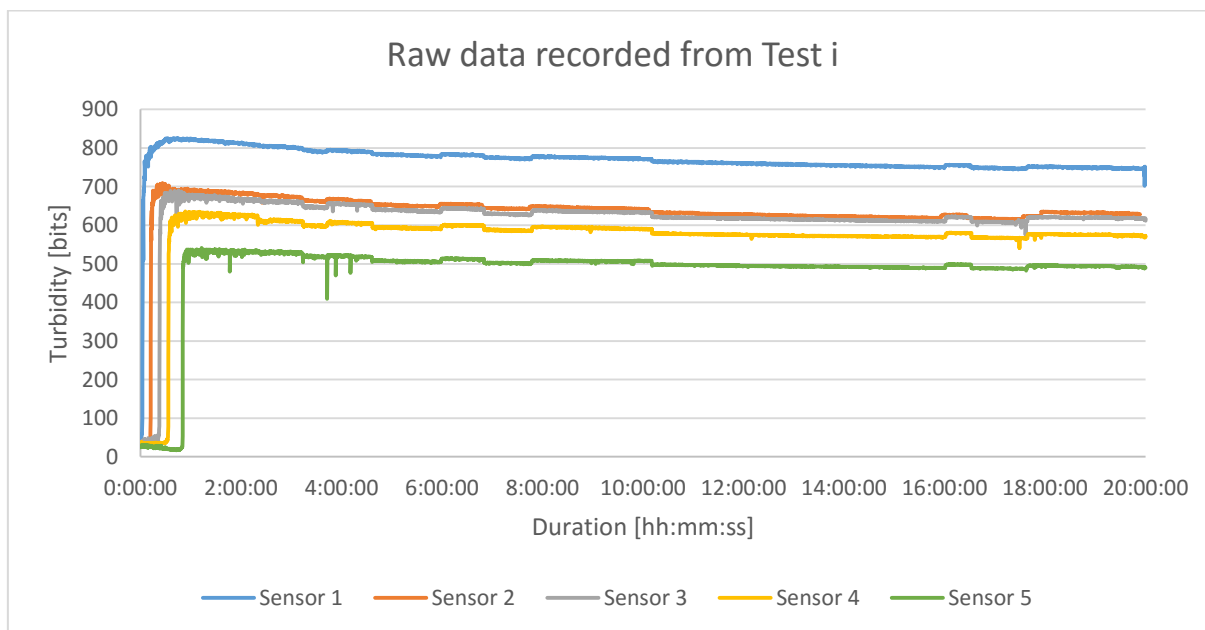


Figure L1: Raw data measured by TSD-10 sensors

Using the relationship for determined in the calibration tests for a mixture of kaolin in tap water, this data was converted such that the concentration of the mixture passing the sensor could be plotted over time. The relevant graph is shown in Figure L2.

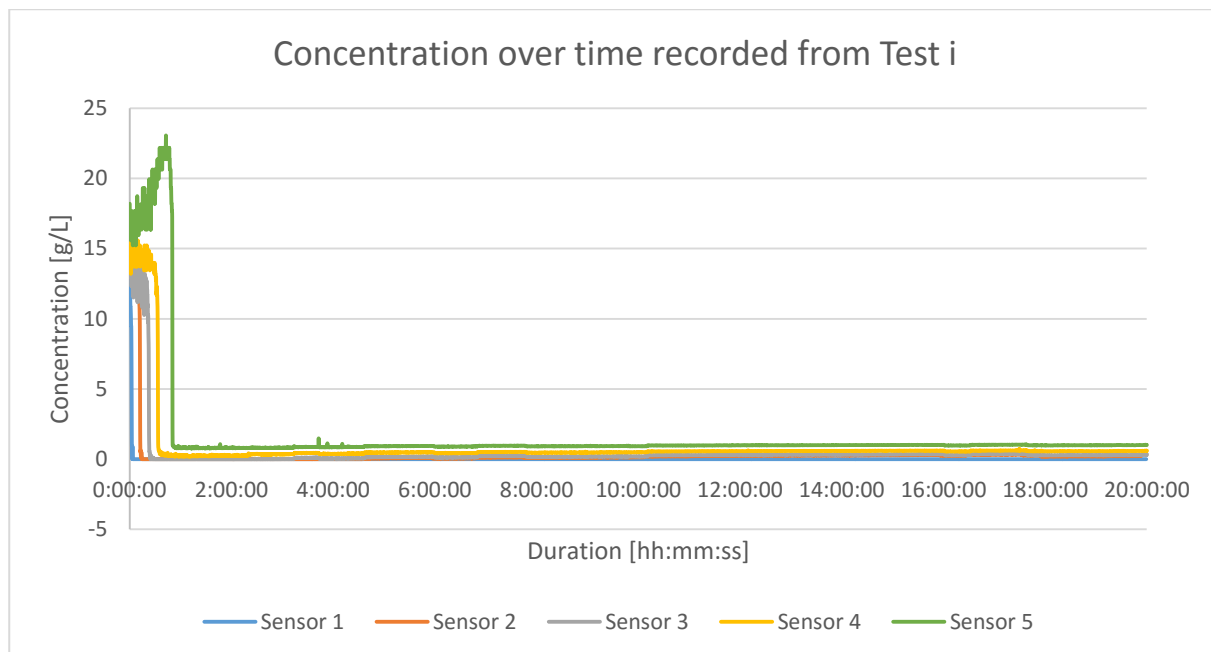


Figure L2: Plot of mixture concentration over time, derived from calibration relationship

From this plot, it is apparent that there is a sharp drop in concentration detected at each of the five sensors within the first hour of the test. To investigate this further, a plot of the concentration over just this period was produced and is shown in Figure L3.

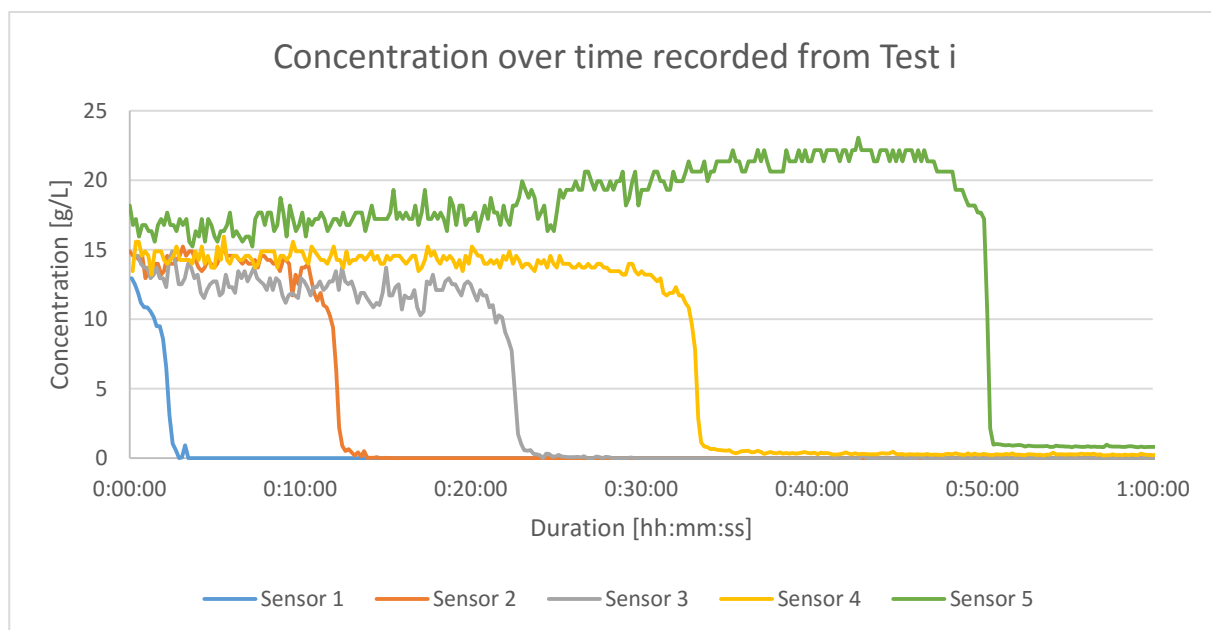


Figure L3: Plot of mixture concentration over time for the first hour

From this, the behaviour of the mixture can be interpreted. In addition to this, the other key area of interest is the variation in the concentration over time after the passing of the settling fronts. For this, a concentration plot of the test data after these sharp drops was made, as seen in Figure L4. Note that the scale of the y-axis has been changed.

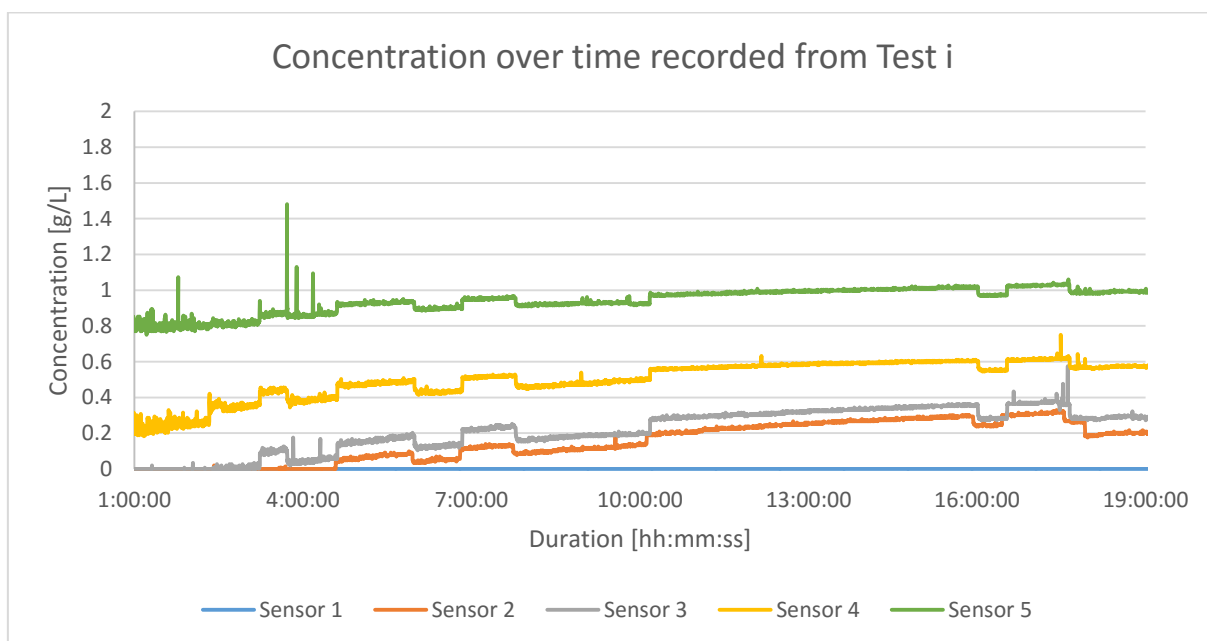


Figure L4: Plot of mixture concentration over time from hour 1 to hour 19

Again, some behaviour of the mixture can be interpreted from this data.

From the oven drying process, the initial concentration of the mixture could be calculated. Measurements of the dried 20mL samples and tins following the oven drying process were conducted, with the results shown in Table L2.

Table L2: Raw mass measurements of tins containing the oven dried samples

Item:		Measurement	Measurement	Measurement	Average
		1 [g]	2 [g]	3 [g]	[g]
Measured at 5:55pm, 12/10/16	Tin mass + sample (1)	18.96	18.95	18.95	18.95
	Tin mass + sample (2)	13.87	13.87	13.87	13.87
	Tin mass + sample (3)	18.83	18.84	18.83	18.83
	Tin mass + sample (1)	18.96	18.96	18.95	18.96
	Tin mass + sample (2)	13.86	13.87	13.87	13.87
	Tin mass + sample (3)	18.84	18.83	18.83	18.83

These were then used to calculate the initial concentration of the mixture, with the results presented in Table L3.

Table L3: Calculated sample masses and initial mixture concentration

Tin:	Average Tin mass [g]	Average Tin + Sample mass [g]	Sample mass [g]	True concentration [g/L]
1	18.38	18.96	0.58	28.83
2	13.28	13.87	0.58	29.17
3	18.30	18.83	0.54	26.83
Average:				28.28

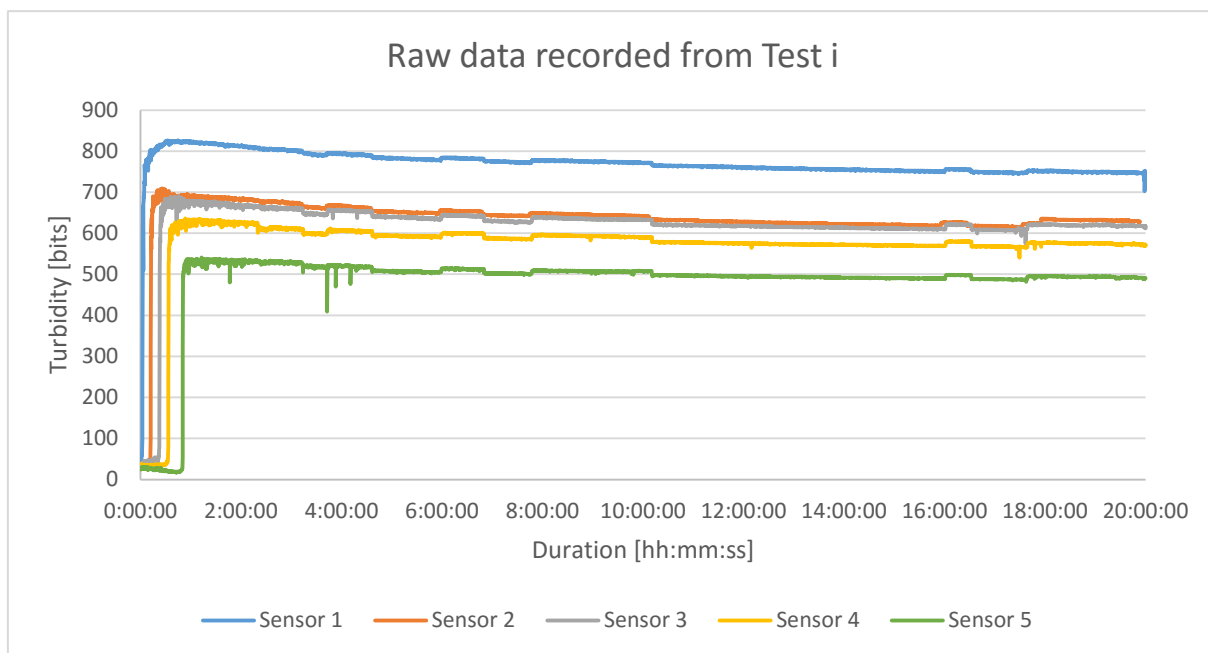
Appendix M: Model column turbidity test results

M1: Test i

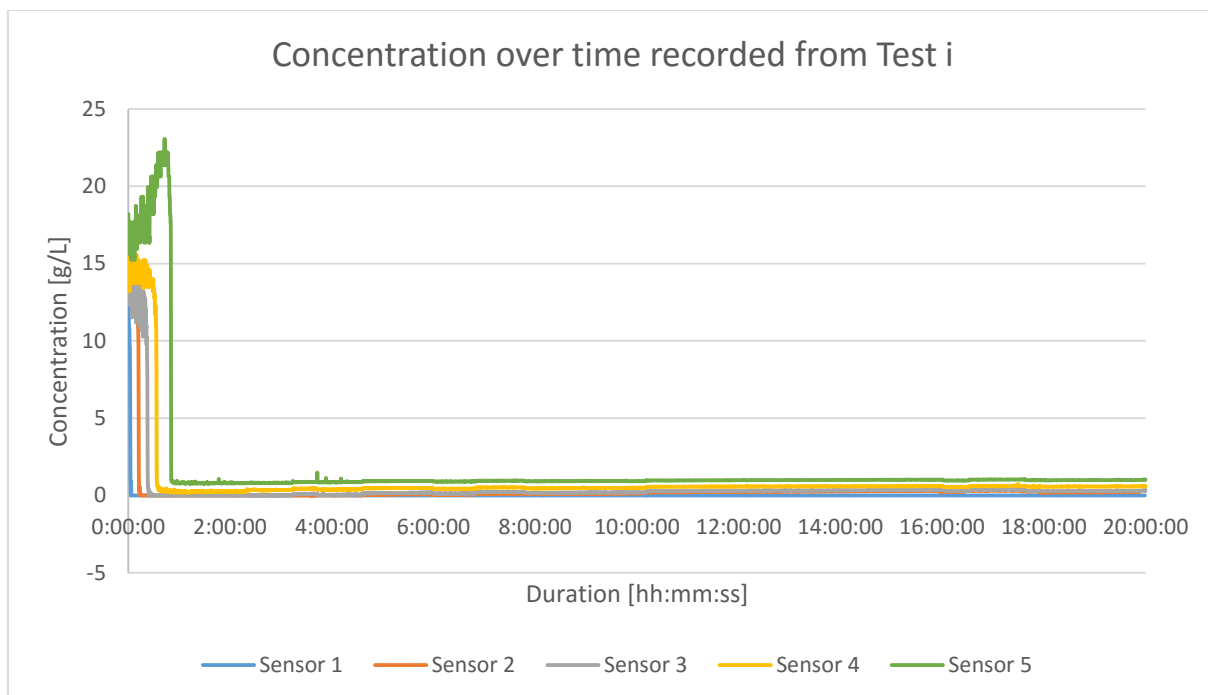
Test details:

- Start date and time of test: 11/10/2016, 3:20pm
- Material being tested: Kaolin in tap water
- Camera settings: 1 minute and 30 second intervals

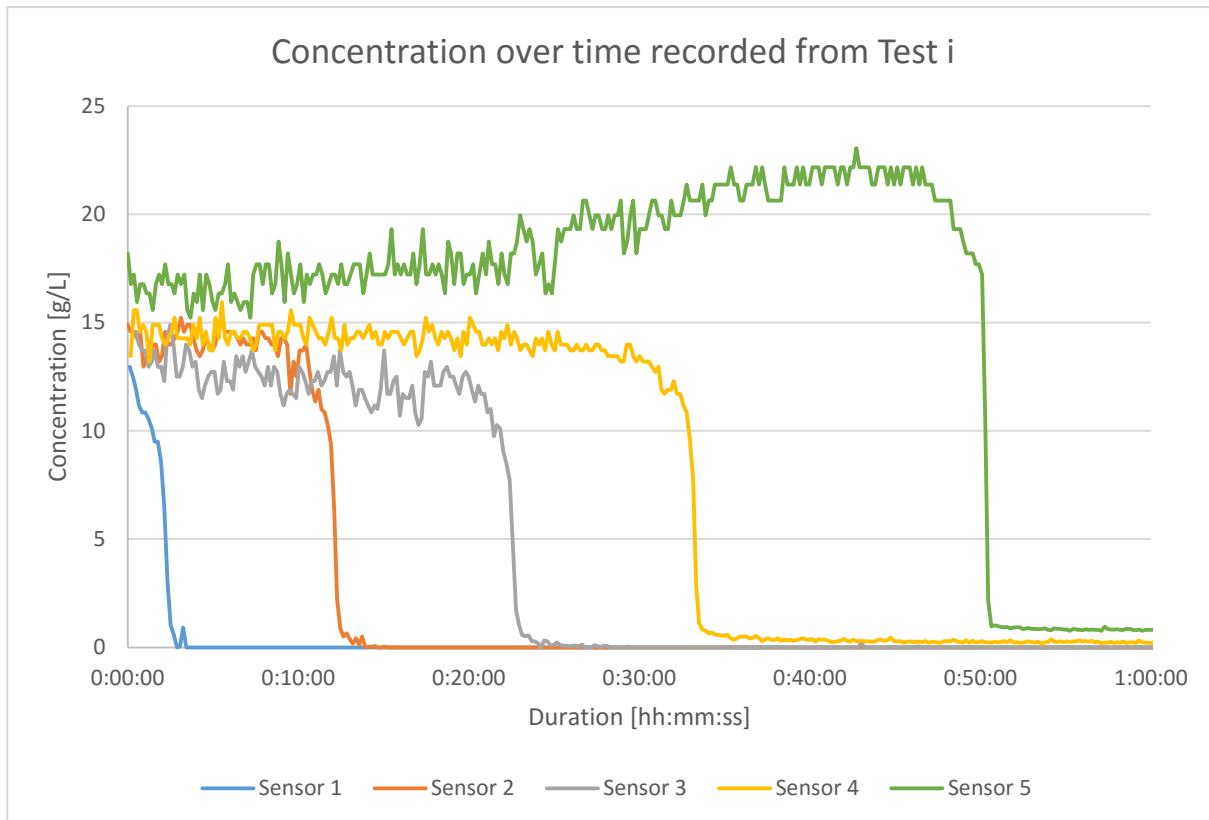
Raw data measured from turbidity sensors:



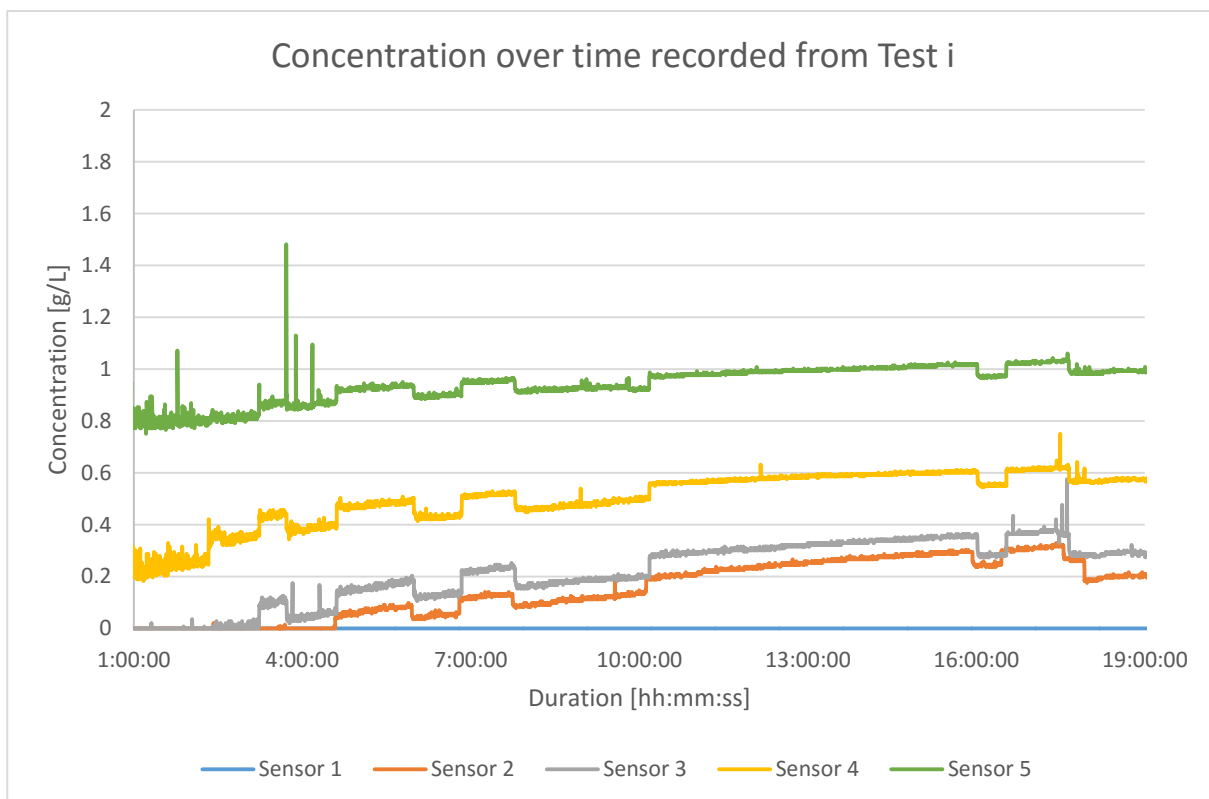
Converted concentration plot over time:



Concentration plot over time capturing passing of settling fronts:



Concentration plot over time after the passing of the settling front:



Mass measurements from oven drying:

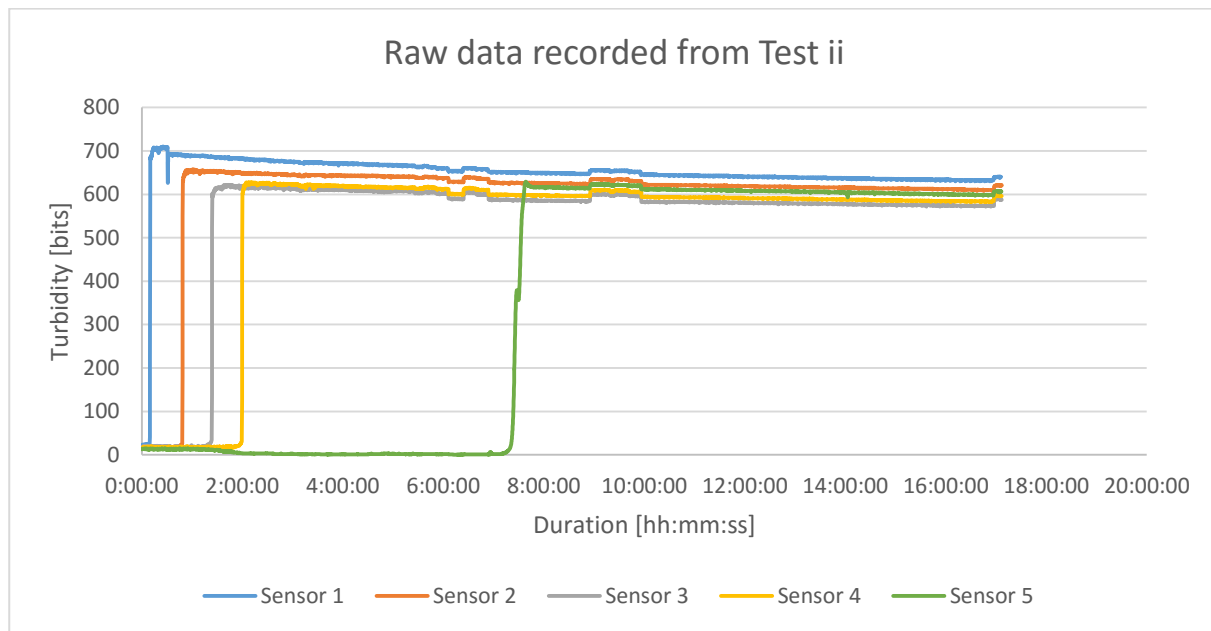
Tin:	Average Tin mass [g]	Average Tin + Sample mass [g]	Sample mass [g]	True concentration [g/L]
1	18.38	18.96	0.58	28.83
2	13.28	13.87	0.58	29.17
3	18.30	18.83	0.54	26.83
Average:				28.28

M2: Test ii

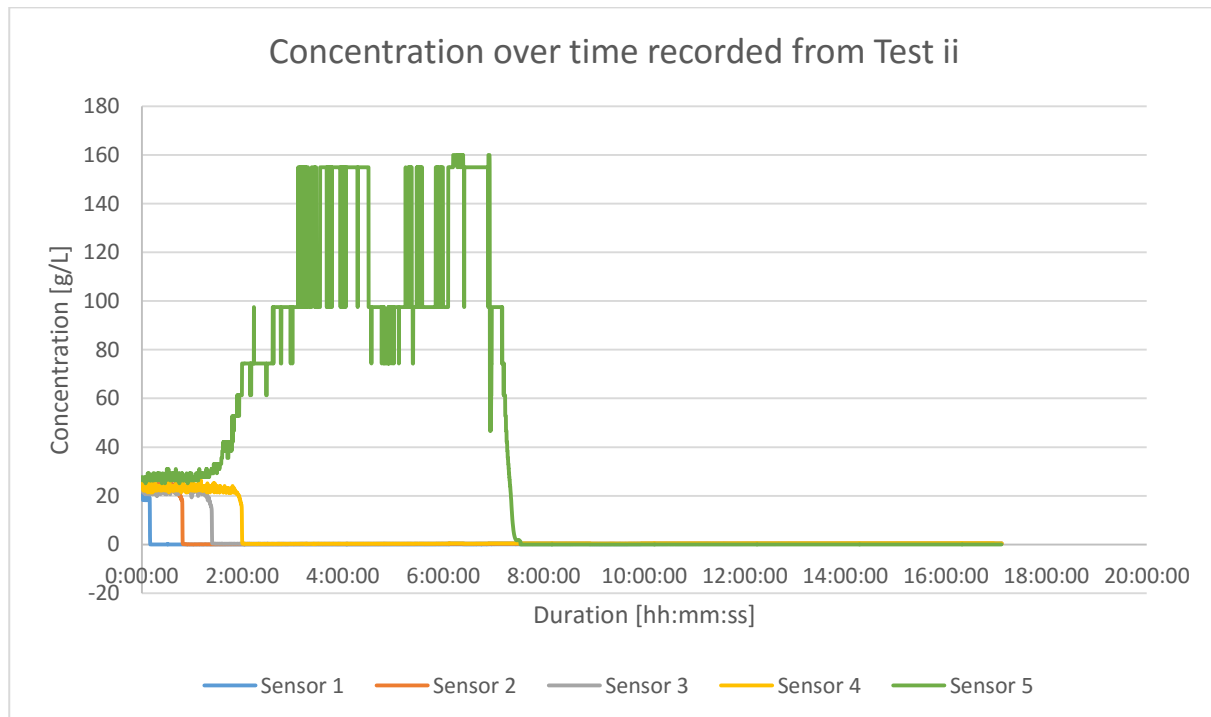
Test details:

- Start date and time of test: 13/10/2016, 2:28pm
- Material being tested: Kaolin in tap water
- Camera settings: 20 second intervals

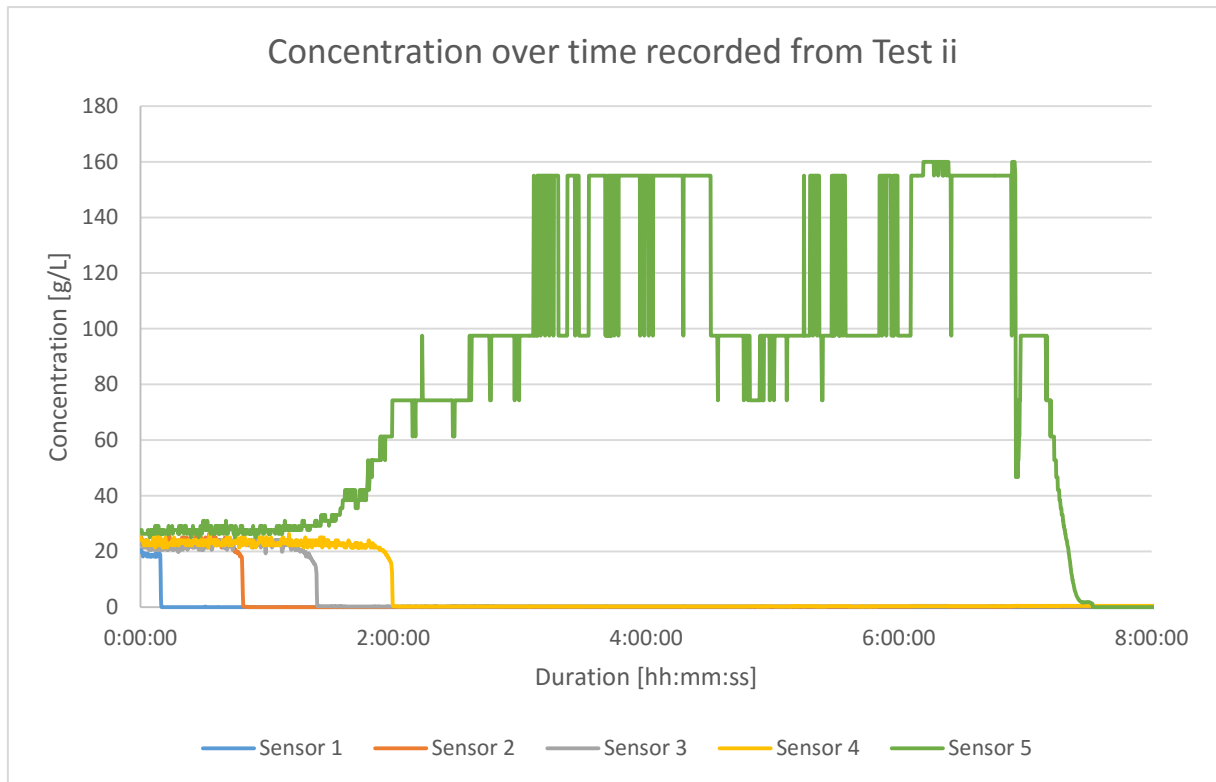
Raw data measured from turbidity sensors:



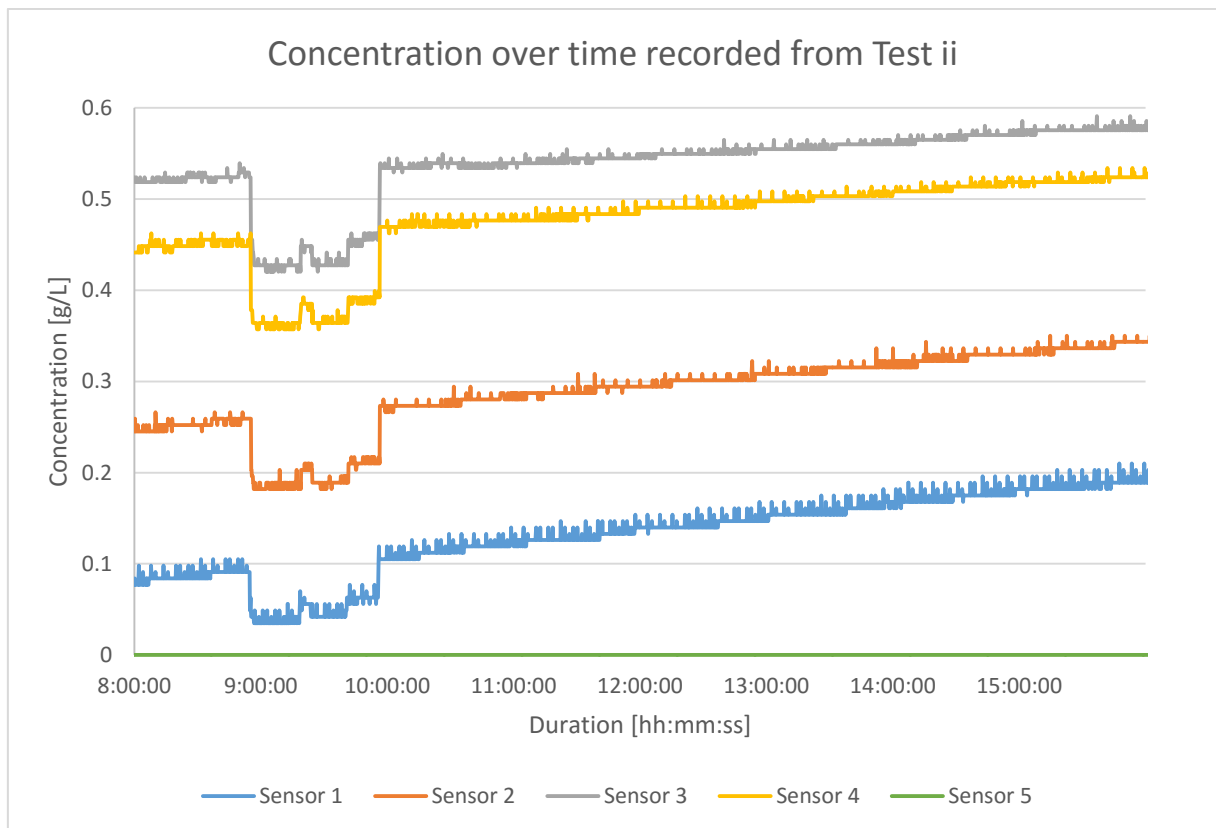
Converted concentration plot over time:



Concentration plot over time capturing passing of settling fronts:



Concentration plot over time after the passing of the settling front:



Mass measurements from oven drying:

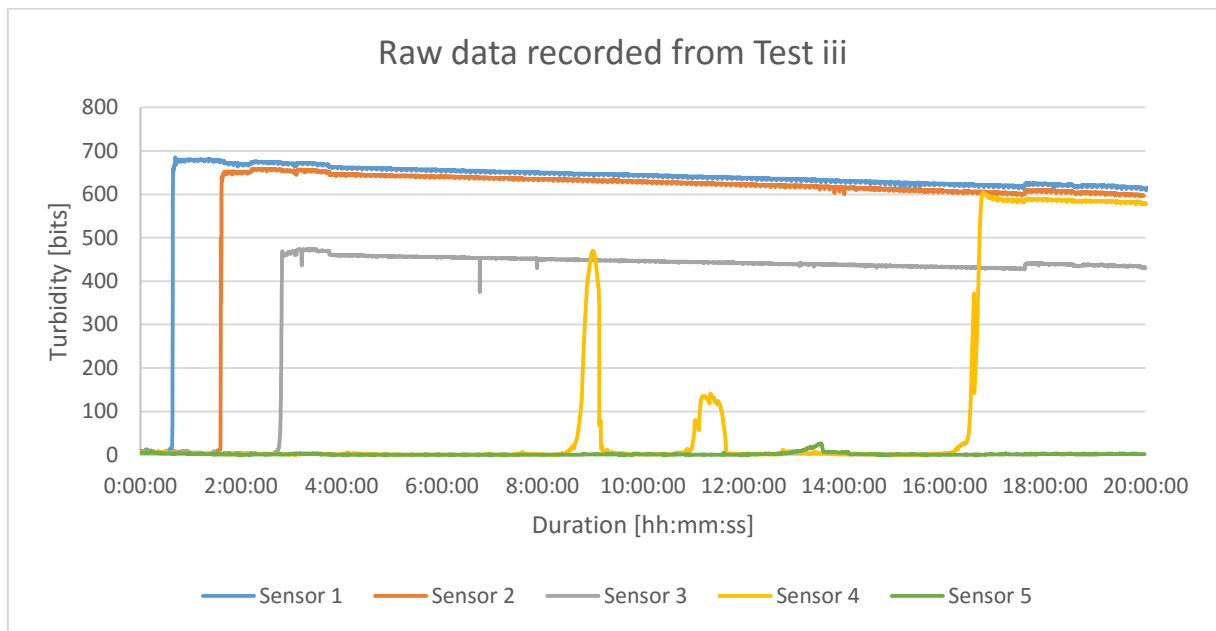
Tin:	Average Tin mass [g]	Average Tin + Sample mass [g]	Sample mass [g]	True concentration [g/L]
1	18.44	19.24	0.79	39.67
2	18.32	19.12	0.80	40.00
3	13.32	14.10	0.78	39.00
Average:				39.56

M3: Test iii

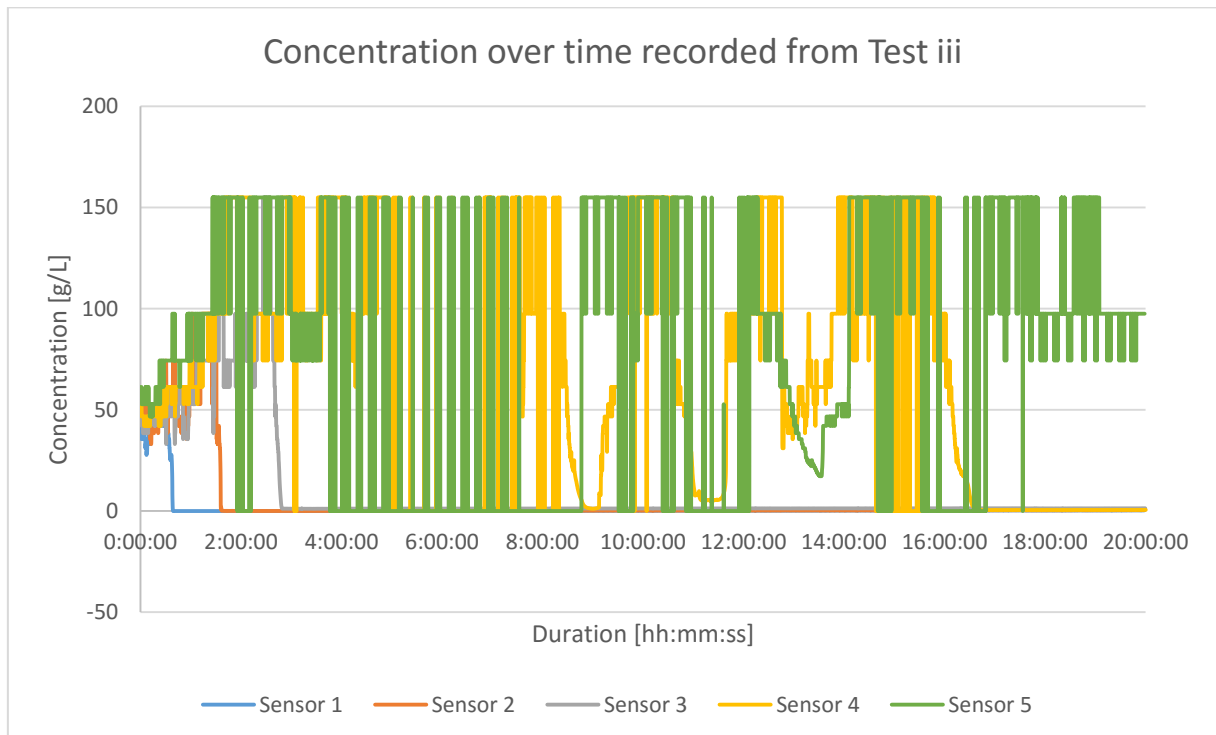
Test details:

- Start date and time of test: 14/10/2016, 2:45pm
- Material being tested: Kaolin in tap water
- Camera settings: Camera malfunctioned, no photos

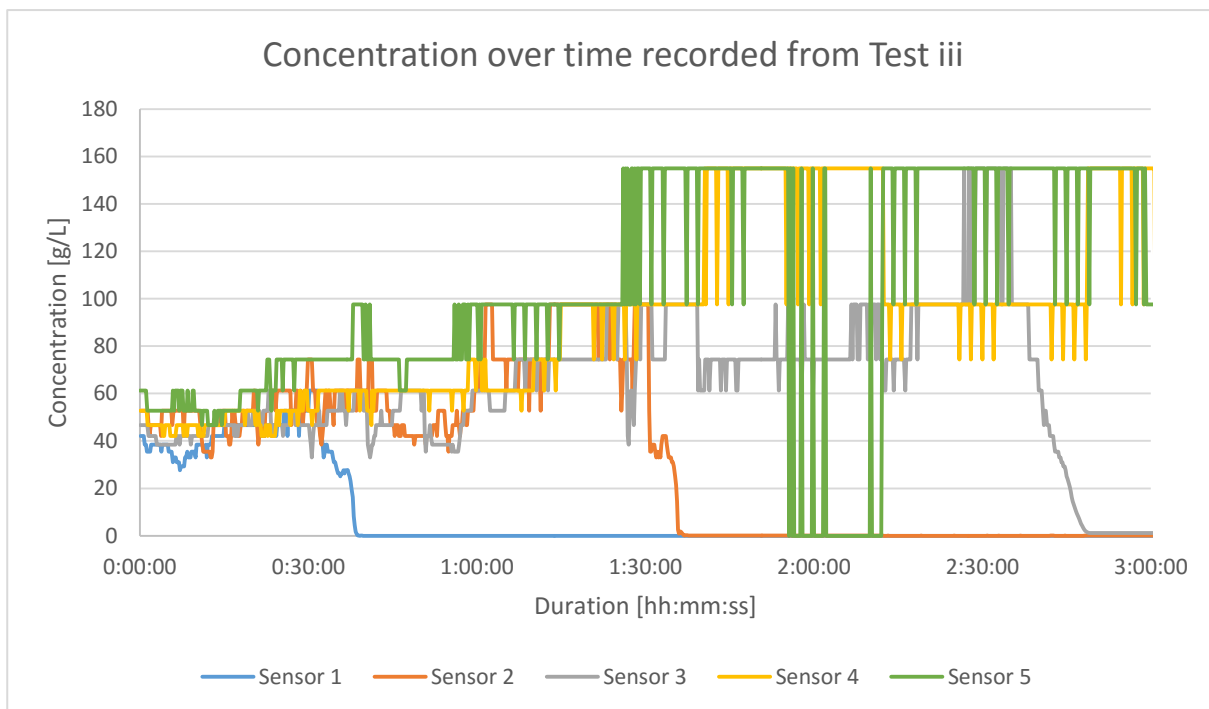
Raw data measured from turbidity sensors:



Converted concentration plot over time:

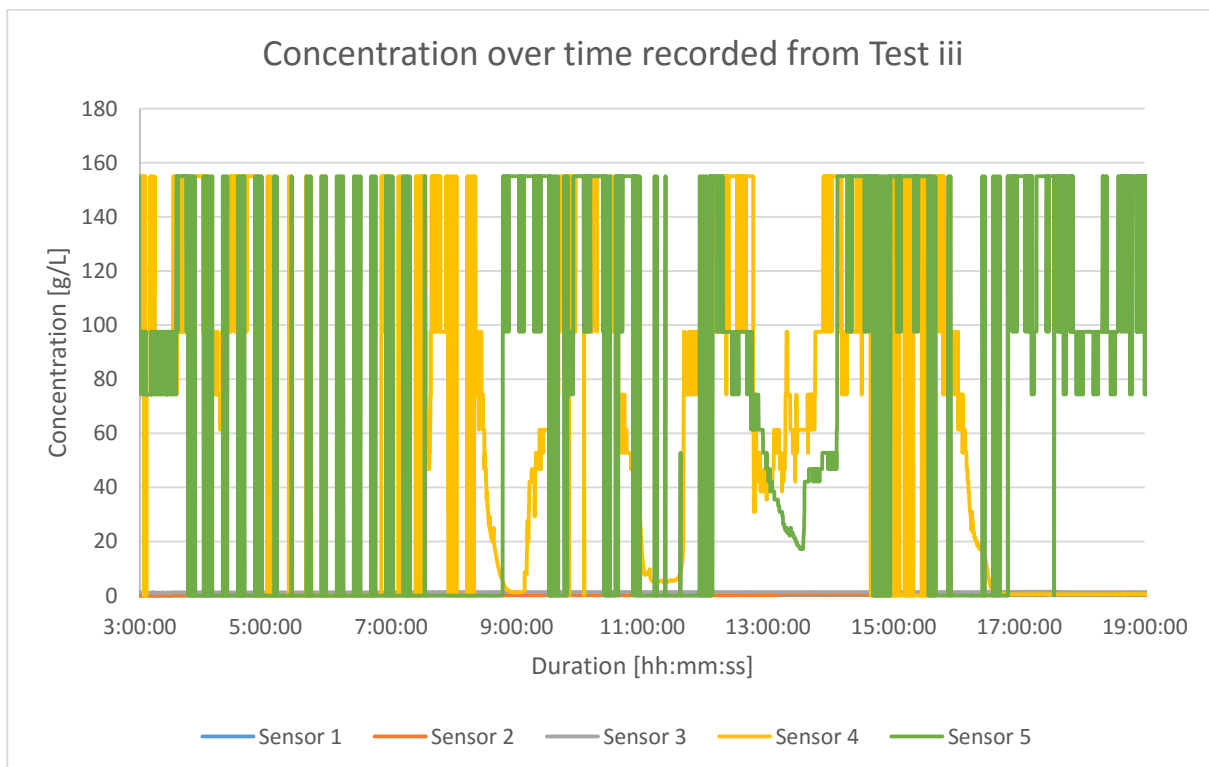


Concentration plot over time capturing passing of settling fronts:



Note: Reliable data for the passing of the settling fronts only appeared to be the case up to sensor 3.

Concentration plot over time after the passing of the settling front:



Mass measurements from oven drying:

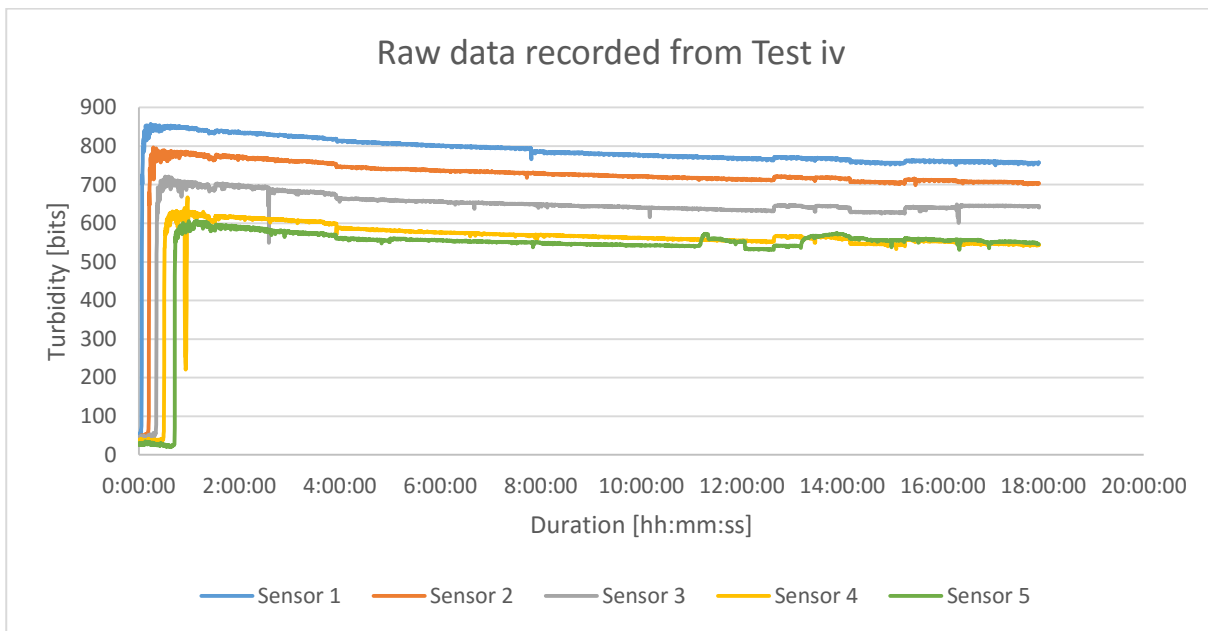
Tin:	Average Tin mass [g]	Average Tin + Sample mass [g]	Sample mass [g]	True concentration [g/L]
1	17.71	19.37	1.65	82.67
2	15.62	17.23	1.61	80.33
3	13.26	14.83	1.57	78.67
Average:				80.56

M4: Test iv

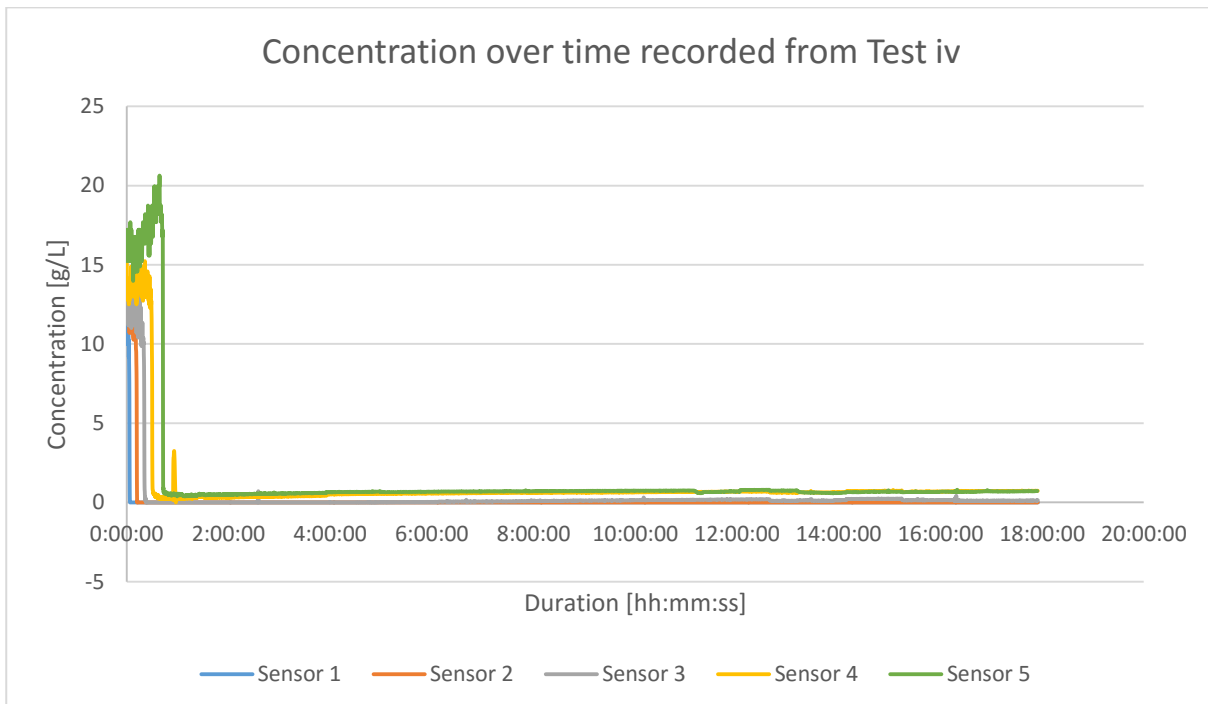
Test details:

- Start date and time of test: 18/10/2016, 4:32pm
- Material being tested: Kaolin in tap water
- Camera settings: 10 second intervals

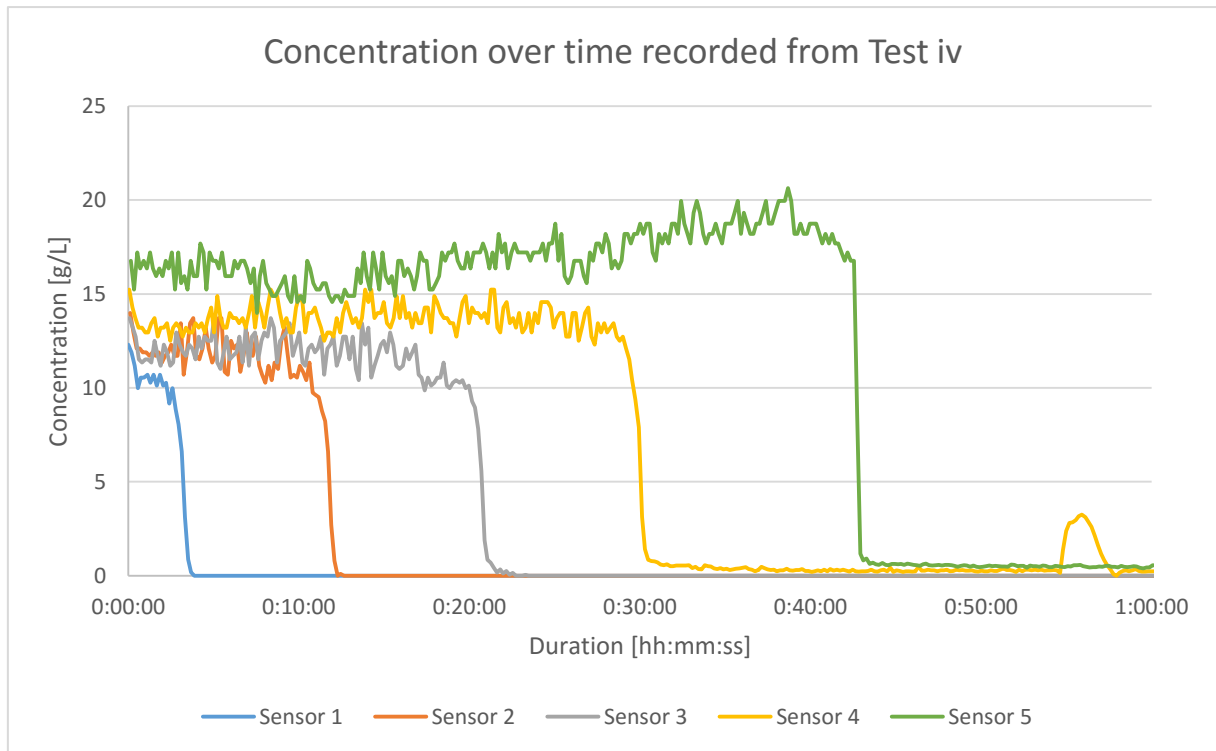
Raw data measured from turbidity sensors:



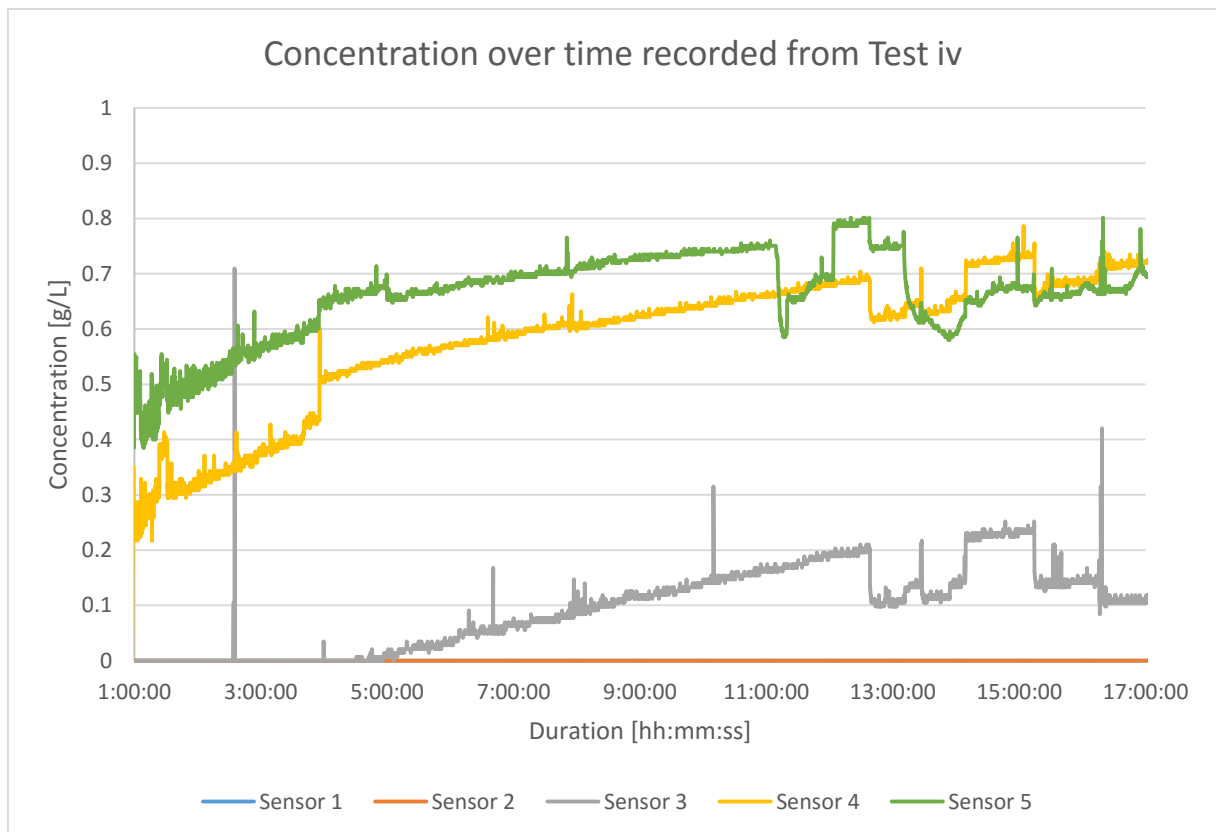
Converted concentration plot over time:



Concentration plot over time capturing passing of settling fronts:



Concentration plot over time after the passing of the settling front:



Mass measurements from oven drying:

Tin:	Average Tin mass [g]	Average Tin + Sample mass [g]	Sample mass [g]	True concentration [g/L]
1	15.60	16.06	0.47	23.33
2	17.70	18.16	0.46	23.00
3	13.20	13.65	0.45	22.50
Average:				22.94