THE EFFECT OF CATCHMENT CHARACTERISTICS ON SEWAGE SETTLING VELOCITY GRADING

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Doctor of Philosophy

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September 1995

The University of Aston in Birmingham

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THESIS SUMMARY

A procedure has been developed which measures the settling velocity distribution of particles within a complete sewage sample. The development of the test method included observations of particle and liquid interaction using both synthetic media and sewage. Comparison studies with two other currently used settling velocity test procedures was undertaken. The method is suitable for use with either DWF or storm sewage.

Information relating to the catchment characteristics of 35 No. wastewater treatment works was collected from the privatised water companies in England and Wales. 29 No. of these sites were used in an experimental programme to determine the settling velocity grading of 33 No. sewage samples.

The collected data were analysed in an attempt to relate the settling velocity distribution to the characteristics of the contributing catchment. Statistical analysis of the catchment data and the measured settling velocity distributions was undertaken. A curve fitting exercise using an S-shaped curve which had the same physical characteristics as the settling velocity distributions was performed. None of these analyses found evidence that the settling velocity distribution of sewage had a significant relationship with the chosen catchment characteristics.

The regression equations produced from the statistical analysis cannot be used to assist in the design of separation devices. However, a grading curve envelope was produced, the limits of which were clearly defined for the measured data set. There was no evidence of a relationship between settling velocity grading and the characteristics of the contributing catchment, particularly the catchment area. The present empirical approach to settling tank design cannot be improved upon at present by considering the variation in catchment parameters.

This study has provided a basis for future research into the settling velocity measurement and should be of benefit to future workers within this field.

Keywords: Settling velocity measurement, urban drainage.

ACKNOWLEDGEMENTS

First of all I must thank my supervisor, Peter Hedges, for all his encouragement and continuing support over the last four years. I would also like to thank all the staff in the Civil Engineering Department at Aston University, including Roger Kettle and Chris Page. No thanks to the department would be complete without thanking the technicians, especially Dave Hall, who helped me to see the lighter side of research and provided me with too many cups of tea to mention.

Although my research was supported by the EPSRC, additional assistance was provided by the Smisson Foundation and Hydro Research and Development Ltd. My thanks go to Bob Smisson and all those at the Smisson Foundation. 'Hydro' played a big part in my research and thanks to Andrew, Wendy, Jane and many others who were great. A huge thank you to Fiona.

Retiring from salaried employment and embarking on another degree really sorts out friends, and I have some very good friends: particularly Jenny, who managed to ply me with enough red wine to last into the next three years; and David and Roger who were always good for a beer (or two). Of course the list here could be endless, but I must mention Andy and Alison who provided many nights accommodation and Thursday nights out 'with the lads'.

On a more serious note, Joan, Malcolm and Jasna were instrumental in their kindness and care when I first returned to University after my back injury. I will never forget how they helped me through some black times.

The greatest thanks should be given to my family, without whom I would never have completed this study. My mother has been my mainstay, always being there, encouraging and bullying me to finish. My father and stepmother have been there in the background when I wanted a break away (or to be rescued) and my sister Caroline, brothers Stephen and Richard and nephew Luke have all been themselves, which has been great.

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CHAPTER 1

INTRODUCTION

1.1 HISTORY OF THE PROJECT

The construction of the main Black Country sewer in the mid 1980's was designed to improve the efficiency of the treatment of foul sewage in the West Midlands, and so help clean up the many polluted rivers, including the River Tame. Severn Trent Water Authority agreed to the installation of two Storm King™ hydrodynamic separators as combined sewer overflows (CSO) at James Bridge, Walsall and instigated a programme to study their performance. This study was part of a research project to produce a quantitative appraisal of storm overflow operation (Hedges and Lockley, 1990). Unfortunately, by the time the Storm Kings were installed the recession had led to a severe reduction in the runoff from the catchment. This reduction was due to the shutdown of many businesses, which in an area with a large proportion of manufacturing industries, led to an increase in the areas of wasteland and to many roofs being removed from buildings to avoid the payment of business rates. The result was a decrease in the impermeable area and so a reduction in storm runoff. In addition a series of dry summers and winters reduced the number of expected storm events during the period of study, which took place between 1986 and 1990. As a consequence it was agreed that pumped tests should be carried out on one separator in order to simulate storm conditions.

As part of the James Bridge study a prototype settlement column was constructed to determine the settling velocity of suspended solids in storm sewage and was used in the pumped tests. The prototype was based on a piece of apparatus developed by the civil engineering department at Heriot Watt University for the Scottish Development Department (Scottish Development Department, 1977). The Heriot Watt apparatus was designed to measure the terminal velocity of the particles within storm sewage and so obtain a distribution of its particulate matter.

The prototype column and test were used to study the solids removal performance of the hydrodynamic separator by comparing the settlement velocity gradings at the inlet and the outlet of the device under simulated storm flow conditions.

In addition to the partial removal of solids from storm sewage at specific types of CSO (Balmforth et al., 1994), solids-liquid separation devices are used widely in order to reduce the suspended solid matter in foul sewage. The devices used vary considerably, but basically they all rely upon gravity to separate the solid particles from the sewage. The devices employed may be at the primary and secondary sedimentation stages of a treatment works or they may be used as part of the chemical dosing of partially treated sewage at the tertiary treatment stage, where pollutants such as heavy metals need to be removed to meet consent standards. The efficiency of the separation devices is dependent on the settling velocities of the individual solid particles within the sewage - the lower the settling velocity the longer the time required for the particles to settle out under gravity. However, if the flow varies, the time the particles spend in the separation device will also vary. As the flow reduces the sewage is retained for longer in the separation device and a greater proportion of particles of different settling velocities is removed from the sewage. A logical conclusion from this is that the separation device for a particular site should be selected on the basis of its ability to provide treatment for the particular settling velocity grading of the sewage under consideration.

At present, design of sewage treatment works is based on empirically derived relationships that do not consider the composition of the sewage as it arrives at the wastewater treatment works for pollutant removal. Design is based solely on the dry weather flow (DWF) which is calculated to include a contribution from industry, where appropriate, and from infiltration into the sewer system (Institute of Water Pollution Control, 1984). A particular separation device is generally chosen because it has worked in a similar situation on another sewage treatment works. The actual performance of the separation device has not been directly related to the settling velocity characteristics of the sewage from the contributing catchment.

There is very little published information on the performance of solids-liquid separation devices in relation to sewage settling velocity grading. The data generally available give global efficiencies based on changes in the measurable properties of the sewage, for example the total suspended solids. However, the sewage that reaches a wastewater treatment works has been subject to many influences. Sewage ages as it travels through the sewer system, more so in large catchments where the time of concentration is considerably longer than in small catchments. In highly industrialised areas the type of pollutants that enter the system may be extremely varied, from abattoir waste with a high organics content, to the effluent from photographic film manufacturers with a high silver content. All these affect the composition of the sewage and the amount of bacterial or flocculating action which occurs within the sewers. Prior to this study no one had attempted to investigate the effects of the contributing catchment on the composition of the sewage, in terms of the settling velocity grading of the suspended solids reaching the wastewater treatment works.

The hydrodynamic separator installed at James Bridge was a Storm King™ designed and manufactured by Hydro Research & Development Ltd.. Mr R.P.M. Smisson of Hydro Research & Development Ltd. had, over several years, developed an interest in grading curves of sewage settling velocity, especially the work carried out by Pisano on vortex separators in the United States (Pisano, 1989). Smisson had discovered that the sum of the total available knowledge amounted to settling velocity grading curves from only 23 catchments (Smisson, 1990). However, these curves appeared to indicate some correlation between catchment size and the shape of the curve.

The paucity of knowledge concerning sewage settling velocity gradings, together with the development of the settling column for the James Bridge study led to the decision that a project to study the effect of catchment characteristics on sewage settling velocity grading should be initiated. Consequently the author was appointed to a SERC (now EPSRC)

Total Technology Studentship, sponsored by Hydro Research & Development Ltd., to research this problem.

1.2 AIMS AND OBJECTIVES

The aim of this project was:

> to develop a methodology that would enable sewage settling velocity grading curves to be determined from the characteristics of the contributing catchment, and hence be used as a tool for evaluating the performance of separation devices.

The objectives to this end were:

1) to develop a simple, economic method of determining the grading characteristics of sewage, which could then be used confidently by non specialists;

2) to examine the settling velocity characteristics of sewage samples from a number of different catchment areas and, from these data, to develop a model for predicting sewage grading curves;

3) to examine the potential for using sewage grading curves for designing and/or determining the performance of gravity, or gravity assisted, separation devices.

1.3 THESIS STRUCTURE

This thesis is a record of the experimental development of a sewage settlement velocity measurement method and its use to determine the relationship between sewage settling velocity gradings and the characteristics of the contributing catchments. The structure of the report is based on the logical progression of the project as it occurred during the three year period.

The thesis begins with a literature review of the available publications relating to wastewater composition and settling velocity measurement. The third chapter then discusses the development of the settling velocity measurement method and some of its advantages and drawbacks compared with other devices that are in use. The fourth chapter reports on the experimental laboratory techniques used in the collection and analysis of samples. Chapter 5 covers the collection of the catchment data, and includes a discussion of the data accuracy. Chapter 6 details the analysis methods used in attempts to develop relationships between the settling velocity grading of the suspended solids and the catchment characteristics, and discussion as to their use in design and for further research. Chapter 7 is a general discussion of the project, its findings and the relevance of the methods used for the settling velocity measurement and analysis. The report concludes with a summary of the project and the main conclusions from the analysis.

CHAPTER 2

WASTEWATER COMPOSITION AND CHARACTERISATION

2.1 INTRODUCTION

To successfully interpret the results of any sewage settling velocity analysis, an understanding of wastewater composition is essential. The composition of wastewater changes as it passes through both the sewer system (Nielsen et al., 1992; Pomeroy and Parkhurst, 1973) and the wastewater treatment works where pollutants are transformed and removed during treatment (Levine et al., 1985). Where techniques for determining the settling velocity of sewage particles have been developed, it is usually in order to obtain a measure of the size of a particle or floccule, which is formed from an aggregation of particles. A variety of methods for particle characterisation have evolved for particular fractions of sewage, including the dissolved, colloidal and suspended components.

This chapter discusses the available literature on sewage composition, particle characterisation and the various methods developed for the measurement of sewage particle settling velocity. The literature searches revealed a varying amount of information in the different fields of wastewater characterisation with most in the field of particle size characterisation and least in the area of sewage settling velocity measurement.

The composition of wastewater has been well documented in standard texts such as Metcalf and Eddy (1991), Peavy et al. (1985) plus many others, and a summary is provided in section 2.2. In addition in depth studies of wastewater under specific conditions such as sewers (Nielsen et al., 1992) have been undertaken. The processes used in wastewater treatment at a treatment works are outlined in section 2.3 of this thesis. In particular the processes that involve the removal of suspended solids by settlement are examined.

Section 2.4 reviews the growing volume of research in recent years into the characteristics of sewer sediments. Sediments have been classified into different groups according to both their position in the sewer and their physical characteristics (Balmforth, 1990). Some of this research has been concerned with the pollutants associated with the sediments, which has led to the characterisation of the solids by both particle size and settling velocity.

Causes of variations in wastewater quality reaching the wastewater treatment works are reviewed in section 2.5. The causes vary from the type of sewer system installed to the frequency and magnitude of storm events.

The development of methods of measuring the size of both discrete particles and flocs are discussed in section 2.6, particularly those methods which have been used to characterise wastewater. Many methods for sizing particles have been developed in the chemical industry where the particles usually have consistent physical characteristics, such as density, shape and size distribution. When considering wastewater, many different materials, both discrete and flocculating have to be sized. With flocculating particles great care needs to be exercised in order to leave the delicate floc structure intact during the sizing process.

Section 2.7 discusses the settlement mechanisms that are present within wastewater treatment processes. For wastewater at the preliminary and primary treatment stages, only discrete, flocculating and hindered settlement occurs. Some debate over modelling the settlement process is included. Section 2.8 goes further and discusses in some detail the processes of measuring the settlement of wastewater particles. There has been little research into measuring sewage settling velocity, the majority having been carried out in the last ten years. The different techniques developed have usually been applicable to one particular situation or fraction. For example, the Owen tube (Owen, 1976) is used to measure the settling velocity of turbulent flocculation of estuarine muds; the Umwelt-und Fluid Technik settling apparatus (Institute für Siedlungswasserwirtshaft Universität Karlsruhe, 1990) was designed to measure the settling velocity of the heaviest fraction of a storm sewage sample. The advantages and disadvantages of the different methods are reviewed and discussed in terms of the total sewage sample.

2.2 COMPOSITION OF WASTEWATER

Wastewater is usually classified as either industrial or domestic (often referred to as municipal, especially in North America). Industrial wastewaters are often given some form of pre-treatment before being discharged into the sewer system, the level of pre-treatment depending on the polluting effect of the discharge. Domestic wastewater is discharged directly into the sewer system and usually receives no pre-treatment before reaching the wastewater treatment works, except that provided by the retention in the sewers (Nielsen et al., 1992). Added to these components is a quantity of infiltration from the groundwater into the sewers through pipe joints and at manholes. The level of infiltration depends upon the groundwater level and the condition of the sewer system.

Wastewater is generally characterised in terms of its physical, chemical and biological composition. The principal contaminants in wastewater are shown in table 2.1. There are slight seasonal variations in composition, reflecting changes in use and levels of infiltration. Daily fluctuations in composition are noticeable, the more so in smaller catchments with more homogenous uses than in the larger ones (Peavy et al., 1985; Institute of Water Pollution Control, 1984). Pearson (1989) carried out a brief study of the quality of dry weather flow in two combined sewer systems. He concluded that different catchments produce very different concentrations of pollutants. In the catchments studied he believed that the variation in concentrations may have been due to three factors:

i) industrial discharges;

ii) population density (population/hectare);

iii) the difference in concentration of suspended solids may be related to pipe gradient at the point of sampling.

Contaminant	Source	Environmental significance
Suspended solids	Domestic use, industrial wastes, erosion by infiltration/inflow	Cause sludge deposits and anaerobic conditions in aquatic environment
Biodegradable organics	Domestic and industrial waste	Cause biological degradation, which may use up oxygen in receiving water and result in undesirable conditions
Pathogens	Domestic waste	Transmit communicable diseases
Nutrients	Domestic and industrial waste	May cause eutrophication
Refractory organics	Industrial waste	May cause taste and odour problems, may be toxic or carcinogenic
Heavy metals	Industrial waste, mining, rainfall, air, roads etc.	Are toxic, may interfere with effluent reuse
Dissolved inorganic solids	Increases above level in water supply by domestic and/or industrial use	May interfere with effluent reuse

Table 2.1 Important wastewater contaminants (Peavy et al., 1985)

Peavy et al. (1985) in discussing the composition of wastewater state that:

> "The most significant components of wastewater are usually suspended solids, biodegradable organics, and pathogens. Suspended solids are primarily organic in nature and are composed of some of the more objectionable material in sewage. Body wastes, food waste, paper, rags, and biological cells form the bulk of suspended solids in wastewater. Even inert materials such as soil particles become fouled by adsorbing organics to their surface. Removal of suspended solids is essential prior to discharge or reuse of wastewater."

The size ranges of the suspended solids, their measurement and removal methods have been well researched and the reader is directed to Levine et al. (1985) for more details of their characteristics. A summary of the composition of the organic materials in wastewater is shown in table 2.2.

Item	Classification			
	Soluble	Colloidal	Supra-colloidal	Settleable
Size range (μm)	<0.08	0.08-1.0	1-100	>100
COD (% of total)	25	15	26	34
TOC (% of total)	31	14	24	31
Organic constituents (% of total solids)				
Grease	12	51	24	19
Protein	4	25	45	25
Carbohydrates	58	7	11	24
Biochemical oxygen rate, k/d	0.39	0.22	0.09	0.08

Table 2.2 Composition of organic materials in wastewater (Levine et al., 1985)

The 'settleable solids' in wastewater are solids that will be removed by primary sedimentation. These solids may be either organic or inorganic, with the minimum particle size removed being about 54 to 67 μm (Levine et al., 1985). The 'total solids' is the material which can be removed from the wastewater by filtering and drying at 103°C to 105°C and will be composed of solids that float, are settleable, supra-colloidal and material in suspension. The filter papers employed have a nominal pore size of 1.2 μm (Whatman GF/C or equivalent) and the particles which pass through, the filterable solids, are colloids and dissolved solids. The dissolved solids can be both organic and inorganic. At the treatment works chemical coagulation or biological oxidation, followed by sedimentation is required to remove the filterable solids.

By heating the solids to 550°C ± 50°C, the organic fraction will oxidise and be released as a gas, leaving an ash. The oxidised organic fraction is called the 'volatile suspended solids', the remaining inorganic material is termed 'fixed suspended solids'. The solids content of an average wastewater is shown in table 2.3.

Total 720 mg/l	Suspended 220 mg/l	Settleable 160 mg/l	Organic 120 mg/l
			Mineral 40 mg/l
		Non-settleable 60 mg/l	Organic 45 mg/l
			Mineral 15 mg/l
	Filterable 500 mg/l	Colloidal 50 mg/l	Organic 40 mg/l
			Mineral 10 mg/l
		Dissolved 450 mg/l	Organic 160 mg/l
			Mineral 290 mg/l

Table 2.3 Classification of solids found in an average wastewater (Metcalf & Eddy, 1991).

Painter and Viney (1959) carried out studies into the organic composition of domestic sewage. They used filtration, centrifugal and settlement methods to obtain the solid organic components and freeze drying to obtain the soluble organic fraction. Chromatography was used to analyse the soluble organic component further. It was found that 70% of the organic carbon was in suspension, the remainder being soluble. Soluble organics are biodegradable materials such as proteins, carbohydrates and lipids. All these soluble organics contain carbons that can be converted to carbon dioxide and so have an oxygen demand. Proteins also contain nitrogen and so have a nitrogenous oxygen demand.

There are three standard measures used to express the oxygen demand of sewage, and hence its organic content. The test for Biochemical Oxygen Demand (BOD) is a measure of the biodegradable organics in sewage. Chemical Oxygen Demand (COD) measures the oxygen required for chemical oxidation of all organic matter. COD values are always greater than BOD values because non-biodegradable organic matter is decomposed in the test. There is however, no uniform relationship between BOD and COD (Hammer, 1991). The Total Organic Carbon (TOC) test is also used to measure the organic content of a sample, and is particularly useful for low levels of organics.

Waterborne pathogens of all forms can be found in sewage because they are discharged by people carrying the relevant infections. Pathogens include bacteria, viruses, protozoa and helminths. In the UK levels of Eschericia coli in final effluent are routinely determined as an indicator of treatment performance because few pathogens survive the wastewater treatment process (Metcalf & Eddy, 1991).

2.3 WASTEWATER TREATMENT

2.3.1 Treatment operations and processes

Suspended solids, biodegradable organics, pathogens, nutrients, toxic pollutants, such as carcinogens, and heavy metals are all removed from wastewater using traditional and modern treatment processes. Unit operations involve pollutant removal by physical forces, whereas unit processes involve biological and/or chemical reactions (Metcalf and Eddy, 1991). Both operations and processes employ natural phenomena, but their performance can be controlled by altering the environment in which the processes take place: i.e. design, temperature control, flow rate into the device, retention time, etc. (Peavy et al., 1985). A summary of appropriate treatment processes for pollutants is given in table 2.4.

A wastewater treatment works is usually comprised of primary and secondary treatment processes, and with tertiary treatment included on works where a further degree of treatment is required to remove pollutants, such as nutrients, in order to meet discharge consent conditions (see figure 2.1).

Contaminant	Unit operation, unit process or treatment system
Suspended solids	Screening and comminution Grit removal Sedimentation Filtration Flotation Chemical polymer addition Coagulation/sedimentation Hydrodynamic separation Natural systems (land treatment)
Biodegradable organics	Activated sludge variation Fixed-film reactors: trickling filters Fixed-film reactors: Rotating biological contactors Lagoon variations Intermittent sand filtration Physical-chemical systems Natural systems
Volatile organics	Air stripping Off gas treatment Carbon adsorption
Pathogens	Chlorination Hypochlorination Bromine chloride Ozonation UV radiation Natural systems
Nutrients: Nitrogen	 Suspended-growth nitrification and denitrification variations Fixed-film nitrification and denitrification variations Ammonia stripping Ion exchange Breakpoint chlorination Natural systems
Phosphorus	Metal-salt addition Lime coagulation/sedimentation Biological phosphorus removal Biological-chemical phosphorus removal Natural systems
Nitrogen and phosphorus	Biological nutrient removal
Refractory organics	Carbon adsorption Tertiary ozonation Natural systems
Heavy metals	Chemical precipitation Ion exchange Natural systems
Dissolved organic solids	Ion exchange Reverse osmosis Electrodialysis

Table 2.4 Unit operations, processes and wastewater treatment systems used to remove major contaminants found in wastewater (Metcalf and Eddy, 1991).

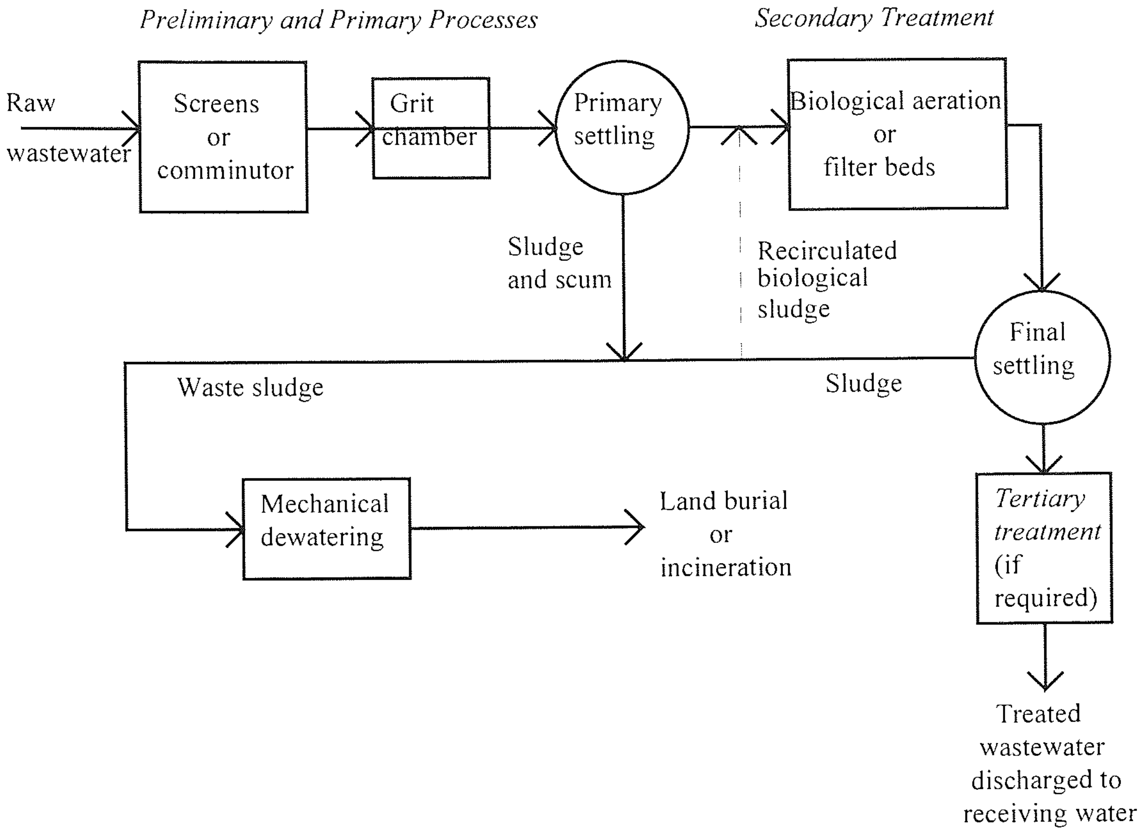

Figure 2.1 Schematic layout of the main wastewater treatment processes.

Traditionally sedimentation and screening are employed to remove the solids from the incoming sewage. The processes are in line and remove the largest solids first using screens, or comminutors to grind the gross solids to smaller sizes. Inorganic material in the form of grit is then removed in grit channels or detritors (Bechteler and Patt, 1987). The flow subsequently passes to the primary sedimentation stage where a large proportion of the organic suspended solids are removed, traditionally by sedimentation in rectangular or circular tanks. Currently new technologies are being researched and introduced into the primary sedimentation stage of treatment, such as the use of hydrodynamic separation (Andoh, 1994) and the use of chemical coagulants. Primary treatment should remove about one half of the suspended solids in the incoming sewage. These solids account for around 30% of the BOD in the influent to the works (Peavy et al., 1985).

Secondary treatment converts the biological dissolved and colloidal organics into a biomass that can be removed by further sedimentation. This biological treatment is carried out by micro-organisms that can be present either suspended in water in an aeration tank, where air is forced mechanically into the tank to provide the oxygen required, or as a culture attached to media on a trickling filter bed or a rotating biological contactor. The effluent from the biological process is then passed through the secondary settlement tank, also referred to as a secondary clarifier or a humus tank, where the dead micro-organisms and the biomass are removed. The sludge from secondary settlement is taken away for further treatment or disposal, depending on the pollutants present and the facilities available. On some treatment works the waste activated sludge is returned to the primary settlement tanks for co-settling with the primary sludge.

Tertiary treatment is used when effluent consent standards are not met by the primary and secondary treatment processes. Further solids removal combined with the removal of nutrients takes place.

2.3.2 The activated sludge process

One form of secondary treatment is the activated sludge process. An activated mass of micro-organisms (an aerobic bacterial culture) is produced that can aerobically break down and stabilise the secondary influent. The resultant activated sludges are then settled out in sedimentation tanks. The process was developed by Arden and Lockett (1914). The settlement of the activated sludge is of interest for the purposes of this project because a significant amount of both theoretical and experimental research has been carried out into the settlement of the activated sludges that are present after the aeration process. This research has led to a greater understanding of the creation and settling of flocs under hindered settling conditions (see section 2.7.4 for an explanation of the settling processes).

In the activated sludge process the concentration of the particles is far greater than 0.5% by volume and so hindered settling takes place (Camp, 1973b). At low concentrations there is little or no interaction between individual sewage particles and hence each settles at its own individual terminal velocity. When concentrations increase a delicate porous structure is built up by aggregation of the particles. As the floc increases in size its terminal velocity increases, but the weight, and hence size, of the structure is limited. The shear force of the water passing through the floc increases with the increasing settling velocity until the structure reaches a size limited by the strength of the bonds between the particles and hence a limiting terminal velocity is reached. As the activated sludge particles enter the secondary settlement tank flocculation under hindered settling conditions takes place. The particles are so densely packed that they appear to be settling as a blanket. Above this sludge blanket there is a clear supernatant layer that is drawn off the tank as effluent. The particles from the sludge blanket slowly settle, but are continually being replaced on top by further flocculating particles and as a consequence the blanket remains stable. The particles in the blanket slowly squeeze the water upwards from the sludge as they settle resulting in a relatively dense sludge layer that can be removed from the base of the tank (Camp, 1973b).

The sludge volume index (SVI) is a measure of the settleability of the solids and is defined as the settled volume of the mixed-liquor after either a half or one hour of quiescent settling in a 1 litre measuring cylinder, the result is expressed per unit weight of solids. The SVI has been used for the design of secondary sedimentation tanks associated with the activated sludge process, mainly because it is simple and quick to measure, with no special apparatus required. White (1975a) has highlighted several shortcomings in the measurement of the SVI:

- the SVI varies in an inconsistent way with the initial concentration of suspended solids;

- the SVI depends on the dimensions of the vessel in which it is measured. In addition Vesilind (1968) found that solids in a low concentration of suspended solids settle more quickly within a cylinder of small diameter than of large diameter. With a high concentration of suspended solids, the solids settle more slowly in a cylinder of small diameter than of large diameter.

- the settlement of the particles in the suspension may be hindered in a shallow vessel, such as a measuring cylinder, by partial support from solids at the bottom of the vessel;

- there does not appear to be a relationship between the SVI and the settling characteristics of activated sludge (Dick and Vesilind, 1969);

- although the SVI can be used for one particular plant, it cannot be used to compare the performance of different plants.

To overcome some of these problems the Water Research Centre (White, 1975a) introduced a stirrer into the measuring cylinder. This reduced the effect of cylinder diameter by preventing the wall effects hindering the settlement. White (1975a) discussed the design of final settlement tanks based on settling velocity. In calculating the downwards mass flow per unit area (mass flux) of solids, it was assumed that the settling velocity could be expressed solely in terms of the mass concentration of the solids, but in the case of activated sludge, the settling velocity might also depend on the depth of the initial suspension.

White (1975a and 1975b) introduced and discussed new parameters for measuring the settling characteristics of activated sludge: the stirred sludge density (SSD expressed as a percentage) and the stirred specific volume (SSV in ml/g). A specially designed settling apparatus was used to measure rates of hindered settling and SSV. This parameter is considered by Water Research Centre to be a better parameter for estimating the maximum solids loading (±20%) that can be introduced to the activated sludge settling tanks without solids being passed out in the final effluent.

Several models for simulating the activated sludge process have been developed. A couple of examples are provided by Anderson and Hanson (1973) and Sollfrank and Gujer (1991). Anderson and Hanson employed hydraulics and consolidation theory in developing their model for simulating the behaviour of particles settling in close proximity to each other. The model was developed specifically for the activated sludge process and was based on empirical measurements using SVI.

Sollfrank and Gujer (1991) developed a mathematical model of the activated sludge process which was based on the rate of oxygen uptake, which in turn was a function of the changes that take place within the sludge during decomposition.

In most cases the concentration of solids within activated sludge tanks is over 1 g/l, which far exceeds that of the wastewater entering a treatment plant (White, 1975b). In addition, most of the inorganic suspended solids have been removed, leaving just the organic particles and flocs to be treated. There has been a considerable quantity of literature published which relates to the theories and activities encountered within the hindered settlement conditions of activated sludge. Although this literature is important within the whole treatment process, it has little relevance to the conditions encountered in the settlement of solids in the crude sewage entering the wastewater treatment works. For further information Metcalf and Eddy (1991) is recommended as a first reference.

2.4 SEWER SEDIMENTS

Sewer sediments are the suspended solids that are deposited onto the invert of the sewers by the wastewater and the organic slimes that build up on the pipe walls. Not all sewers have deposits of sediments in them, but where there are sediments they are deposited in the sewers during periods of low flow and subsequently much, if not all are re-suspended into the flow during and after rainfall when flow velocities are increased (Ashley et al., 1992; Jefferies and Ashley, 1994). Since sediments form an important component of combined sewage (see section 2.5.1) an understanding of their characteristics is relevant to this research.

WRc and Hydraulics Research Limited jointly carried out a considerable amount of research into the nature of sewer sediments to assist in the design and development of MOSQITO, a model developed to improve the design of sewer rehabilitation schemes (Crabtree, 1989). As part of the initial research the sediments deposited in sewers were classified into five types according to their nature and location within the sewer system, as shown in table 2.5. Physical particle size characterisation of sewer sediment samples was carried out by dry sieving their ashed mineral residue. The particle distribution was then expressed as percentages of dry weight of gravel, sand and silt. The chemical analysis showed there was a great deal of variability of pollutant strength within each of the classes, although there was evidence that the Type D sediments, which were the slimes on the pipe walls with high organics content, had a greater polluting effect per unit mass than the coarse, loose, mainly mineral Type A sediments found in the pipe inverts. This has been confirmed by CIRIA (1987), Chebbo et al. (1990), Ashley and Crabtree (1992) and Michelbach and Wöhrle (1993). It should be remembered however, that the quantities of the wall slimes will be lower than the bed sediments when re-suspended into stormwater and so their polluting impact will be lower. Type C sediments are mobile, fine grained deposits found in slack zones, either on their own or overlying the coarser Type A sediments. These Type C sediments may be the most polluting and are associated with the 'first foul flush' at the start of many storm events (Crabtree, 1989; Verbank and Ashley, 1993).

Sediment Type	Characteristics
A	Coarse, loose, granular, predominantly mineral, material found in the inverts of pipes.
B	As A but concreted by the addition of fat, bitumen, cement, etc. into a solid mass.
C	Mobile, fine grained deposits found in slack flow zones, either in isolation or above Type A material.
D	Organic pipe wall slimes and zoological biofilms around the mean flow level.
E	Fine-grained mineral and organic deposits found in storm sewer overflow storage tanks.

Table 2.5 Categories of sewer sediments based on observations of the provenance, nature and location of the deposits within the sewer system (Crabtree, 1989).

Sediments have generally been considered to be non-cohesive, individual particles for the purposes of design. Crabtree's study (1989), together with those of other research workers (Chebbo et al. 1990; Chebbo, 1992 ; Michelbach and Wöhrle, 1992a and 1993; Novak and Nalluri, 1987), have shown that there may be considerable amounts of organic material within the sediments that may lend some cohesive property to the particles. This means that a higher bed shear stress may be required to erode the sediment than if these cohesive forces were not creating a higher critical yield stress.

In recent years there has been a considerable amount of research into the mechanisms of sediment transport within sewer systems (CIRIA, 1987; Perrusquía et al., 1987; Novak and Nalluri, 1987; Ashley and Jefferies, 1988; Crabtree, 1989; Goodison and Ashley, 1989; Laplace et al., 1990; Ashley and Crabtree, 1992; Ashley et al., 1992; Nalluri, 1992; Verbank and Ashley, 1993; Kleijwegt and Clemens, 1993, and many more). The sediment bed type is a very important factor in the resistance to flow and sediment transport mechanism. The bed may be flat, rippled or duned, or a combination of a flat bed with isolated bedforms (Kleijwegt and Clemens, 1993). These different bed types are produced at varying shear stresses and affect flow resistance.

Perrusquía (1993) provides an excellent summary of the factors affecting sediment transport in pipe channels:

> "The rate of motion of particles in stream traction in a fluid medium contained within the loose bed, pipe walls and free water surface is a function of the flow conditions (velocity, depth, energy gradient and acceleration due to gravity), fluid (density and viscosity) and sediment (density and size) properties, geometric characteristics of the hydraulic section (bed thickness, bed width and pipe diameter) and roughness of both sediment and pipe walls."

Chebbo (Chebbo et al., 1990 and Chebbo, 1992) carried out research into the characterisation of sewer sediments in terms of size, settling velocity and density of suspended solids. This was related to the pollutants associated with the sediments. Particle settling velocity measurements were made using a settling column for particles greater than 50 μm in diameter and using a pipette for particles less than 50 μm in diameter (see section 2.8.2.4). The sediment settling velocities were generally very high, even for particles less than 50 μm. Using an Imhoff cone, 70-80% of the sediments were deposited after 15 minutes and more than 97% after one hour.

Michelbach and Wöhrle (1992a, 1992b and 1993) undertook a three year study of the settling velocity of sewer sediment and the pollutants associated with them. They made separate analyses of sediment, slime and wastewater, and found that there appeared to be a relationship between the settling velocity of the particles and the load of heavy metals. More heavy metals were bound to the slime than the bed load because the heavy metals were absorbed into the skins of the micro-organisms (Michelbach and Wöhrle, 1993). The method of settling velocity measurement used is discussed in section 2.8.2.5

2.5 VARIATIONS IN WASTEWATER QUALITY

2.5.1 Combined sewage

2.5.1.1 Characteristics of combined sewage

There are three basic types of sewer system in use in the UK.

> "a) Combined System - the foul sewage and surface water from roads, streets, yards and roofs discharge into a common sewer for conveyance to the sewage works for treatment.
>
> b) Separate System - the sewage discharges into a foul sewer which conveys it to the sewage works for treatment; all the surface water runs into a separate surface-water sewer and is discharged into the nearest suitable watercourse.
>
> c) Partially Separate System - most of the surface water (generally water from roads, paths and roofs of buildings) runs into a surface water sewer and is discharged into the nearest watercourse; the foul sewage plus some surface water (generally water from back roofs of buildings) discharges into the foul sewer which conveys it to the sewage works for treatment."
>
> (Bolton and Klein, 1971)

The majority of the sewers installed in Britain use the combined sewer system due to the historical development of sewage disposal. As new sewer systems are being built they are generally being created as separate systems, but it will be a long time before the problems associated with the fouling caused by combined sewers under storm flow conditions are eliminated.

For the purposes of this research, storm runoff has not been considered except in that it contributes to the combined sewage that is received by the wastewater treatment works for cleaning. When rainfall occurs any excess water that does not infiltrate into the ground, or is not ponded, flows across the surface until it enters the sewer system through roadside gullies, roof drains, manhole covers etc. In a combined sewer system this stormwater mixes with the domestic, industrial and infiltration flows that occur in dry weather to produce a diluted wastewater (Metcalf and Eddy, 1991).

Early work on the composition of storm sewage expressed the results in terms of suspended solids, BOD, ammoniacal nitrogen and chloride ions. The rise and fall velocities of the particulate matter was not measured. When trying to determine the relationship between crude and storm sewage, the Water Research Centre (1975) and the Scottish Development Department (1977) considered storm sewage to be crude sewage diluted with surface water for all the pollutants except suspended solids. They found that the suspended solids load was much higher in storm sewage than was expected by dilution. Crabtree (1989), Ashley et al. (1992), Michelbach and Wöhrle (1993) and other researchers have suggested that this increase in suspended solids loading may be due not just to the solids being washed from the surfaces into the sewer but also to the re-suspension of the sewer sediments.

Metcalf and Eddy (1991) proposed table 2.6 as a summary of the factors affecting the quality of combined wastewater.

Other research workers have found that the antecedent conditions can be an important influence on the runoff quality. Pollutants can build up within the sewer and the catchment prior to a storm event. During a storm event the sewer solids are re-suspended into the flow and the pollutants that have collected in the catchment are washed into the sewer system (for example: Fletcher et al., 1978; Hémain, 1982; Ellis et al., 1987; Pearson, 1989; Crabtree, 1989; Ashley and Crabtree, 1992).

During long dry spells, the build up of pollutants on roads and other impermeable surfaces may be very high and this leads to a heavy pollutant load arriving at the treatment works at the start of the storm. This forms part of the 'first flush' phenomena (Tucker and Mortimer, 1978; Ellis et al., 1982). The accumulation of pollutants also occurs when there are snowfalls that do not melt for long periods of time, such as occurs in North America and Scandinavian countries. Heavy metals and other pollutants build up in dust trapped within the settled snow, and are then discharged with the melt water into the watercourse in spring (Lygren and Damhaug, 1986; Viklander and Malmqvist, 1993). In dry periods, the potential pollutant load may be partially controlled by the effective sweeping of roads to remove the dust in which they are contained (Fletcher et al., 1978; CIRIA, 1990).

Parameter	Quantity-related factors	Quality-related factors
Precipitation	Rainfall depth and volume Storm intensity Storm duration	Regional atmospheric quality
Wastewater	Flow rate and variability Type of contributing sources (residential, commercial, etc.)	Type of contributing sources
Drainage basin	Size, time of concentration Land use and type Impervious area Soil characteristics Runoff control practices	Pollutant build-up and wash-off Watershed management practices
Sewer system, interceptor	Pipe size, slope and shape Quantity of infiltration Surcharging or backwater conditions Type of flow regulation or diversion Capacity reduction from sediment build up	Chemical and biological transformations Quality of infiltration Sediment load re-suspended from collection system

Table 2.6 Typical factors influencing the characteristics of combined wastewater (Metcalf and Eddy 1991).

The characteristics of combined wastewater vary extensively between storm events, even at the same locations. The rainfall itself contains pollutants in the form of a BOD, heavy metals and nutrients which are washed out of the atmosphere. Bacteria, solids, oxygen-demanding materials, nutrients and metals are then added to the rainfall as it becomes runoff and washes the impervious surfaces of streets and buildings (Metcalf and Eddy, 1991).

Ellis (1977, 1982 and 1979) carried out extensive research on the composition of suspended solids in urban wastewater. He found that the range of particle size in suspended solids is due to pollution from different sources, both above ground and in the sewer system. The initial storm flow appeared to be characterised by finer particles followed by larger sized particles during peak flow. The recession limb of the storm hydrograph also appeared to contain finer particles.

The BOD and faecal coliforms concentrations drop as storm runoff increases, returning to dry weather flow levels as the runoff ceases at the end of the storm. In general the suspended solids concentrations rise at the beginning of the storm and then return to the normal levels throughout the remainder of the storm although there may be several peaks in suspended solids concentration depending on the storm pattern and the catchment shape. The fall in BOD concentration indicates that the storm runoff contains little oxygen demanding material and bacteria compared to the DWF sewage, but that there are similar concentrations of inorganic suspended solids. The increase in suspended solids at the start of the storm is probably due to the 'first flush' effect where there is an initial washing of pollutants from the impermeable sources into the sewer system and some erosion of any deposited bed sediments. The level of pollutants in the first flush depend not only on the catchment characteristics, but also on those of the storm. (Metcalf and Eddy, 1991).

Table 2.7 provides a comparison with the characteristics of combined sewage compared to rainfall and wastewaters from other sources. It should be noted that the characteristics of the combined wastewater lie between those of the stormwater and the untreated municipal wastewater and are dependent on the mix of the two (Metcalf and Eddy, 1991).

Parameter	Unit	Range of parameter concentrations			
		Rainfall	Stormwater runoff	Combined wastewater	Municipal wastewater
Suspended solids	mg/l		67-101	270-550	100-350
BOD_5	mg/l	1-13	8-10	60-220	110-400
COD	mg/l	9-16	40-73	260-480	250-1,000
Faecal coliform bacteria	MPN/100ml		1,000-21,000	200,000-1,100,000	10^6-10^7
Nitrogen (total as N)	mg/l	0.05-1.0		4-17	20-85
total kjeldahl nitrogen			0.43-1.00		20-85
nitrate			0.48-0.91		0
Phosphorus (total as P)	mg/l	0.02-0.15	0.67-1.66	1.2-2.8	4-15
Metals	µg/l				
copper			27-33		
lead		30-70	30-144	140-600	
zinc			135-226		

Table 2.7 Comparison of characteristics of combined wastewater with those from other sources (Metcalf and Eddy, 1991)

2.5.1.2 Storm overflow pollutants

The flow through a combined sewer will increase during and immediately after a storm event. Traditionally in England and Wales combined sewer overflows (CSO's) are used to limit the flow of combined wastewater both through the sewer network and into the wastewater treatment plant under storm flow conditions. CSO's are employed because the costs of providing a sewer system and treatment facility capable of handling all storm flows are prohibitive (Balmforth et al., 1994). The capacity of the sewers, that is the limiting flow through the sewer system to the treatment works, is set using Formula 'A' (this is expanded upon in section 4.2.3). Once the maximum flow to treatment has been reached the combined sewage is discharged into a receiving watercourse. At the wastewater treatment works only three times the DWF is passed forward for treatment, the remainder is passed to storm tanks where it is either returned to the main line for treatment when the storm subsides, or undergoes partial treatment by settlement before being discharged, via the overflow, to a watercourse.

There has been a lot of concern about the pollutants that are discharged at CSO's. The storm overflow will contain all the pollutants in DWF plus the pollutants contributed by the storm runoff, which may include oil, grit and chemicals, along with a suspended solids load. The total suspended solids load in storm water may exceed that in DWF sewage, particularly during the "first flush" phenomena (Tucker and Mortimer, 1978; Ashley et al., 1992).

The pollutants in storm-overflow discharges fall into a number of categories:

- pollutants containing carbon compounds, e.g. faecal matter;
- toxic pollutants, e.g. ammonia, hydrogen, copper, phenol, cyanide and other poisons;
- nutrients which cause eutrophication;
- bacterial pollution, e.g. E.coli.

Although it is the above factors that cause serious damage to the watercourse, it is the presence of gross solids in the water that cause most public complaints. The gross solids are usually carried over the storm-overflow at the start of the storm when the impervious surfaces are first washed clean of debris (Balmforth, 1990). This first flush will contain a high concentration of pollutants. Urban areas have more problems with surface runoff because they generally have a larger impervious area than rural areas.

This sub-section has been a very brief summary of the problems associated with the pollutants in combined wastewater under storm flow conditions. This research is not concerned with storm flow conditions and therefore no great detail is included in this thesis. For more information the reader is directed in the first instance to: the Urban Pollution Management Manual (Urban Pollution Management Steering Group, 1994); the Guide to the Design of Combined Sewer Overflows (Balmforth et al., 1994); and to the proceedings of the six past International Conferences On Urban Storm Drainage (Helliwell, 1978; Yen, 1981; Balmer et al., 1984; Yen, 1987; Marsalek and Torno, 1993).

2.5.2 The effect of the sewer system on wastewater characteristics

When a pumped sewerage system is installed, ideally a series of grinder pumps at each of the inlets is required. This reduces the size of the material in the wastewater so that it may be pumped without damaging any pumping equipment (Metcalf & Eddy, 1991). However, although this is a rare occurrence one can surmise that the passage of sewage through a pump will result in degradation in the size of some of the larger solids.

No specific research into the effect of time of concentration on wastewater quality was found by the author. The majority of research has been directed to modelling the time of concentration of rainfall runoff on the storm hydrograph, for example: Akan, 1984; Jenson, 1984 and Ben-Zvi, 1987. For illustration, Agiralioglu (1984) carried out a mathematical study of the difference in time of concentration of storm runoff for a rectangular and a converging triangular catchment. He concluded that a rectangular catchment has a longer time of concentration than a converging triangular one. This was not confirmed experimentally.

Nielsen et al. (1992) have produced a summary of the transformation of wastewater in sewer systems that includes a large section referring to the composition of wastewater. Domestic wastewater is a very complex combination of inorganic and organic compounds. The time that the sewage spends in the sewers has a major effect on its composition due to the effect on: microbial growth; respiration in the bulk water, and in the biofilms; solubilisation; enzymatic hydrolysis of macromolecules; hydraulic shear forces; and sedimentation and re-suspension.

2.6 PARTICLE SIZE ANALYSIS

It is generally accepted by the wastewater industry that a greater understanding of the size distribution of the solids within sewage would help to improve the design of treatment processes: the size characterisation of particles is a prerequisite to understanding their roles in the sedimentation process. Discrete particles such as gravels and sands can have their sizes measured directly by sieving. The fine grained suspended particle fraction is the most difficult to size because the particles tend to be present in the form of flocs, which are difficult to maintain during sampling and analysis (Swift et al., 1972; Task Committee on Preparation of Sedimentation Manual, 1969).

Some research methods use dispersants to break down the bonds within the flocs and then measure the sizes of the constituent particles (Chebbo, 1992). Breaking down the bonds is acceptable if one is only interested in the chemical composition of the suspended solids element of the sewage, but is not of use if an understanding of the particle sizes of the sewage as encountered in field conditions is required. In the author's opinion the flocs formed by aggregation are an integral part of the sewage and should, where possible, be maintained during the measurement process.

Only spherical objects have the same physical properties in all directions, whereas most naturally occurring particles have properties that vary in direction. These properties include the projected area, settling velocity, volume, length and size of hole through which particles will pass. In addition to the wastewater treatment industry, the chemical industry require particles to be characterised, but their particles usually fall within a defined range of size, shape and specific gravity, therefore many of the sophisticated instruments that have been developed also measure particle size within a narrow range. This is partly because the instruments were designed for specific purposes, for example: the Coulter Counter was designed to measure blood cells; the laser particle sizer to measure fuel spray droplet size (McCave and Syvitski, 1991). Where there are large size and characterisation ranges, as in the case of wastewater where particle sizes range from colloids to sands and gravels, more than one analytical method has to be employed. In addition, wastewater particles are composed of a wide range of inorganic and living and dead organic materials. The different materials may occur as individual particles or as aggregates of different particles bound together, usually by organic materials such as slimes or fats (Matthews, 1991b). This leads to the projected areas, volumes, and diameters of the particles being highly variable (Swift et al., 1972).

Wastewater particles do not just have varying physical properties, but due to their diverse nature also have varying chemical properties. The many different methods of particle size analysis measure different physical, chemical and electrical properties in their procedures and so can be expected to produce slightly different results for the same sample. The method chosen should be carefully considered in terms of the property to be measured before a study is undertaken, and in reporting the results of a size analysis, the method used should be clearly stated (Swift et al., 1972; Levine et al., 1985; McCave and Syvitski, 1991). The same principle applies to the measurement of particle shape: there are numerous methods available, but they all produce slightly different results (Matthews, 1991a).

The size distribution may give some means of identifying the origins of sediments. The most commonly used method of characterising the size of a particle is its diameter. Most particles that occur naturally do not have a regular shape, let alone a spherical one. In order to categorise and compare the size of a particle irrespective of the analysis method employed, an 'equivalent particle diameter' is used. In microscopy the 'diameter' used is the equivalent projected diameter, i.e. the diameter of a circle with the equivalent cross-sectional area as the particle. In sedimentation methods, the diameter of a sphere with the same density and settling velocity as the particle is calculated using Stokes law. The Coulter Counter measures the equivalent volume diameter by sensing the electrical resistance of particles in an electrolytic solution as they pass through an orifice.

Great care must be taken not to destroy the number or structure of composite particles during sampling, transport and analysis. For example: sedimentation techniques will usually alter the structure by disruption; clay particles are very sensitive to the strength of an electrolyte solution - the stronger the solution, the greater the flocculation of the particles (Swift et al. 1972).

In sediment transport particles do not all travel discretely - many form aggregates with the organics within the sediments binding the particles together (Ozturgut and Lavelle, 1984). Almost every sample collected for size analysis undergoes some form of pre-treatment. The pre-treatment varies from stirring to disperse any lumps that may have formed, to the use of ultrasonics or chemicals to remove the organics, carbonates or iron oxides that may be binding the individual particles together (Matthews, 1991b). This is particularly true in the case of gravels and sands that are relatively large and have their particle sizes measured directly by sieving. In order to remove the organic matter from a sediment sample, hydrogen peroxide can be added. This reduces flocculation, destroying the bonds between the particles. The organic material is oxidised and can be skimmed off the top of the sample (Task Committee on Preparation of Sedimentation Manual, 1969; Owen, 1976).

Levine et al. (1985) have produced a very good summary of the types and sizes of organic matter in wastewater and the techniques used for characterising their particle size distributions. They also went one step further and discussed the implications of particle size on different wastewater treatment processes. The main conclusions from their study were that:

- organic particles can be classified by particle size using a variety of techniques:

  a) electronic particle counters;
  b) light scattering devices;
  c) light microscopy;
  d) scanning electron microscopy (SEM);
  e) centrifugation;
  f) gradient sedimentation;
  g) serial filtration;
  h) field flow fractionation (FFF);
  i) gel filtration chromatography.

- the organic particulate matter in settled municipal wastewater ranges from 0.1μm to 50 μm;

- the organic material larger than 0.1 μm in settled municipal wastewater ranges from 30 to 85% of the total material load depending on whether grit removal processes are present and on the design and operating processes at the treatment plant; and

- the main removal mechanisms for most wastewater treatment processes are related to particle size.

The accuracy of the methods used to measure the distribution of particle sizes is dependent on the size range being measured. In addition, the instruments used are most accurate when measuring the particles for which the instrument was designed to measure. The precision of a measurement method can be determined by the reproducibility of the results. For most modern methods, the errors in precision are less than 2% (McCave and Syvitski, 1991).

Flocs are particularly difficult to size accurately. Akers et al. (1992) have very clearly summarised these difficulties:

> "a) the floc size may be very large with respect to the primary particle size, e.g. 2 mm flocs of 0.6 μm primary particles so that wide dynamic ranges are needed,
>
> b) the flocs may be very irregular in shape,
>
> c) flocs have a low (20%) to very low (<2%) volume fraction of solids in them,
>
> d) their structure and porosity distribution is usually very irregular,
>
> e) they are generally extremely fragile and liable to disruption in sampling and measurement systems,
>
> f) the concentration of flocs may range from an extremely dilute to a concentrated suspension depending on the context, and
>
> g) the process of flocculation, i.e. aggregate growth may occur whilst the sample is waiting for analysis and during the analysis itself."

A lot of particle size measurement techniques are not suitable for measuring the particle size of flocs in wastewater for the above reasons, in particular, all types of sedimentation methods are inapplicable.

2.6.1 Sedimentation methods

Sedimentation methods of particle size analysis use the principle that particulate matter can be separated from water by gravitational settling. The rate of sedimentation, or settlement, is measured, and using Stokes Law the size of an equivalent spherical particle is calculated.

McCave and Syvitski (1991) used settling tubes filled with clean water to measure the settling velocity of geological particles. The particles were placed at the top of the tube and allowed to settle through the water. McCave and Syvitski noted a number of problems associated with the settlement method.

1) Hindered settling - the counterflow from the falling of an individual particle affects the settling of the surrounding particles.

2) Settling convection - vortices and pressure gradients caused by the falling particles disturb the quiescence of the water and so the path of falling particles.

3) Thermal convection - due to a temperature differential within the column.

4) Mass settling - small particles are dragged down the column by larger particles.

There are also errors that may be associated with the column itself:

1) the method in which the sample is introduced into the column will affect the initial velocity of the particles;

2) the particle behaviour within the column, as described above, but also including the wall effects and the initial concentration of the sample;

3) the method of detecting or removing the particles at the bottom of the tube.

In addition to the above work by McCave and Syvitski on the accuracy of the methods used to size geological particles, Bernhardt (1992) has discussed the disturbances that affect the measurement of the true size of identical particles during sedimentation. Because of these disturbance factors an apparent size distribution is obtained. This apparent size distribution is polydisperse, i.e. formed of particles of more than one size, rather than monodisperse. The factors, listed below, that contribute to this effect can be either caused by the particles or the device in which they are being measured.

a) Brownian motion of the particles.

   The motion of the settling particles due to Brownian motion affects their apparent concentration across the cross section of the measurement container. This changes the rate of settlement and hence the apparent particle size distribution measured will differ slightly from the actual particle size. The errors are very small and only affect particles up to 0.1 μm in size.

b) Deviation from the spherical shape.

   The method of calculating the size of an individual particle based on the sedimentation rate assumes that the particle is spherical. If a particle is say plate-shaped, the direction in which it falls may not be directly downward. This may not only provide a false value for the concentration of particles, but by increasing the settlement length, underestimate the particle size based on the rate of sedimentation. Likewise a particle with a pitted or rough surface will be affected by greater drag forces than a smooth particle. Any deviation from the perfect sphere will affect the calculated particle size and so some account for non-sphericity should be made. This allowance is easier to make in such cases as powder technology, when all or most of the particles will be exhibiting similar geometries. In these cases a shape factor can be included in the calculations. For suspended sewage particles which may be composed of an almost infinite number of inorganic and organic materials, it is not possible to apply this shape factor.

c) Heterogeneity of the solid.

This is again linked to the calculation of particle size based on the assumption of a heterogeneous particle. If a sample of particles, which are not heterogeneous, is analysed then the factors that will influence the results are: changes in density and changes in the particle size distribution. This confirms that it is not possible to use settlement rate to accurately determine the particle size distribution of wastewater particles.

d) Horizontal and vertical limitations of the vessel.

The proximity of the measuring container's walls has a retarding effect on the settlement rate of falling particles, as discussed in more detail in sections 3.2.2 and 3.2.3.2. In addition, the ratio of the size of the particle to the settlement length, i.e. the measured length through which the particle falls, should not be greater than 0.01 for a representative distribution to be obtained. The settlement length is not usually a problem with most settling velocity apparatus for discrete particles. The effect of settling length on flocculating particles is discussed in more detail in section 3.2.2.

e) Extension of the measuring gap.

For apparatuses that measure the sedimentation rate between two points, the length of the measurement gap between the two points over which the concentration of particle size is measured will affect the distribution of the concentration. Where small measuring gaps are used a narrow range of particle settling velocities are detected and hence a more accurate distribution of the particle size is obtained. This same principle would apply to apparatuses where a volume containing the settled solids is withdrawn from the base of the column. The smaller the height of liquid/solid withdrawn from the column, the narrower the band of settling velocities captured and hence the more accurate the distribution obtained.

Allen (1992) has carried out extensive research into the use of sedimentation for the sizing of powder particles. All these methods rely on Stokes law which relates particle size with settling velocity at low Reynolds Number. There are many different sedimentation methods available, many of them are in common use in characterising wastewater particles. The principles behind each method are well covered by Allen, in his 1992 paper. The methods vary from the simple pipette method to expensive high resolution Scanning X-Ray Centrifuge. In the field of powder technology, the need in industry is for fast, on-line methods that produce results for a very wide range of sizes varying from sub-micron upwards. The main comment that should be made again is, that in the case of powders, the particles being analysed have many of the same physical characteristics, such as density and surface roughness. The main characteristics that are different are shape and size, and it is these factors that have a major influence upon the settling velocity measured. In sewage there is a multitude of different particles, all with different physical and chemical characteristics, therefore the particular sedimentation method needs to be carefully selected and will depend on the analysis required.

2.6.2 Electronic particle counters

The Coulter counter is the most commonly used version of the electrical sensing zone technique for measuring the size of particles. The Coulter counter is a very versatile method that measures the 'equivalent volume diameter' that is, the diameter of a spherical particle of equivalent volume, by sensing the electrical resistance of the particles in an electrolytic solution as they pass through an orifice (Task Committee on Preparation of Sedimentation Manual, 1969; Swift et al., 1972). This means, for wastewater, that the particles must be removed from the wastewater and placed in an electrolytic solution, which both disturbs the particles and means that they are in a medium unrepresentative of their normal environment. In addition the strength of the electrolytic solution affects the formation of flocs. Although the Coulter Counter is often used for measuring floc sizes, the results should be used with caution, because in addition to the effect of the electrolytic solution, it imposes a very high shear stress on the flocs as they pass through the orifice which can cause their degradation. When combined with a mass balance the Coulter Counter or electrical sensing zone technique can be used for measuring the size of discrete particles in the 0.2-30 μm range (Merkus et al., 1992).

2.6.3 Optical methods

Sommer et al. (1992) summarise their evaluation of Optical Particle Counters as follows.

> "Optical Particle Counters (OPC) possess many favourable characteristics such as high size resolution and speed in counting and measuring distributions of particles in suspensions....These methods determine the particle size distribution indirectly by assuming the shape of the distribution function and fitting two or more parameters, relating the distribution to the light scattering from many particles. In many cases, the presumed distribution does not include details of the actual distribution as a larger number of fitting parameters is need(ed) to describe these details than global methods can provide. OPC's are able to size and count individual particles with very high resolution.... Scattering techniques are commonly used to detect and size particles in the sub micron range, (0.1μm - 1.0μm) and extinction methods (obscuration) are suitable to determine the size of larger particles (> 1.0μm)."

2.6.3.1 Light obscuration

Optical methods of size analysis are affected by the presence of organic matter. A given dry weight of organic matter, being so diffuse, will intercept light far more readily than the same dry weight of inorganic matter (Swift et al., 1972) and so will overestimate the particle sizes.

A light obscuration sensor does not result in as much shear stress being applied to the particles as the Coulter Counter. The sensing range is 2-120 μm. The sensor works by measuring the fraction of the light obscured as a particle passes through it. This is then converted to a particle size. The sensor does cause some degradation of the most weakly bonded flocs, but not enough to make it unusable (Akers et al., 1992).

2.6.3.2 Light scattering

Light scattering has been used to measure the size of flocs, but produces inconsistent results over a wide range of floc sizes and so will not be discussed further within the scope of this project. The reader is directed to Azzopardi (1992) and Jimbo et al. (1992) for details.

2.6.4 Field flow fractionation

Field-flow fractionation is used to separate sub-micron size fine particles, polymers and macromolecules in solution. Sedimentation field-flow fractionation (SdFFF) uses particle masses to separate a wide range of particles for sizing. There are a few disadvantages of SdFFF that are caused by the carrier solution and zone broadening (Mori et al., 1992).

2.7 SETTLEMENT MECHANISMS IN WASTEWATER TREATMENT

2.7.1 Introduction

In wastewater treatment settlement is the physical process of separating solids from water. If the solids are less dense than the water separation takes place by flotation. If the solids are more dense than water, which is the case for the majority of particles in wastewater, downwards settlement takes place. Sedimentation with the assistance of gravity is the most common technique for separation (Peavy et al., 1985; Metcalf and Eddy, 1991).

There are four types of settlement mechanism that may occur. In a given situation the actual mechanism which takes place is dependent on the physical and chemical characteristics of the particles and the suspension. For discrete particles which do not change their shape, size or specific gravity, type-1 settling occurs. For flocculating particles in dilute suspensions which aggregate with other particles on contact and so change size, shape and specific gravity, type-2 settling develops. Hindered, or type-3 settling is found in intermediate concentration suspensions, whereas type-4, or compression settlement takes place in very high concentration suspensions.

2.7.2 Type-1 settling

Discrete particle settlement is the main process that takes place where sands and grits are removed in the inlet works (Metcalf and Eddy, 1991). Grit chambers are used at wastewater treatment plants to remove the heavy inorganic solids that may damage plant and cannot be treated by subsequent processes. Grit chambers remove particles with specific gravities of 1.2 to 2.7 and diameters greater than 0.2 mm (Camp, 1973a).

Type-1 settling is also discussed in more detail in section 3.2.3.5, but the principles behind the measurement of velocity and particle size are based on Stokes law, where for laminar flow

$$u_s = \frac{d^2(\rho_p - \rho)g}{18\mu} \qquad \text{eqn 2.1}$$

where u_s is the terminal velocity of a sphere in a liquid
d is the diameter of the falling sphere
μ is the viscosity of the liquid
ρ_p is the density of the particle
ρ is the density of the fluid.

Batchelor (1972) studied the effect of particle interaction on the measurement of the settling velocity of spheres through a Newtonian fluid. He confirmed that the settling velocity of a single particle falling freely through a fluid is greater than that of a particle settling through a dispersion of particles where 'hindered settling' takes place. In addition, he found that the presence of other particles had a greater effect on settlement than the boundary walls of the vessel they were contained in, the relative distance of the walls from the particle being far greater than the average distance between the particles.

2.7.3 Type-2 settling

Type-2 settling occurs when flocculating particles settle in a dilute suspension, for example in primary sedimentation and in the top portion of secondary sedimentation tanks (Metcalf and Eddy, 1991). The aim of the primary sedimentation tank is to remove the organic suspended solids from sewage. These organic solids include proteins and fats with some cellulose and varying amounts of entrained water and gas. The specific gravity of these particles varies between less than 1.0 and 1.2. Their size can range from colloids to several centimetres. The less dense particles such as greases and fatty particles will rise and form a scum layer on the surface (Camp, 1973a).

> "...flocculation depends on two separate processes - collision and cohesion. Particles collide due to Brownian motion, turbulence, velocity gradients, and differential settling, and under certain conditions adhere to each other, being held by the cohesive forces. Both these processes have been reported extensively by Krone (1962), Einstein and Krone (1961 and 1962) and Partheniades (1962 and 1964)."
>
> (Owen, 1970)

The use of Stokes law for flocculating suspensions is not appropriate because the size, shape and specific gravity of the flocs are continually changing. There is no appropriate equation to model type-2 settlement because of the continually changing nature of the flocculating particles. Instead, general trends have been identified using settlement columns (Camp, 1973c and Owen, 1970). It has been found that the size of the flocs increases with the depth they have fallen, as does their velocity. This is because of the collision and aggregation with other particles and flocs as they settle. In contrast to this increase in size, flocculated particles may contain up to 99% water by volume, which reduces their density. A limiting size and fall velocity will be reached when the shear forces on the floc prevent the bonding of further particles to it (Camp, 1973c).

Camp carried out a significant amount of research into the settlement and flocculation of sewage to improve the design of settling tanks and contributed an enormous amount to the understanding of sedimentation. He has provided a very good summary of the settling process in a number of his papers (Camp, 1953; Camp, 1973a, b, c and Camp and

Meserve, 1974). Much work since has been based upon his findings in the 1940s and '50s and he extended his work to the practical design of sedimentation tanks (Dick, 1982).

All organic particles will flocculate. During the flocculation process two particles coalesce, lose their individual settling velocities and then fall at a new settling velocity. This new settling velocity is usually faster than their previous individual ones (Camp, 1973a). The particles may have an organic coating which may cause aggregation (Ozturgut and Lavelle, 1984). This process is continuous and so the settling velocities are continually changing, unlike the case of discrete particles (Camp, 1973a). The rate of flocculation is a function of the number of contacts between particles per unit time (Camp, 1973c).

The volumetric concentration of a suspension must exceed 0.5% before there is an appreciable reduction in settlement due to hindered settling. Therefore primary sedimentation may be considered as a free settling process (Camp, 1973a).

> "Flocculation in a settling tank is due to two causes:
>
> 1) Differences in the settling velocities of the particles whereby faster settling particles overtake those which settle more slowly and coalesce with them; and
>
> 2) Velocity gradients in the liquid which cause particles in a region of higher velocity to overtake those in adjacent stream paths moving at slower velocity."
>
> (Camp, 1973c)

2.7.4 Type-3 settling

Hindered settlement occurs where there is a high concentration of particles, such as in secondary settlement tanks after biological treatment and in particular the activated sludge process (Metcalf and Eddy, 1991). At high concentrations the liquid phase is displaced upwards through the spaces between the flocculating particles by their settling action. These particles, in close contact with each other, then tend to settle downward at the same velocity as a 'blanket'. In general there is a layer of clear liquid above this settling 'blanket' layer, as has been discussed in section 2.3.2.

2.7.5 Type-4 settling

With type-4 settling compression takes place in the lower layers of a sludge mass, as in deep secondary sludge tanks and in sludge thickening. This type of settlement is outside the scope of this project and so is not discussed in detail. More information may be obtained from Metcalf and Eddy, (1991).

2.7.6 Modelling settlement mechanisms

Richardson and Zaki (1954) carried out research into the effect of concentration on the sedimentation and fluidisation of uniformly sized spherical particles. They considered that the particles were uniformly dispersed throughout the liquid so that each was under the same external effects throughout the suspension. An expression relating concentration to sedimentation was derived from experimental results and was compared with the expressions developed theoretically. This approach has also been used by other researchers, but empirically derived equations to determine the effect of concentration on sedimentation have not confirmed theoretically derived models (Batchelor, 1972).

Theoretically derived models to explain the effect of particle concentration on the falling velocity of an individual particle (Richardson and Zaki, 1954 and Batchelor, 1972) have not been successful, mainly because of the difficulty of assessing the interaction between all the particles. The theoretical expressions were mainly based on Stokes Law, but researchers encountered problems in modelling the effect of a range of particle sizes settling in a suspension. The disturbance caused at a distance r from a sphere of radius a falling at velocity u varies as:

$$\text{Disturbance} = fn\left(u\frac{a}{r}\right) \qquad \text{eqn 2.2}$$

The difficulty is in the summation of the disturbances caused at a point in the liquid by the particles in dispersion. Batchelor (1972) used statistical methods to prove that the settling velocity of a sphere subject to particle interaction in a dilute concentration is proportional to c, the fraction of the total volume that is occupied by the sphere.

Nix and Heaney (1984) used multiple-order kinetics to model the removal of pollutants and the settling of suspended solids in urban runoff. The use of first-order kinetics is flawed in that removal efficiency is independent of the initial concentration of suspended solids and it is unsuitable for long detention periods or low settling velocities. However, first-order kinetics are simple and so have been used for a long time in suspended solids settling models. Multiple order kinetics also have their drawbacks. For more in depth information on this subject, the author would suggest reading Nix and Heaney (1984) as a first source of information.

McNown and Malaika (1950) carried out research at the Iowa Institute of Hydraulic Research into the effect of particle shape on the settling velocity and stability of orientation of a range of axisymmetric shapes. In most other studies of settling velocity the particles are all assumed to be equal to spheres of an equivalent diameter. McNown and Malaika adapted Stokes law for ellipsoidal shapes. The principal shape factor affecting the settling velocity of a particle was found to be the ratio of its principle axis lengths. Proportionality factors for different particle shapes were derived experimentally and were introduced into a general form of the Stokes equation (equation 2.3) so that the settling velocities for almost any particle shape could be estimated.

$$R = (3\pi d u \mu)K \qquad \text{eqn 2.3}$$

where R is the resistance to the motion of a spherical particle through a viscous fluid

d is the diameter of the falling sphere

u is the velocity of the sphere through the liquid

μ is the viscosity of the liquid

K is the proportionality factor

2.8 SEWAGE SETTLING VELOCITY MEASUREMENT

2.8.1 Introduction

As shown in the previous sections, the constituents of sewage are varied in both their composition and the ways in which they behave as suspended solids. Many methods for separating and measuring the settling velocities of particular fractions of sewage have been developed, mainly in order to size the particles (section 2.6), particularly in the chemical industry where the specific gravity is already known.

Solid-liquid separation processes are still the main method by which pollutants in the form of grits and suspended solids are removed from wastewater. With the advance of new technologies such as hydrodynamic separation it may not now be true that sedimentation is the most economical technique, but its importance in removing both organic and inorganic pollutants is still valid. In addition, the use of chemical coagulants and biological processes to remove the soluble contaminants also produce solids that need to be separated from the liquid phase (Dick, 1982). It is recognised that information on the size distribution of solids in wastewater is important in order to understand treatment processes (Metcalf and Eddy, 1991; Levine et al. 1985). To take this one step further, it is of importance to the solids-liquid separation process to have an understanding of the range of settling velocities of the solids within a particular sewage (see section 1.1). This will assist in the design of treatment works to produce the most efficient and cost effective method of treatment. There has been very little published about the settling velocity grading of wastewater and this section will cover the main body of research within this field.

2.8.2 Methods of measuring sewage settling velocity

There is, at present, no single acknowledged method for measuring the settling velocity of wastewater. As with particle size analysis, methods have been developed to study the settling velocity of sewage with particular needs in mind. Often the sewage is separated into particular fractions, according to the needs of the study.

The most basic device used to measure the settleable solids in wastewater is the Imhoff cone, which is an inverted conical container mounted vertically so that the solids collect in the apex at the bottom. The sewage is place in the Imhoff cone and allowed to settle for 60 minutes. The solids that settle to the bottom during this period are the "settleable solids" and are expressed as ml/l (Metcalf & Eddy, 1991). This represents the quantity of solids that will be removed by sedimentation during retention in a conventional sedimentation tank. The Imhoff cone has been commonly used in wastewater treatment works operation for all stages of sedimentation, including chemical coagulation (Camp, 1973b).

Settling tubes have been developed to measure the fall velocity of individual particles, such as grits and sewer sediments. Settling tubes are based on the principle that particles settle through a fluid individually, without hindrance from other particles or from flow patterns within the fluid. Syvitski et al. (1991) have produced a summary of settling tube technology for the measurement of individual sediment particles. Their work included a study of the systems for introducing the sediment into the tube, particle behaviour, errors in measurement due to column design and the importance of calibrating the tube. These are all very valid for individual particles greater than 50 μm passing through a clean liquid, but do not apply to the case of sewage particles passing through a liquid containing dissolved organics and fine suspended particles and colloids. In addition sewage particles, as discussed previously in section 2.2, are composed of a wide variety of materials forming a range of particle sizes and densities. One problem in using settling tubes is that there is no one standard size of column or test method, many laboratories have developed their own tubes and methods of use. The problems associated with the use of settling tubes, such as wall effects, column length etc., are discussed in Chapter 3.

Having stated that settling tube techniques are not ideal for measuring the settling velocity of particles within sewage, most of the methods that have been developed for a complete wastewater sample have been based on the settlement tube or column principle. A sample is placed into the column and at timed intervals the quantity of solids reaching a set point is measured. The methods used to prepare the sample, enter it into the column and measure its velocity vary between devices. The principle devices and methods used are discussed in more detail below.

2.8.2.1 Multi-port settling columns

These operate by measuring the concentration of suspended solids at set positions down a column. The sewage to be analysed is distributed evenly down the column at the start of the test, with as little disturbance as possible. The ports allow samples to be withdrawn for analysis, be it for suspended solids, iron, BOD etc. (Camp, 1973b). Turbidity and colour can be measured directly in the settling column using photoelectric or comparator methods. The column is sometimes suspended in a water bath at the same temperature as the sample to minimise convection currents, as shown in figure 2.2.

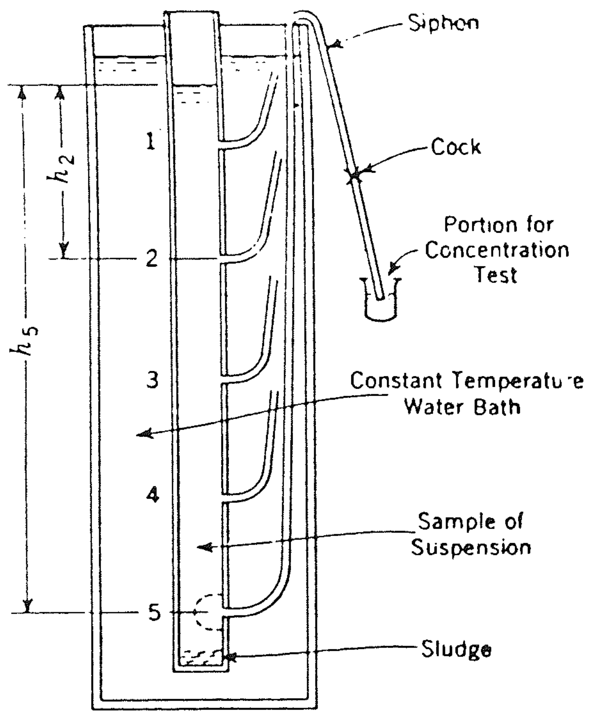

Figure 2.2 Apparatus for quiescent settling analysis (Camp, 1973b)

As the samples are removed from each port, the column of fluid immediately above the sampling port is drawn down a vertical distance corresponding to the volume removed. There is virtually no disturbance to the relative positions of the suspended particles. This means that the distances travelled between the ports are reduced for each period at which samples are taken, which can lead to errors in the settling velocity calculations (Camp, 1973b).

When used for type-1 settling, i.e. discrete particles in dilute suspension, this multi-port method will produce a single grading curve. When used for type-2 settling, i.e. settling of flocculating particles in low concentration suspensions, a different grading curve will be obtained for each port. This is because flocs increase in size with depth due to aggregation with other particles which causes an increase in the velocity of the flocs (Camp, 1973b). It should be noted that samples with a single settling velocity are not obtained, a range of settling velocities are included in each sample as with all methods where particles are removed from within the settling length of the column.

It is obvious from descriptions of multi-port column use that are provided in several texts (Camp, 1973b; Peavy et al., 1985; San, 1989; Metcalf and Eddy, 1991), that the method was designed to be used on particular fractions of the sewage. For raw sewage the discrete and flocculating fractions must be divided. The multi-port column is best suited to the measurement of particular fractions of the wastewater as it passes through the treatment process, for example in activated sludge settling, where most of the particulate material that settles discretely has already been removed.

2.8.2.2 Bottom withdrawal columns

Bottom withdrawal tubes are used by HRS Wallingford to determine the settling velocity of a suspension of estuarine mud flocs. The results produce a settling velocity grading curve for the suspension of mud flocs at the same salinity and concentration as sampled in the estuary. Because both the flocculation and settling velocity of the muds are a function of depth, the choice of column length is important. A standard column length has been decided upon in order to be able to compare results (Owen, 1970 and 1976).

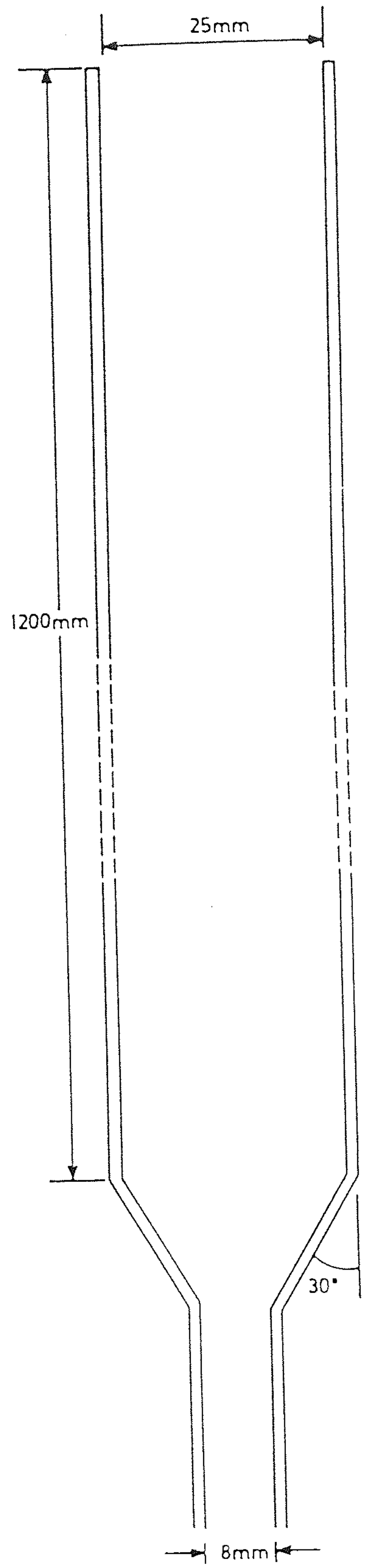

Figure 2.3 Bottom withdrawal tube (Owen, 1976).

The column consists of a 1.20 m long and 25 mm internal diameter Pyrex glass tube. The bottom end is tapered to 8 mm and a piece of rubber tubing is attached to the taper and closed with a spring clip. The tube is marked with a linear scale, and calibrated volumetrically (see figure 2.3).

> "In the laboratory the only sample preparation necessary is to thoroughly mix the suspension, to bring all the material which has deposited at the bottom of the container back into suspension again. If a number of samples at concentrations less than about 200 mg/l are expected, then in order to be able to determine the settling velocities accurately, a larger diameter settling tube should be used. A tube of internal diameter 50 mm would enable measurements to be made on suspended concentrations down to 50 mg/l. There should always be at least 0.1 g of mud in suspension in the tube.
>
> The clean sedimentation tube is filled with the thoroughly mixed sample, filling up to the 1.00 m mark. The suspension in the tube is then mixed again by repeatedly turning the tube over and over, and the stopwatch started on the last inversion just as the air bubble leaves the bottom... Samples are withdrawn from the bottom of the tube at times 100 seconds, 3, 6, 12, 30, 90 and 180 minutes at water levels of 0.86, 0.72, 0.58, 0.44, 0.30, 0.15 and 0.05 m.."
>
> (Owen, 1976)

The samples are then dried and weighed and the settling velocity distribution calculated graphically.

The importance of the tube length and diameter are discussed in more detail in chapter 3, section 3.2.2.

2.8.2.3 Owen tube

The Owen tube was developed to sample and test a turbulent suspension of mud flocs in a single tube. An undisturbed sample is obtained and then immediately tested in the sampling apparatus by the bottom withdrawal method.

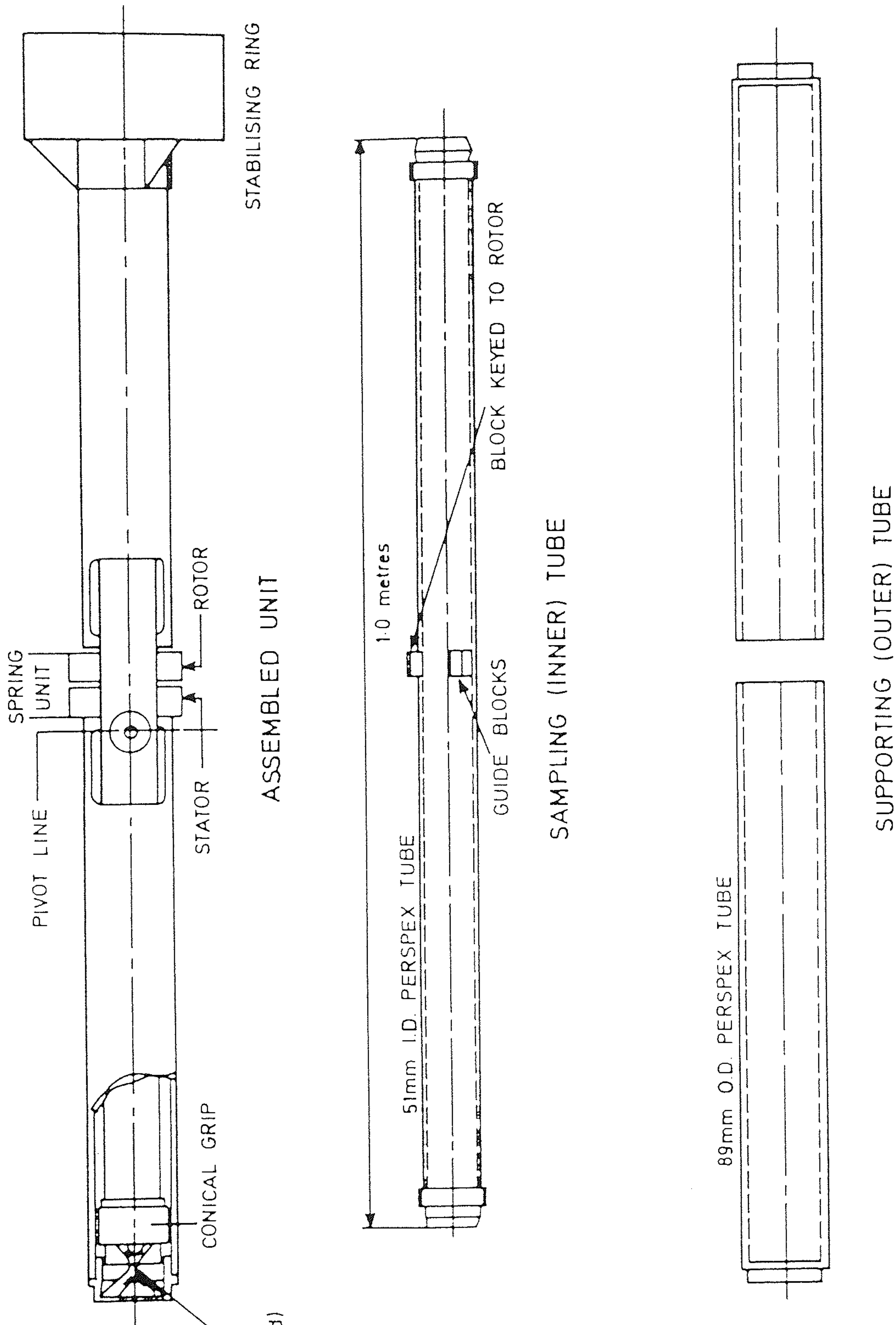

Figure 2.4 Outline drawing of the Owen Tube (Owen, 1976).

The tube is fairly complicated in its construction and use. Briefly, the main column is 1 m long, 50 mm internal diameter and is supported inside another tube of 90 mm internal diameter. Rubber seals to close the ends of the main column are fixed at each end of the tubes and are operated by the tubes twisting in opposite directions (see figure 2.4).

To collect a sample the entire column is lowered horizontally into the water. By a system of hand pumps and pistons a sample is collected as the river water flows through the tube. The tube is immediately hauled up onto the survey boat where it is suspended vertically on a frame. The stopwatch for the start of the bottom withdrawal test begins as soon as the column is fixed into the vertical position. More detailed descriptions of the apparatus and test method are given in Owen (1976).

Owen (1976) found that the settling velocities obtained using the Owen tube were higher than those from laboratory methods.

This method has been used to sample and analyse the suspended solids in sewers by researchers at the University of Abertay Dundee (Jefferies, 1992). However, results of this work have not been published to date.

2.8.2.4 CERGRENE (ENPC) settling column method

Chebbo (1992) used and reported on a settlement column developed at l'Institit de la Filtration et des Techniques Separatives in France, in his studies on storm sewer sediments.

The settlement column consists of a 1.815 m long and 50.8 mm diameter settlement tube. Each end of the tube is closed with a bung. The bottom of the tube is then suspended in a water filled tank in which there is a rotating disc carrying six dishes and the bottom bung is removed. The dishes collect the solid particles that reach the end of the settling tube which is below water in the tank. See figure 2.5.

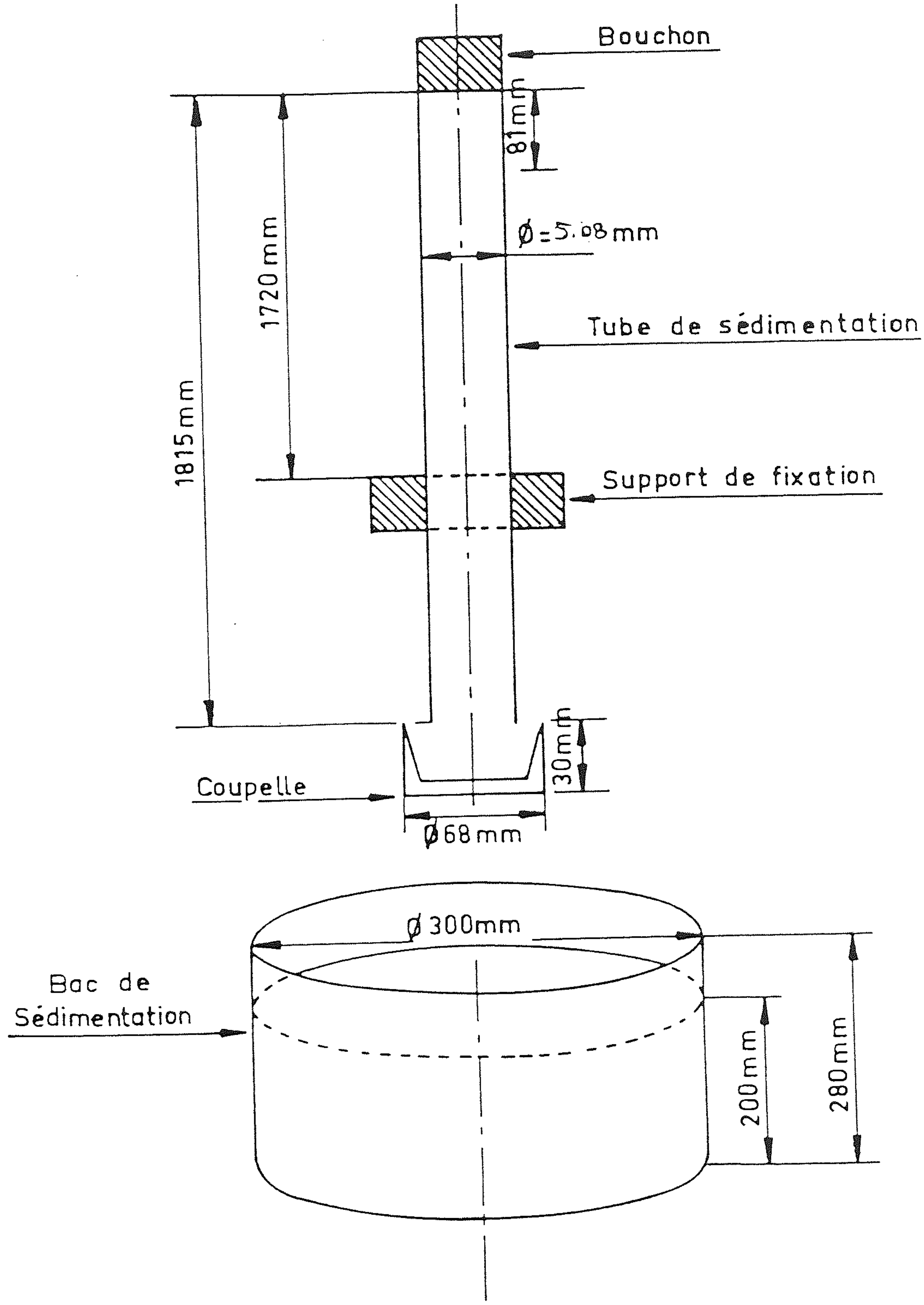

Figure 2.5 The CERGRENE (ENPC) settlement column used by Chebbo (Chebbo, 1992).

In this method the column is filled with tap water and left for several hours for the dissolved gases to be released. Any gas bubbles that settle on the tube walls are removed. The cork at the base of the tube is left fixed in place whilst a thin layer of prepared, concentrated sediment is then quickly, but carefully poured as a layer onto the top of the water column and the top cork fixed in place. The bottom cork is then removed, the column of water remaining in place due to the vacuum created by the top cork. The solid particles fall down the tube and are collected at timed intervals by the dishes at its base. The dishes are rotated on the disc to enable sample collection and removal. The samples are subsequently dried and weighed and a settling velocity distribution obtained.

Chebbo used this settlement column for particles between 50 μm and a few millimetres in size. For particles less than 50 μm in size, the Andreason pipette was used to determine settling velocity. In addition a large amount of preparation had to be carried out on the samples before use. The sewer sediments had been stored for long periods of time. Samples were then split into their size fractions by wet sieving, in the process destroying many of the bonds between the particles. Only concentrated samples were used in the settlement column test. When using methods such as this where a sample is placed into a water filled column, concentrated samples must be used in order to obtain a detectable mass in each sub-sample.

2.8.2.5 The Umwelt-und Fluid Technik (UFT) settling apparatus

Michelbach and Wöhrle (1992a) developed a piece of apparatus to measure the settling velocity of settleable solids in a combined sewer system.

The settling apparatus consists of a perspex cylinder with a section of an Imhoff cone at the bottom. The overall settling length is 700 mm. The bottom of the Imhoff cone is sealed with a clamp on a piece of tubing, which allows the sub-samples to be withdrawn. The top of the column is fixed to a small tank with a feeding mechanism attached, in which the sample is placed (see figure 2.6 for the apparatus layout).

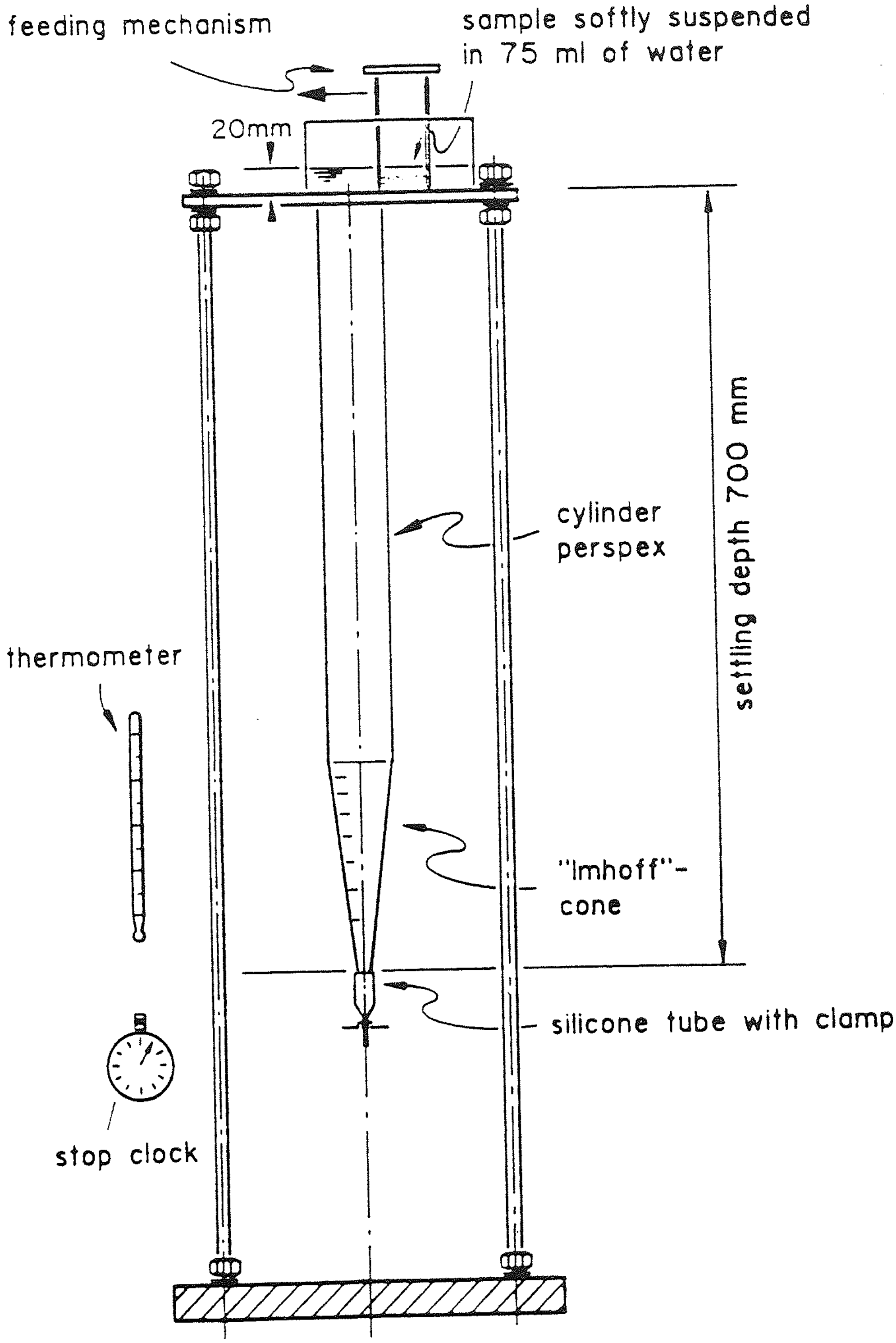

Figure 2.6 The Umwelt-und Fluid Technik (UFT) settling apparatus (Michelbach and Wöhrle, 1992a).

The procedure developed by UFT requires a one litre sample of raw sewage to settle for two hours in an Imhoff cone. The settled solids are then drained off and their volume made up to 75 ml with distilled water. The settling apparatus is filled with distilled water to 20 mm above the top of the column. The cylindrical feeding mechanism is filled with the prepared sample, which is stirred thoroughly to break up any flocs that may have formed. The feeding mechanism is then slid across the top of the column and the stop watch started. Twelve samples are drawn off into test tubes from the bottom of the Imhoff cone at timed intervals from 4 sec to 117 min (Institute für Siedlungswasserwirtshaft Universität Karlsruhe, 1990).

The sample is prepared so that only settleable solids are tested. No allowance is made for the fraction that does not settle in the initial two hour sample preparation time, or for the solids that are left in the settling apparatus at the end of the test. This is satisfactory if only the fast settling fraction is to be studied, as in the case of sediments.

Samples of sediment, slime and urban runoff were taken from the combined sewer system in Bad Mergentheim. The settling velocity of the settleable solids were measured using the apparatus. Some samples were analysed for heavy metals and organic micro-pollution and Michelbach and Wöhrle (1992b) were able to produce a relationship between settling velocity and heavy metal load.

2.8.2.6 Scottish Development Department

In the mid 1970's the Scottish Development Department commissioned Heriot-Watt University to develop a settling velocity apparatus and test method to measure the settling velocity grading of storm sewage (Scottish Development Department, 1977). The apparatus consisted of a perspex tube, 50 mm in diameter and 1.8 m long. The column had a ball valve at each end, with an additional valve 300 mm from one end to create a separate cell. The column could also be pivoted about its mid-point. Before the test began the floating and sinking particles in the sewage were separated in another column. The divided floating and sinking fractions had their settling velocity distributions determined separately.

The operating procedure for the column as described in the Scottish Development Department report (1980) is:

> "Now, using the modified apparatus, with the perspex tube vertical and the intermediate valve in its highest position, close the bottom valve, open the other valves and fill the tube with the contents of the lower half of the WRC apparatus [used to separate the floating and sinking fractions], topping up with clean water as necessary to exclude air. Close the top valve. Leave for at least 10 minutes then turn the apparatus through 180° fairly, but not too quickly and immediately start a stop watch. After 10 seconds close the intermediate valve. Open the bottom valve and drain the sub-sample of liquid contained between the intermediate and bottom valves into a bucket. Turn the apparatus through 180°, open intermediate valve and fill up with clean water. Close top valve. Leave for at least 10 minutes to let the particles settle. Then turn through 180° and start a stop watch. Repeat the previous procedure several times adopting a different time interval each time; say 20, 40, 80 and 180 seconds."

Using this method, after each sub-sample is withdrawn, the particles are all allowed to settle back to their original positions before the column is rotated and the settling process repeated to obtain another sub-sample. This makes the test very time consuming, and may cause the sewage to degrade.

2.8.2.7 Aston column

The prototype Aston column and test method were developed from the column used by the Scottish Development Department (1977 and 1980). The prototype was developed as part of a project to monitor the quantitative performance of the Storm King™ hydrodynamic separator under storm overflow conditions (Hedges and Lockley, 1990).

The prototype test method has been developed further in this research project, to provide an improved test for both storm and DWF sewage. More details on the background to the column, its development and the test method are given in chapter 3.

2.8.2.8 Other methods for determining settling velocity

Ozturgut and Lavelle (1984) developed a method of determining the settling velocity distribution of particles in the 1.0-6.4 μm size range by measurement of their wet density. The measurements were carried out at very low suspended solids concentrations in order to reduce the possibility of particle flocculation. The reason for this was that the study was to determine the settling characteristics of sewage when discharged into the sea. The test involved the gradual introduction of the sample into a column of inorganic salt solution. The particles formed layers of increasing density with depth over a 171 hour period. The layers were then withdrawn and analysed for density from which the settling velocities were calculated. It was assumed that the particles were all spherical in shape and Stokes law applied.

Li and Ganczarczyk (1987) used stroboscopic methods to determine the settling velocity, size and porosity of activated sludge flocs. Using experimental data they found that the relationship between the floc settling velocity and the floc size could be either linear or a fractional power function. In addition the floc porosity was found to increase as the floc size increased.

A method of settling velocity measurement in order to determine particle size, density etc. was devised by Lygren and Damhaug (1986). This was used to characterise wastewater in their study of swirl concentrator performance. The test used a 600 mm long tube filled with clean water into which a 500 ml sample was introduced from the top. The column was then operated in a similar method to that of Michelbach and Wöhrle (see section 2.8.2.5).

Reid and Nason (1993) reported the development of an on-line method of measuring the settling characteristics of activated sludge. The apparatus measured the initial settling rate and the stirred specific volume index (SSV). The settling column was 100 mm in diameter and had a 500 mm settling zone which incorporated a stirrer.

"On one side of the cylinder there is a vertical array of light-emitting diodes and on the other side a complementary array of photodiodes. ... The settling sludge/water interface is monitored by scanning the photodiodes. As the sludge settles the photodiodes are uncovered and receive light from the opposite light emitting diode; the position of the interface is registered by the computer."

(Reid and Nason, 1993)

2.8.3 Mathematical modelling of particle settling velocity

Bhargava and Rajagopal (1989 and 1992) evolved a mathematical model and ready to use nomograms to directly predict the settling velocity of discrete particles. The nomograms provide a relationship between settling velocity and particle diameter at a variety of temperatures. Bhargava and Rajagopal (1990) have also attempted to model the zone settling process that takes place within secondary sedimentation tanks. The mathematical models were tested against experimental data collected by other researchers and Bhargava and Rajagopal found the correlation between the model and the data to be very strong. To the author's knowledge this model and the nomograms have not been tested by any other workers.

2.8.4 Sample collection

Samples should be representative of the flow by containing proportions of all the particles flowing in the sewer: the heavy particles close to the invert; the finer particles suspended throughout the flow; and the light and floating particles at or near the liquid surface (Scottish Development Department, 1977). In practice this is very difficult to achieve and great care should be taken in the choice of sampling method and in the actual collection.

Camp (1973b) carried out a series of tests into the settling characteristics of flocculating sewage under quiescent conditions. He stated that for accurate results the following practices should be adopted.

i) The sample should be collected in such a way that the least possible disturbance to the flocculation of the particles would occur. This includes the fact that there should be the least possible time lapse between sampling and testing.

ii) The sample should be kept at the same temperature throughout in order to reduce convection currents.

iii) If practical, the test should be carried out in a column/tank that is equal to or greater than the depth of the sedimentation tank, particularly if sludge production is to be studied.

In the studies carried out for the Scottish Development Department (1980), it was recognised that it is difficult to obtain a sample that truly represents the distribution of solids entrained within the flow throughout the depth of the sewer. Instead of designing a piece of equipment to overcome this problem, the researchers were able to select sampling sites with shallow depths and well mixed sewage. A metal bucket tied to a rope was used to collect the sample.

The US EPA in their handbooks for sampling (US. Environmental Protection Agency, 1973 and 1982) state that a representative sample should typify the whole sewage, but there can be a bias due to:

- the site sampling conditions;
- sampling frequency;
- sampling collection;
- sampling devices;
- sample handling.

The handbooks also recommend that a sample should be taken at a point between 0.4 and 0.6 of the total depth to obtain the most homogenous sample. This is the range of depth within which the mean flow velocity occurs. In addition taking a sample within this depth range avoids skimming the surface or dragging the bed.

Stephan and Johnson (1992) developed a mathematical model to assist in the sampling of wastewater effluent. They recognised the problems of obtaining a mixed effluent for conditions where the operational processes produced fluctuations in concentration. Although these are not quite the same as the conditions pertaining to raw sewage reaching the treatment works, the fluctuations in quality are still there in terms of industrial discharges etc. These fluctuations are smaller for the larger catchments as discussed in section 2.2.

The guidelines that were proposed by Stephan and Johnson (1992) were not applied to this project in the detail suggested. The proposals involved a study of the variation in concentration both across the channel and with time. This would have been a sensible process if the same site was to be sampled repeatedly, but for this project where the time available limited site visits to once throughout the duration of the project, a simpler, less accurate method was adopted through necessity.

Stephan and Johnson (1992) also suggest that composite sampling at as many sites as possible should be undertaken. Spot sampling is only appropriate when the concentrations of pollutants do not vary with time. This is practical when pollutant levels are being monitored, but for many studies a spot sample is all that can be obtained. Ideally a large sample should be collected and than split down to obtain a representative sample.

The sampling methods and collection used in this research project are covered in detail in chapter 4.

2.9 SUMMARY

The discussion in this chapter shows that there is a wide range of research being carried out into characterising the physical properties of solids in wastewater. However, because of the variable nature of wastewater, a great variety of methods have been developed to study the characteristics of different fractions of wastewater, both in the sewer system and at the wastewater treatment works. In particular there is no standard method of measuring the settling velocity distribution of a wastewater. The following chapter discusses the development of a method of measuring the settling velocity of wastewater that could be used in a variety of different situations.

CHAPTER 3

DEVELOPMENT OF SETTLEMENT VELOCITY MEASUREMENT METHODS

3.1 INTRODUCTION

3.1.1 Background to the prototype column

The prototype of the settling velocity measurement column was developed at Aston University for use in the James Bridge pump tests (see section 1.1) (Hedges and Lockley, 1990). The apparatus was designed to measure the terminal velocity of the particles within storm sewage and so obtain a settling velocity distribution of the suspended solids. The initial objectives of the prototype column and test methods were as below.

- The column was to be cheap and easy to construct using proprietary materials and parts.
- The Heriot Watt model would be modified so that the prototype column could be rotated to measure the settling velocities of both the sinking and floating particles simultaneously.
- Once the column could be rotated, the test was to be altered so that a settling velocity distribution could be obtained far more quickly i.e. within 36 hours rather than one week.
- The equipment was to be easy to use.

- Discrete samples of known settling velocities were to be obtained, not composite samples of varying settling velocities.

A column was duly constructed from proprietary materials: grey PVC pipe and fittings mounted on a frame of Dexion mild steel angle. The resultant test method developed for the project is provided in Appendix A.1, but a summary is given in section 3.1.2.

3.1.2 Prototype method of assessing the settling velocity distributions of sewage/storm sewage

On commencement of the research project, the details of the operating method for the column were as described below (Hedges and Lockley, 1990).

1) With reference to figures 3.1 and 3.2, the central section of the column between valves 2 and 3 was filled with the well mixed sewage sample (approx. 5 litres were required). Care had to be taken to ensure that no air was left inside valves 2 and 3.

2) The end cells, A and B were filled with clean water and the column was locked in the vertical position with cell B uppermost.

3) The column was then left overnight (or for at least 12 hours). This resulted in all the floaters collecting beneath valve 2 and all the sinkers above valve 3. The floaters are those particles with a negative settling velocity, i.e. that float, and the sinkers are those with a positive settling velocity, i.e. that sink.

4) First thing in the morning the column was rotated through 180 degrees to bring cell B to the bottom. The stop clock was started and valves 2 and 3 were opened.
The concept behind this being that the floaters would rise for collection into cell A and the sinkers would fall for collection in cell B. In the process the solids would become distributed according to their relative settling velocities thereby enabling distinct settling velocity fractions to be sampled.

5) After a pre-selected time t_1, valves 2 and 3 were closed. Valve 1 was opened and cell B drained.

6) 1 min after time t_1, the column was rotated through 180 degrees, valve 4 opened and cell A drained. Cell B was refilled with clean water.

7) 2 mins after time t_1, the rotation was reversed. The timer was started for the next sample period and valve 2 opened. Cell A was now uppermost and was refilled with clean water. Valve 3 was opened.
Providing that there was strict adherence to the specified time intervals during steps 6 and 7, movement in the 'as test' and reverse modes would ensure that particles returned to their original positions at the start of the sampling phase, prior to the subsequent time step.

8) After time period (t_2 - t_1) steps 6 and 7 were repeated. This process was continued for as long as required.

9) When the final samples had been taken from cells A and B, the central section of the column was drained into a container so that the residual concentration, hence mass of SS could be determined.

10) The samples were then filtered on previously washed, dried and weighed filter papers. The filter papers were then dried and weighed again to obtain the mass of suspended solids.

Knowing the dry mass of all the sub-samples, including the residue left in the centre of the column at the end of the test, the total sample mass could be obtained. Each filtered sub-sample yielded the mass of solids with that specific settling velocity range. The settling velocity was determined by dividing the average distance travelled by the solids by the total settling time to the point of sampling. A settling velocity grading curve of percentage of the total sample mass with a settling velocity less than a known value could be plotted from this data.

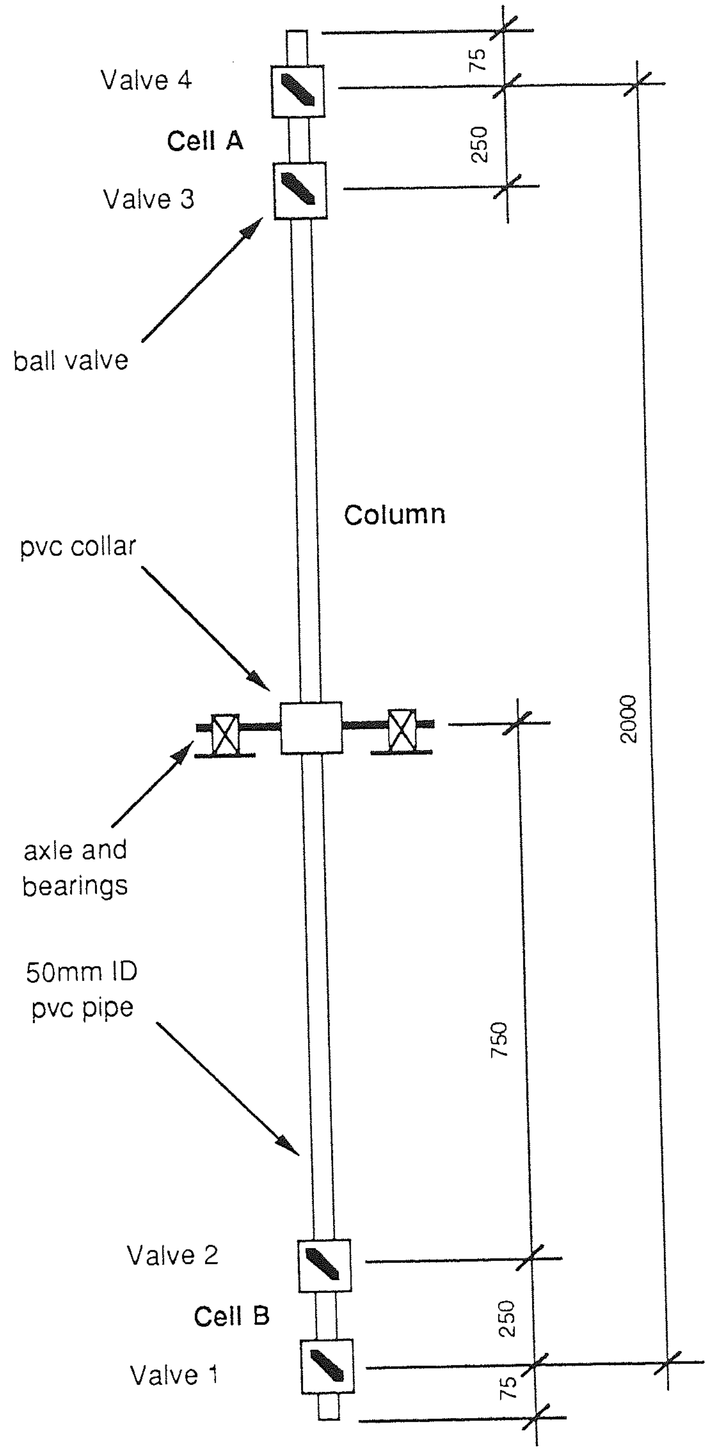

Figure 3.1 Arrangement of the settling column apparatus

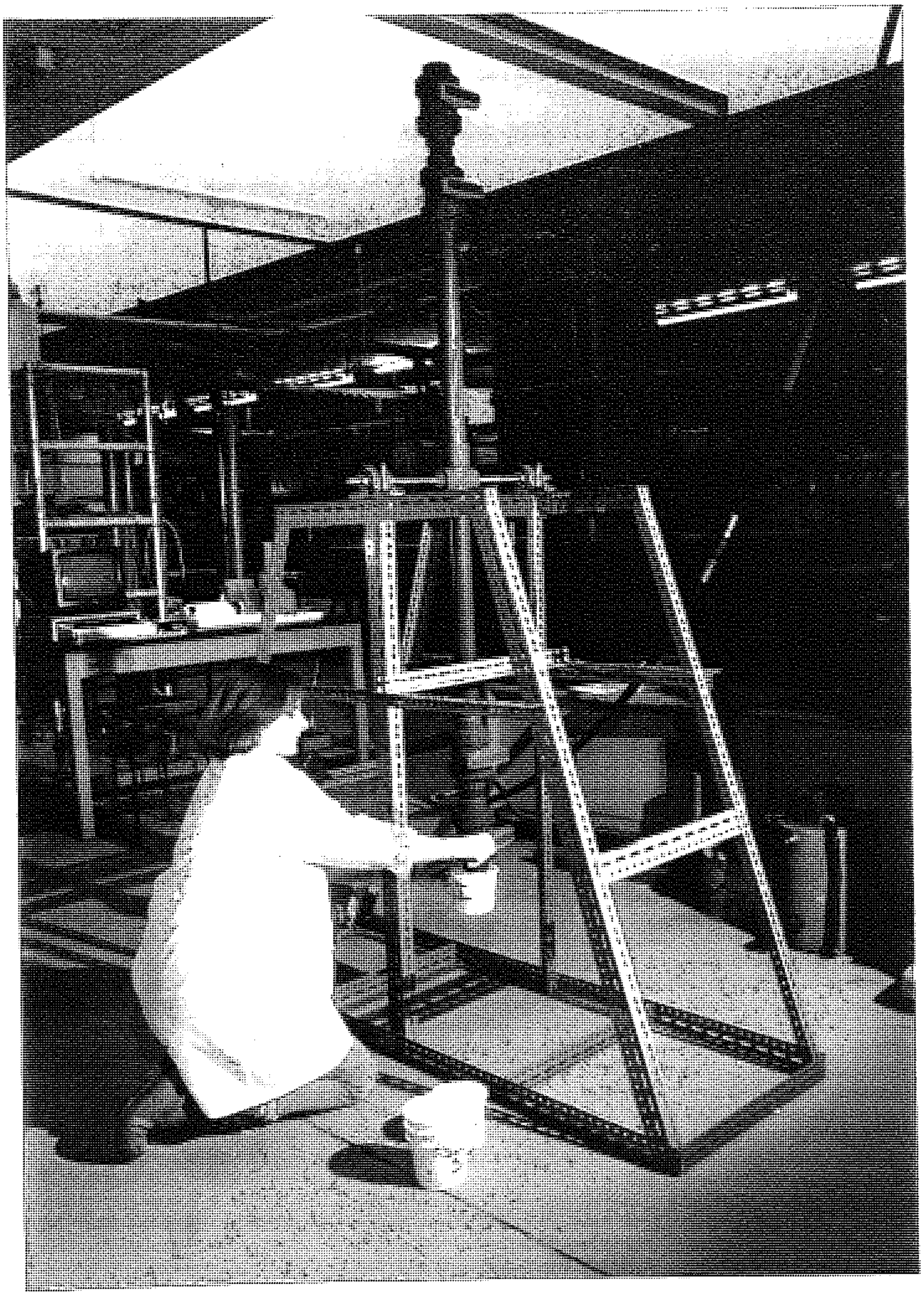

Figure 3.2 The settling column apparatus

The apparent success of the settlement column in the study of the separation characteristics of the Storm King™ hydrodynamic separator was of great interest to both Aston University and to the Storm King™ manufacturers, Hydro Research & Development Ltd. On the strength of the original work carried out into settling velocity gradings by Hydro Research & Development Ltd. and the project at James Bridge, Walsall by Aston University, the current project was established to develop and evaluate the test procedure and to determine if there was a relationship between grading curves and the characteristics of the contributing catchment.

3.2 DEVELOPMENT OF THE TEST METHOD

3.2.1 Criteria for investigation of column performance

Before any investigations into the behaviour within the column were planned, some settling velocity measurement tests were carried using the prototype method (see section 3.1.2). The tests were undertaken in a 54 mm internal diameter clear column using crude sewage. This was so that a true picture of what was happening inside the column during the original test method could be gained. These initial tests brought two important points to light that had not been realised previously using the opaque grey plastic prototype column.

i) The main problem was the formation of a large floc of the sinking particles above the valve at the bottom end of the column during the overnight settlement period. When the column was rotated to start the test this floc did not break down into individual particles, but fell as one solid mass.

ii) The second problem was the amount of air trapped within the column when the test was set up. Rising air bubbles disrupted the contents of the column as it was rotated. Both these points are discussed in more detail in section 3.2.4.

The investigations into the particle activity within the column and the refining of the test procedure were interdependent and so ran hand in hand. The main criterion was to produce a test that was reliable, repeatable and able to be carried out by inexperienced personnel. In order to achieve this any internal or external influences on the column had to be investigated and any that had an adverse effect be remedied or their effect reduced to a known, manageable level. The key aspects for investigation were identified in part from work documented by previous researchers, for example Allen (1992), Camp (1973b and c), Camp and Meserve (1974), Chebbo (1992), Delo (1988), Li and Ganczarczyk (1987), Lygren and Damhaug (1986), Matthews (1991a and b), Michelbach and Wöhrle (1992a, 1992b and 1993), Ockenden and Delo (1991), Owen (1970, 1971 and 1976), Peavy et al. (1985), Smisson (1979), Scottish Development Department (1980), Syvitski et al. (1991), Water Research Centre (1975), White (1975a and 1975b), in part through observation of the prototype test procedure and in part from logical deductions by the author.

Internal influences thought likely to affect the test were:

i) the effect of the column length on the interaction of the particles as they rose and fell;

ii) the effect of the column wall on the settling velocity of the particles and the influence of the column diameter;

iii) the effect of air, trapped in the column or valves, rising through the test sample when the column was rotated;

iv) consolidation of the sinking fraction during the initial 12 hour settlement period specified in the original method statement (see section 3.2.1 and Appendix A.1);

v) effect of the liquid medium through which the solids pass.

External influences thought likely to affect the test were:

i) the effect of the ambient temperature on the settlement velocity of the particles;

ii) the deterioration of the sample due to the standing time between sampling and testing;

iii) the effect of transport time on the deterioration of the samples whilst being returned to the laboratory;

iv) the method of sampling the sewage at the wastewater treatment works;

v) the frequency of sub-samples taken during the test to produce a reliable settling velocity grading curve.

The influence of all these factors on the test are discussed in the following text.

Once the settling column and the test procedure were developed so that the results produced were more reliable and repeatable, the column was compared with other settling velocity measurement devices, as discussed in section 3.4. This helped in the assessment of its performance and the proving of its validity for the measurement of sewage settling velocity.

3.2.2 Construction of the test columns

A study of the optimum lengths of settlement velocity measurement columns for estuarine muds, not sewage, was carried out at Hydraulics Research Station (Owen 1970). It is accepted that a solid particle will reach its terminal velocity within a very short time span, often a small fraction of a second (Michell, 1970). However, from the study at Hydraulics Research Station, it was concluded that for solids concentrations below 4 mg/l, flocculating particles reach their terminal velocities after falling a distance of between 1.5 and 2 m.

Owen did not know the reason for the existence of a stable settling velocity at about 1.5 m, but put forward the following as a possible explanation.

"Because of the extremely small size of the primary particles of mud, the suspension will be stable until some flocculation occurs. At the beginning of each settling test, there is therefore an interval, during which flocculation due to Brownian collision occurs, before settling begins. The resulting flocs are made up of a small number of particles, and therefore have a relatively high density, and settle relatively rapidly through water, gathering up other flocs as they settle. Because of the time available, and height involved, the flocs settling in the 0.5 metre tube do not increase appreciably from their initial size as a result of the Brownian flocculation. In the 1.0 metre tube however, the extra depth of settling means that, as the flocs settle this distance, and gather up other flocs in the process, they become very large and loose, having a relatively low density. This low density implies a high volume concentration in the suspension, which, as explained previously, retards the settling process, and causes considerable counter-flow of the water, which could be observed in the 1.0 metre tube during the tests. As further depth of settling is made available in the 1.5 and 2.0 metre settling tubes, the flocs increase in size, and reduce in density, until they become so large and loose that the fluid shear exerted by virtue of the settling velocity is greater than the weaker cohesive bonds, and they break up to form stronger, higher density flocs with an increased settling velocity. Eventually a stage is reached at which the fluid shear is equal to the strongest cohesive bonds, and an equilibrium settling velocity is maintained."

This is an example of type-2 settling that is discussed in more detail in section 2.7.3.

The prototype settlement column developed at Aston University had a central settlement length of 1.5 m, with an average settlement depth of 1.5 m for the original test and 1.625 m for the test developed for use in this study. On the assumption that the flocculation of particles of sewage follow a similar pattern to those of estuarine muds it was decided to follow Owen's work and maintain the settlement length of 1.5 m as the minimum length necessary to achieve terminal velocity within the concentrations of crude sewage. Making the column longer would have made the apparatus unwieldy and decreasing the length would have reduced the accuracy of the results by preventing the flocs reaching their terminal size and velocity.

The bottom withdrawal method is the standard test used by Hydraulics Research Station, Wallingford for measuring the settling velocity of a suspension of mud flocs in the laboratory (Owen, 1976). The standard column diameter is 25 mm, with an average sample concentration of 4 mg/l, but Owen recommends that for sample concentrations between 200 mg/l and 50 mg/l, where particles are hindered to a greater extent by other particles, an internal diameter of 50 mm should be used to measure the settling velocities more accurately. The greater the diameter of the column, the more accurate the determination of the settling velocities. Although the internal diameter of the prototype settlement column was 50 mm, and the sewage concentrations fell within 200 mg/l and 50 mg/l, it was felt that the choice of internal diameter should be investigated further. The main reason for this being that sewage and not estuarine muds were being studied.

One major disadvantage of the prototype was that it was made from opaque grey plastic, which meant that it was not possible to observe the activity within the column during the test. It was therefore decided that a test column, identical to the prototype, should be constructed out of clear plastic pipe, the equivalent size being 54 mm internal diameter. This made it possible to observe the particle activity within the column, and then investigate and assess the effects on the test performance, as discussed in section 3.2.1.

It was not known whether the column diameter affected the test results, due to perhaps the influence of the column walls on the sewage, or the creation of a range of settling velocities across the column, in effect a settling velocity profile, that altered the settlement pattern of the particles. To investigate this two more clear plastic columns were constructed: one of 68 mm internal diameter and one 34 mm internal diameter. Unfortunately the only valves that were obtainable in a clear form were made of glass and these proved too expensive to warrant their use in this trial. Instead of glass valves, standard grey plastic ones were fitted to the columns, but the walls of the end cells were transparent.

3.2.3 Particle activity

3.2.3.1 Method of investigation

To understand what was happening within the column itself plastic beads suspended in salt water were initially used to simulate the action of the sewage particles. The main aim of using beads was to observe particle motion on a large scale. By gradually reducing the particles in size and introducing irregular shapes, further particle activity could be easily observed. The underlying philosophy of this approach being that when sewage was introduced into the columns, if specific particle movement patterns, similar to those observed using the synthetic media, were identified, then these could be explained using earlier research findings and established theories.

Despite an extensive search, it was not possible to identify synthetic material of a suitable specific gravity to adequately simulate sewage particles. Consequently salt was added to the water to alter its relative density and thereby change the settling velocity of the beads to ensure that they were at approximately neutral buoyancy, and that some rose whilst others sank. Several trials were carried out using different beads in different concentrations of salt water to determine an appropriate combination of bead type and salt water concentration. This was performed in a smaller column, which had been designed in a previous study to measure the settling velocity of individual particles. It was not possible to use several different sized beads in the column at the same time because they required very different concentrations of salt water to create the near neutral buoyancy conditions required due to their varying specific gravities. When an appropriate combination of bead type and salt water concentration was found, it was introduced into the largest diameter (68 mm) clear plastic column.

In this study the specific gravity of individual beads of approximately 10 mm diameter were measured and the saline solution was such that roughly equal proportions of the balls sank and rose, with a few particles being neutrally buoyant. The activity of the beads within the column was observed. Each bead was individually numbered and the pattern of the floating or sinking of individual beads within the column was investigated. The flow patterns within the column were noted, especially when the valves were first opened and when the column was rotated through 180 degrees. There did not appear to be any consistent pattern as to whether the beads rose or sank.

Following the experiments with plastic beads, black nylon extrusions were placed into the column. These were smaller than the beads and were approximately cylindrical in shape. It was considered that these extrusions would more closely resemble the pattern of sewage particles, being irregular in both size and shape. The particle activity was again closely observed and video taped for a record of the activity.

The final synthetic media used was wood chips, which were in fact very small cubes of wood that, if soaked in water, would sink. These chips were the smallest that could be used within the column whilst remaining easily visible and traceable. The wood chips were placed into all three clear plastic settling columns to investigate the effect of the column diameter on the settlement of the particles.

Finally, crude sewage was placed in the columns and various tests were carried out to determine the best method for settling velocity measurement. Many of the phenomena observed using the synthetic media were found to be present. Comparisons of different trial test methods were carried out simultaneously in the two medium diameter columns (the prototype and the clear column), the large and small diameter columns to determine which was the best approach.

3.2.3.2 Wall effects

The column walls influenced flow conditions by imposing definite boundaries that affected the equations of motion for a particle falling freely through a stationary liquid phase. The aim of the settling velocity measurement test was to simulate, as far as possible, the settling of sewage particles under ideal conditions, i.e. in an infinite liquid, where particles could reach their terminal velocity ($u_{s\infty}$) . Therefore, the aim was to bring the velocity ratio K_u (Clift et al., 1978) as close to unity as possible, where

$$K_u = \frac{\text{terminal velocity in an infinite liquid}}{\text{terminal velocity in a bounded liquid}} = \frac{u_{s\infty}}{u_s} \qquad \text{eqn 3.1}$$

Clift et al. studied spherical particles falling through stationary liquids and found that for a spherical particle, K_u is a function of the diameter ratio

$$\lambda = \frac{d}{D} \qquad \text{eqn 3.2}$$

where d = diameter of the rigid particle

D = diameter of the column.

As λ decreases K_u tends to unity.

The particles within sewage are very varied in their composition, density, size and shape and hence the effect of the same boundary conditions on the terminal velocity of different particles may not be consistent. Within the constraints of the project it was not possible to undertake an extensive investigation of this aspect. However, an adequate understanding of the process was obtained by studying the effects of the walls on the synthetic media and then the sewage.

When observing the behaviour of sewage in the settlement column, the downwards sinking motion of the particles displaced the surrounding fluid and established an upwards counter movement within the continuous liquid phase. This movement was particularly visible at the start of the test when there were a lot of larger, heavier particles moving through the liquid creating more turbulence and motion. Later in the test when only the finer, slower moving particles were left to settle, the motion was less noticeable. This particle motion was visible as a parabolic settling velocity profile across the diameter of the column. The smaller the pipe diameter the greater the effect of the walls on those particles closest to the boundary, as was expected. As the column diameter increased the effect of the walls on particles moving in the centre of the column was reduced and the effective settling velocity profile became flatter. This movement was most clearly observed in tests using the wood chips and sewage, but was also visible in the bead tests where there were fewer, larger, particles. Although it was not clear from the experimental tests whether the greatest effect was from the displacement of the fluid by the particles or the effect of the boundaries, or whether the two phenomena influenced the motion at different times, the reduced effects with the larger diameter columns were unmistakable.

The observed effect of the walls on the settling velocity profile of the 54 mm diameter column, although still quite marked, was much reduced compared with the 34 mm diameter column, and was not significantly dissimilar to the larger 68 mm diameter column. As a result the medium sized column, rather than the large diameter column which was slightly less easy to manipulate, was chosen to be used in the finalised test method. This decision agrees with the observations of Owen (1976), as discussed in section 3.2.2, who recommended that a column of 50 mm internal diameter should be used to measure the settling velocities of suspensions of estuarine muds with concentrations between 50 and 200 mg/l.

3.2.3.3 Interaction of particles and fluid

The test column was an enclosed system and therefore any motion of either the particles or the liquid was initiated by either the turning of the column, the sinking or rising action of the particles, or thermal convection currents. The occurrence of thermal convection currents is covered in section 3.2.3.5. As noted above, when the particles in the heavier fractions began to settle through the continuous liquid phase, they set up motion within the column, encountering least downwards resistance in the centre of the column where the wall effects were least. Whilst this downwards motion was continuing there was also an upward movement of lighter and floating particles and fluid. This motion was most clearly observed at the start of the test during the settlement of the first sub-sample fraction, i.e. before t_1 had elapsed (see section 3.1.2). The turning of the column to refill the sub-sample cell with clean water disrupted this motion slightly.

From the second sub-sample period, i.e. from t_2 onwards, the settlement process began to change. Separate zones appeared vertically down the column as the sewage particles began to sink or float to the opposite ends of the column. The flow on the one side of the column was upward and on the other side downwards, as illustrated by figure 3.3. The two movements were clearly separated from each other along a vertical plane that appeared to be in the centre of the column perpendicular to its rotational direction, i.e. in line with the pivot. The zones were most noticeable just after the column was rotated to empty and refill the end cells at each sub-sampling time, and were probably caused by this rotation and the relative speed of the sinking particles to the neutrally buoyant and floating particles.

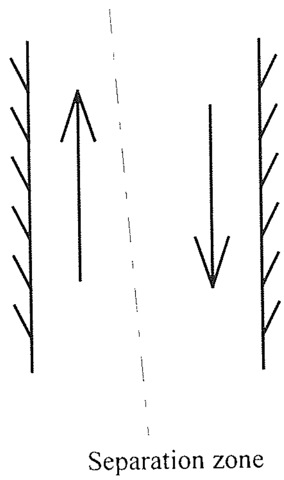

Figure 3.3 Diagram to show the effect of the separation zones on particle and fluid flow within the settlement column.

A third form of motion occurred when the particles remaining in the column were in the lower settling velocities ranges. The distinct separation zones faded out and a more stable pattern of motion as described in section 3.2.3.2 was established. In this third phase the fluid appeared to trickle up the walls of the column to the top with some of the floating particles and fines. The movement of the floating particles towards the walls of the column and the sinking particles towards its centre was noted with all the particles used in the investigation, from the plastic balls down to the wood chips and sewage. It should be noted that this upward movement, although noticeable, was very small in comparison to the much greater downward flow of particles. This phenomena has been observed by other researchers, most notably Allen throughout his many years of work in the field of powder characterisation (Allen, 1990, 1992; McCave and Syvitski, 1991; Lucas-Aiguier and Chebbo, 1995).

In all three types of motion the separating activity of floaters and sinkers faded out about 3 minutes after each sub-sampling and refilling action. Subsequently a much more random movement of the floating and sinking particles was then observed. This was noted with the nylon extrusions, wood chips and with those sewage particles which were large enough to trace individually.

The factor that seemed to affect the settlement of the synthetic media most, particularly the plastic balls and nylon extrusions, was the presence of small air bubbles that attached themselves to the particles and the side walls of the column. The air bubbles had the effect of joining the media together to form a chain or group. These aggregates would then float or sink, often breaking up and then reforming with other groups or individual particles. This movement in turn often affected the settlement of other particles or groups of particles. The resulting effect could be considered to be comparable to the flocculation of the sewage particles that occurs in type-2 settlement and that was seen to occur within the settlement column. Within the column sewage flocs usually sank due to an apparent increase in mass. Air bubbles that were trapped within the column did occasionally attach themselves to the sewage flocs and they would then rise. This problem was not significant during tests because most of the air was released from the column during the initial settlement period. This phenomena was also observed by Chebbo (1992) who used water rather than sewage as his continuous phase. Chebbo's research confirmed the findings here that the gas within distilled or tap water tends to be released on standing, whereas the gas within sewage does not tend to be released during the test period even after storing in a refrigerator. This is likely to be in part because gases, particularly oxygen, have been removed by microbial action in the sewer system prior to arrival at the wastewater treatment works (Nielsen et al., 1992).

The three different patterns of particle/liquid interaction occurred within the column after each rotation. Consequently the rotation of the column probably had the most significant effect on the test results. This rotational effect was not quantified experimentally, but it should be noted that at the start of the test the time between each sub-sample was least and the falling particles captured in the end cell had the highest settling velocities and densities.

3.2.3.4 Choice of liquid phase

Consideration was given to changing the liquid phase of the test from sewage liquor containing neutrally buoyant suspended solids, to clean tap water or distilled water. Sewage residue was kept as the continuous phase for the following reasons.

i) A major consideration in developing the test was to simulate primary settlement conditions as far as possible. This meant that the particles should pass through the sewage and not distilled or tap water. Either tap or distilled water would slightly change the viscosity and density of the liquid through which the particles fell and hence would change the terminal velocities measured in the test. The relevance of using the supernatant is stated by the Task Committee on Preparation of Sedimentation Manual (1969):

> "If the analysis requires the use of the "natural" settling medium, then only supernatant water from the sample can be used to handle the sediment and dilute the mixture in the tube - the dispersing agent would not be used."

ii) As discussed in section 3.2.3.3, the use of clean water would introduce the problem of degassing the water which could significantly increase the length of the test. The test could not be completed in one day without either a store of degassed water, or two test columns, one in which to prepare and degas the water in readiness for the test, and the second in which to separate out the fractions of the sewage.

iii) For type-2 settlement to occur the flocculating particles must settle through a suspension of suspended solids. Changing the suspension from sewage residue to water would inhibit flocculation and so alter the mass and settling velocity of the falling particles and flocs. The effect of concentration on the settlement mechanisms within sewage is discussed in more detail in section 2.7.

iv) There was concern over the possibility of diffusion of chemicals from the particles into the water, if used. This might have affected the chemical attraction between the particles and hindered or even reversed flocculation during settlement. By using residue as the continuous phase this possibility was designed out of the test.

3.2.3.5 Effect of temperature

Wastewater temperature is usually higher than that of tap water direct from the supply system because of the warm water discharging from domestic and industrial processes. The annual variation in wastewater temperature is approximately 10 to 21°C with an average value of 15.6°C. The temperature for optimum bacterial activity is between 25 and 35°C (Metcalf and Eddy, 1991).

> "Aerobic digestion and nitrification stop when the temperature rises to 50°C. When the temperature drops to about 15°C, methane-producing bacteria become quite inactive, and at about 5°C, the autotrophic-nitrifying bacteria practically cease functioning. At 2°C, even the chemoheterotrophic bacteria acting on carbonaceous material become essentially dormant."
>
> (Metcalf and Eddy, 1991)

The temperature of a fluid affects its viscosity and hence the terminal velocity of any particles falling through it. The viscosity of a liquid decreases with an increase in temperature which results in a decrease in the drag forces on any particle moving through the liquid. The result of this increase in temperature is an increase in the terminal velocity of the particle moving through it.

R is the resistance or frictional force on a sphere falling freely through a stationary liquid and is expressed (Michell, 1970) as

$$R = 3\pi d u \mu \qquad \text{eqn 3.3}$$

where d is the diameter of the falling sphere

u is the velocity of the sphere through the liquid

μ is the viscosity of the liquid

F is the gravitational force acting on the sphere and can be expressed as

$$F = \frac{\pi d^3}{6}(\rho_p - \rho)g \qquad \text{eqn 3.4}$$

where ρ_p is the density of the particle

ρ is the density of the fluid

When terminal velocity has been reached

$$F = R \qquad \text{eqn 3.5}$$

If u_s is the terminal velocity, then by substitution

$$3\pi d u_s \mu = \frac{\pi d^3}{6}(\rho_p - \rho)g$$

and

$$u_s = \frac{d^2(\rho_p - \rho)g}{18\mu} \qquad \text{eqn 2.1}$$

which is a form of Stokes equation.

Considering a spherical piece of grit of 1 mm diameter and specific gravity 2.67 falling through water at 15°C and 20°C, the change in the terminal velocity can be calculated. Using data from Lencastre (1987):

At 15°C

d = 0.001m
μ = 1139 N/m^2
ρ_p = 2670 kg/m^2
ρ = 999.1 kg/m^2

from equation 2.1: u_s = **0.800 m/sec**

At 20⁰C

d = 0.001m
μ = 1002 N/m^2
ρ_p = 2670 kg/m^2
ρ = 998.2 kg/m^2

from equation 2.1: u_s = **0.909 m/sec**

Therefore an increase in temperature of 5⁰C will produce a 13.6% increase in the terminal velocity of a sphere falling through water.

Unfortunately investigation into the effect of temperature on the settling velocity of sewage particles was not carried out. This was due to the lack of a temperature controlled environment, the cost of which, to house such a large piece of test equipment, was prohibitive.

To reduce likely errors due to variations in temperature it was recognised that both the ambient temperature and the sewage temperature during the test had to be controlled as much as possible. Once the samples were taken at the wastewater treatment works they were transported back to the laboratory where they were refrigerated overnight. The cooling of the samples reduced the microbial action and so preserved the organic materials in their original state as far as was possible. The following day the samples were removed from the refrigerator and poured into the settlement column. The pouring action and the three hour settlement period brought the sewage up to the ambient temperature. As far as possible room temperature was maintained at 18 - 20°C throughout all the tests, using thermostatically controlled heaters.

Maintaining the room and the liquid within the test column at the same temperature was important for a second reason. When changes in water temperature occur thermal convection currents are created. Within a buried sedimentation tank the effect of these currents would be minimised. The body of water would be so large that the effect of a change in external temperature would have a minimal effect due to the relatively short residence time within the tank and with the movement created by the action of the sludge removal mechanism. However, convection currents would alter the settlement of particles within a small piece of apparatus, such as a settlement column, with a large surface area to volume ratio. This phenomenon has been recognised by other researchers, some of whom submerse the settling apparatus in a water bath to reduce temperature fluctuations (Camp, 1973b).

It is worth noting that on the basis of equation 2.1, that if there are changes in temperature during the test, the shape of the grading curve will be affected. The curve will be stretched and shifted slightly along the x-axis with a rise in temperature.

3.2.4 Problems associated with the prototype test method

3.2.4.1 Air trapped within the ball valves

When the prototype test column was filled with sewage at the beginning of the test, the ball valves were purged of the air trapped in them by opening and closing the valves 3 or 4 times (see Appendix A.1 for the detailed prototype test method). This was to remove any air trapped inside the valves and the column so that when the column was rotated air bubbles did not disturb the settling particles and also create turbulence within the column. However, with the clear plastic columns, after the column had been rotated air still appeared to be leaking from the valves when they were operated. This consequently upset the column contents throughout that test period, breaking up some flocs that had formed as they passed and upsetting the settlement by introducing turbulence and adverse currents.

To determine where this air was coming from the valves were stripped down, and it was found that the chamber holding the ball of the valve was moulded in such a way that air could be trapped inside it. As the column was rotated this air was gradually being released from the main chamber behind the ball of the valve into the column as the valve was operated. To prevent this happening the voids in the main valve chamber were packed with plasticine and painted with a polyurethane sealant before the valve was reassembled. Fortunately the valves employed on the opaque grey plastic prototype were formed in such a way that air could not become trapped and so no remedial action was necessary in that case.

3.2.4.2 Consolidation of the sinking fraction

During the tests using the prototype method in the 54 mm diameter clear column, it was observed that after the overnight (12 hour minimum) settlement period a large floc of sinking particles had formed in the bottom cell. When the column was rotated to start measuring the settling velocities of the sinking and floating particles, the floc started sinking very slowly as one and formed a plug down the column. Smaller flocs either broke off this larger one to settle more quickly, or were separated by shear forces as the liquid flowed between the column wall and the falling floc. As the smaller flocs broke off the main one it sank more quickly and continued breaking up. This slow initial movement was also reported by Coutanceau (Clift et al., 1978) who studied the action of flow around a large spherical body moving along the axis of a tube containing a stationary fluid. He found that the walls of the tube delayed the formation of a recirculatory wake, as observed here. Most of the large floc reached the bottom cell between 3 and 5 minutes into the test. This obviously produced results that were unrepresentative of the true settling velocity distribution of the particles within the sewage.

To try to prevent the sinking particles forming a single mass during the overnight settlement period, the use of an anti-flocculant was considered. Experiments into the effects of anti-flocculant on floc formation in the sewage were carried out using a specially designed piece of apparatus (figure 3.4). The test rig consisted of a board of five 34 mm internal diameter tubes approximately 500 mm long. The tubes clipped onto the board so that they could be removed for filling and were sealed using rubber bungs at each end. The board could be rotated through 180 degrees so that sewage could be allowed to settle and the settlement characteristics could be closely observed, photographed or video recorded for comparison between the different conditions in the tubes. A number of tests were carried out using the anti-flocculant Deflox, which was available in the laboratory, in different concentrations. A tube with no Deflox was always included as a control.

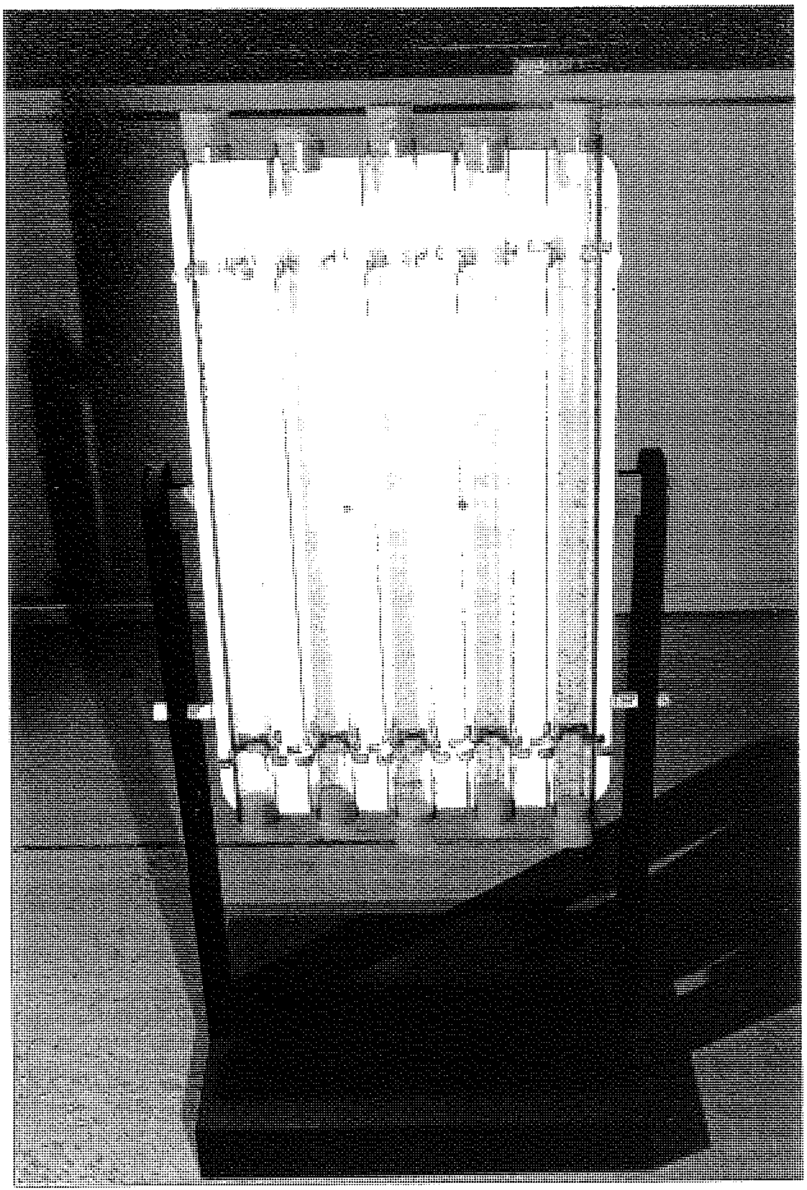

Figure 3.4 Test rig designed for anti-flocculant tests.

As a result of these investigations the use of anti-flocculants in the test was dismissed because Deflox had little or no effect on either floc formation during the initial settlement period or the breakdown of flocs when the test started. The main effect was to increase the viscosity of the water, which was not desirable because it changed the settlement conditions and reduced the terminal velocities of the sinking particles. It was decided instead that the test should be revised to try to reduce the floc formation during the initial standing time.

The control tube in the anti-flocculant tests had shown that a plug of particles could form in under 20 minutes settlement time. To avoid the plug interfering with the measurement of the settling velocity distribution the initial settlement period was reduced from 12 hours to just half an hour longer than the final sub-sample time. For example, if the last sub-sample was taken 2½ hours after the test started, the initial settlement time would be 3 hours. The aim of the initial settlement period was to separate the floating and sinking fractions and allow them to collect in the two end cells, A and B (figure 3.1). Reducing the settlement period down from 12 hours to around 3 hours meant that all the floating and sinking particles that would be captured in the sub-samples during the test should have reached the end cells. After this reduced settlement period, the floating and sinking fractions were removed from the column and shaken vigorously in 1 litre lidded buckets in order to break down any flocs that might have formed. The concentrated particles were not blended, filtered or separated as by other researchers (Chebbo, 1992; Michelbach and Wöhrle, 1992a and 1992b) because it was considered that the composition of the individual sewage particles could be destroyed, and so not truly represent what was present under field conditions.

Reducing the initial settlement time had two other advantages:

i) the test could be set up and carried out within one day;

ii) temperature control within the laboratory was easier without the nightly drop in temperature to consider.

3.2.4.3 Revised test method

The initial investigations into the prototype test method, as described above, showed that the settling mechanisms during the test were not truly representative of those that occurred in reality. This was due partly to the wall effects discussed in section 3.2.3.2 and partly to the disturbance created by the repeated rotation of the column to empty and refill both the end cells at each sub-sampling time.

To reduce the disturbance to particle settlement the test was redesigned to be carried out in three stages. The first stage of the test was the settlement period to separate the floating and sinking fractions as before. The second and third stages were concerned with the separate measurement of the settling velocities of the sinking and floating fractions respectively. Although this meant that the measurement part of the test was lengthened, it was considered to have two advantages over the prototype method.

i) The number of rotations of the column was not reduced, but having the sinkers and floaters tested separately meant that the possibility of the floating particles being trapped and dragged down into the bottom cell by the dominant number of sinking particles was removed. During the initial separating period the floaters and sinkers pass through each other on the way to the end cells. By testing the two fractions together the particles would interact a second time which is not representative of settlement in practice.

ii) For the more dilute sewages and most storm sewage samples the test could be ended after the sinking fraction had been tested and a straightforward bulk sample of the floating fraction could be determined. For any future studies this curtailed test is recommended for the reasons discussed in sections 3.3 and 4.4.1.

In a real situation the floating and sinking fractions separate out together, a process which is mirrored in the initial separation period. It was considered that the redesigned test had significant advantages over the prototype method of simultaneous measurement, where the particles interacted twice, in achieving an accurate representation of the particle settling velocities. It was also more adaptable to differing conditions e.g. storm and DWF sewage.

3.2.4.4 Length of the revised test

In the prototype test method sub-samples were taken for 5 hours. When the grading curves were studied, it was decided that this was an unnecessarily long test period. In the latter stages of the test the weights of solids measured were so low (sometimes in the region of 0.001g) that the results did not represent a significant change to the grading and many readings were reaching the limit of accuracy of the balance used to weigh the filtered samples.

It was decided to recommend a period of 2.5 hours as the maximum settling time for the sinking fraction, giving the last sub-sample a settling velocity of 0.18 mm/sec. A period of 2 hours maximum was recommended for the floating fraction, giving the last sub-sample a settling velocity of 0.23 mm/sec. This reduced time for testing the floating fraction was used because the weights of suspended solids captured in the end cell were very much less than those for the sinking fraction. The reduced weights were difficult to detect using the precision balance and at the longer sub-sampling times, often nothing was recorded. These maximum sub-sampling times were flexible according to the condition of the sample, but were adhered to, in most cases, for the testing carried out in this study to ensure continuity and comparable results.

In the prototype test method the first sub-samples were taken after 5 minutes. These sub-samples were kept, and after the test was completed they were tested separately to determine the fractions by weight with settling velocities greater than 5 mm/sec. With the new test method, where the sinking and floating fractions were tested separately, it was considered that this was unnecessary due to the simplification of the test procedure. The first sub-sampling time intervals for the revised test method were 1 min, 3 min and 5 min from the start of the test.

3.2.5 The test method adopted for the experimental programme

At the end of the developmental phase, the most suitable test method for determining the settling velocity grading of DWF sewage within the time and cost constraints of the project had been developed. It was understood that with the experience gained from the test programme that followed and the analysis of the results, further changes could be made and recommended for future projects.

The main points of the test used within the experimental test programme are as below. Full details have been provided in Appendix A.2.

1) Between 10 and 11 am (see section 4.2.1) a 10 litre sample of sewage is taken from the inlet to the wastewater treatment works, before the screens and grit removal. The sample is returned to the laboratory as soon as possible and refrigerated overnight.

2) The following morning the sample is split into two using a specially designed riffle box (see section 4.2.5). One sample is used in the test, the other is filtered to use in a mass balance as a check on the test results.

3) With reference to figure 3.1, the entire length of the settlement column, including the end cells, is filled with a well mixed sewage sample. The valves are purged of air.

4) The column is left in the vertical position, with cell A uppermost and valves 2 and 3 open, for 3 hours (or ½ hour longer than the time to the last sub-sample period). This results in the sinking fraction being collected in the bottom cell (B) and the floating fraction in the top cell (A).

5) At the end of the 3 hour settlement period valves 2 and 3 are closed and the contents of the end cells drained into separate containers.

6) With cell B uppermost and valve 2 closed, the sinking fraction is poured back into cell B. Valve 1 is closed. Cell A is filled with clean water. The column is rotated so that cell B is uppermost, valves 2 and 3 are opened and the stop clock started. Cell B is filled with the sinking fraction so that the column will be in the reverse position for this part of the test to the initial settlement period. This reversal of standing position avoids settlement into the end cells of particles in the residue with settling velocities less than 0.15 mm/sec. These particles are now travelling in the reverse direction to that of the initial settlement period and hence stay in the residue.

7) After a pre-selected time t_1, valve 3 is closed and cell A emptied into a container by opening valve 4. 30 sec after t_1, the column is rotated through 180 degrees and cell A refilled with clean water. 1 min after t_1, the column is rotated through 180 degrees so that cell B is uppermost, valve 3 is opened and the test continues. The column is held for 30 sec in each position so that, theoretically, any particles that move in the 30 sec are back in their original positions when the test is restarted.

8) Step 7 is repeated at timed intervals until the last sub-sample has been withdrawn from cell A 2½ hours after the start of the test. The contents of cell B are then drained into a container. Cell B is then filled with the retained floating fraction and the test repeated, but with cell B at the bottom of the column and cell A uppermost to receive the rising particles. The positions of the column end cells are reversed for this part of the test for the same reason as explained in (6).

9) At the end of the test the contents of cell B and the central column are drained into separate containers.

10) The samples are then filtered on previously washed, dried and weighed filter papers. The filter papers are then dried and weighed again to obtain the mass of suspended solids in accordance with standard procedures (HMSO, 1980).

Knowing the dry mass of all the sub-samples, including the residue left in the centre of the column at the end of the test, the total sample mass can be obtained. Each filtered sub-sample yields the mass of solids with a specific settling/terminal velocity range. As a check that the total mass of suspended solids is correct, or that something has gone awry during the test, a mass balance with the split crude sample (see step 2) is undertaken. Any large discrepancies in the concentrations should be investigated. With this data a settling velocity grading curve of the percentage of the total sample mass with a settling velocity less than a known value can be plotted.

3.3 EVALUATION OF THE SETTLING VELOCITY TEST METHOD

The settlement velocity measurement method developed in this study has been investigated as far as possible within the time available. Using the test apparatus constructed for the James Bridge study (Hedges et al., 1990) and drawing on other settling velocity measurement methods and related literature, the most suitable test was developed within the time and cost constraints of the project. No settlement velocity measurement method is ideal, all have their advantages and drawbacks as discussed in Chapter 2. As such, this test is no different.

The prototype apparatus was constructed for the measurement of storm sewage settling velocities. When the prototype was constructed it was employed with simulated storm sewage from pumped tests that was a diluted form of DWF sewage, with a lower concentration of suspended solids. Due to this it was decided that a large bulk volume would be required in order to detect the mass of particles in each sub-sample. However, from work carried out on the column length and diameter by Owen (1970 and 1976) and during this study, it was concluded that the column was the optimum size for DWF sewage settling velocity measurement. The concentrations of suspended solids in storm and DWF sewage are of the same order of magnitude, although their composition and particle size distribution may vary (see section 2.5). From the observations and investigations made when testing both storm and DWF sewage it was confirmed that the size requirements of the test column were the same for both storm and DWF sewage. This size requirement made the apparatus large and difficult to transport but, provided a safe working platform was available, it had many advantages over smaller, more portable apparatuses in allowing the whole sewage sample to be tested without significant pre-concentration of the suspended solid material.

The size of the apparatus meant that a 5 litre sample of sewage could be tested. Sewage is variable in its nature and by testing a large sample it was hoped that a more representative settling velocity distribution could be obtained than from other methods. Other tests that are commonly in use, such as the Bottom Withdrawal Tube (see section 2.8.2.2), the Umwelt-und Fluid Technik settling apparatus (see section 2.8.2.5), or the CERGRENE (ENPC) settlement measurement column (see section 2.8.2.4), all use a smaller quantity of sewage, approximately 1 litre, in their analyses. Using 5 litres of sewage ensured that the mass of solids collected in each sub-sample could be detected using a precision balance. This was especially important where the weights of the fractions were at or near the limits of detection of the precision balance used, which weighed to the nearest milligramme.

Human judgement was removed as far as possible in the test procedure. No volumes were required to be withdrawn from the central section of the column. The particles settled into the end cells and were withdrawn on closing the valves to the cells, preventing the collection of any particles that had not travelled the full length of the column.

There was a disadvantage in having the particles settle from a sewage containing suspended particles into cells containing clean water. When the valve separating the column and the sub-sample cell was opened, some transfer of fine suspended particles from the residual fraction into the clear water occurred. This transfer of neutrally buoyant particles appeared to be caused by turbulence when the valve was rotated, rather than by diffusion, because the particles could be seen to 'billow' into the clear water.

An experiment was designed to detect and quantify this particle transfer. A sample of sewage was collected and treated as normal with overnight refrigeration. The following morning, the sample was poured into the column and left for the 3 hour settlement period. At the end of settlement, both the end cells were emptied. The settling velocity measurement test was then carried out, but without the sinkers or floaters being replaced in the top or bottom end cell (see section 3.2.5 for the test method). The sub-sample cell was allowed to collect only the suspended solids that were transferred into it from the residual fraction by turbulence. At the end of the test the column was drained as normal and all the different sub-samples filtered, dried and weighed. The results of the test are provided in table 3.1 and figure 3.5.

SETTLING VELOCITY (mm/sec)	% OF TOTAL SUSPENDED SOLIDS MASS	% OF TOTAL SAMPLE WITH SETTLING VELOCITY LESS THAN VALUE
-27.08	0.00	0.00
-7.74	0.18	0.18
-5.42	0.09	0.18
-2.46	0.18	0.27
-1.35	0.45	0.45
-0.90	0.64	0.90
0	75.13	
0.18	1.18	76.67
0.23	1.91	77.85
0.30	2.45	79.76
0.45	2.72	82.21
0.68	2.27	84.93
0.90	2.72	87.2
1.35	3.18	89.92
2.71	2.27	93.1
5.42	1.36	95.37
9.03	1.63	96.73
27.08	1.63	98.36

Table 3.1 Results of the test to investigate the significance of suspended particles entering the sub-sample cell due to turbulence within the closed column system.

Both table 3.1 and figure 3.5 confirm that particles are entering the sub-sample cell due to turbulence. Approximately the same mass enters the sub-sample cell during each interval regardless of the change in duration. The rotation of both the valve and the column were thought to contribute to this turbulence.

These results have been confirmed by further research carried out at Aston University (Hasselt, 1995) which was part supervised by the author.

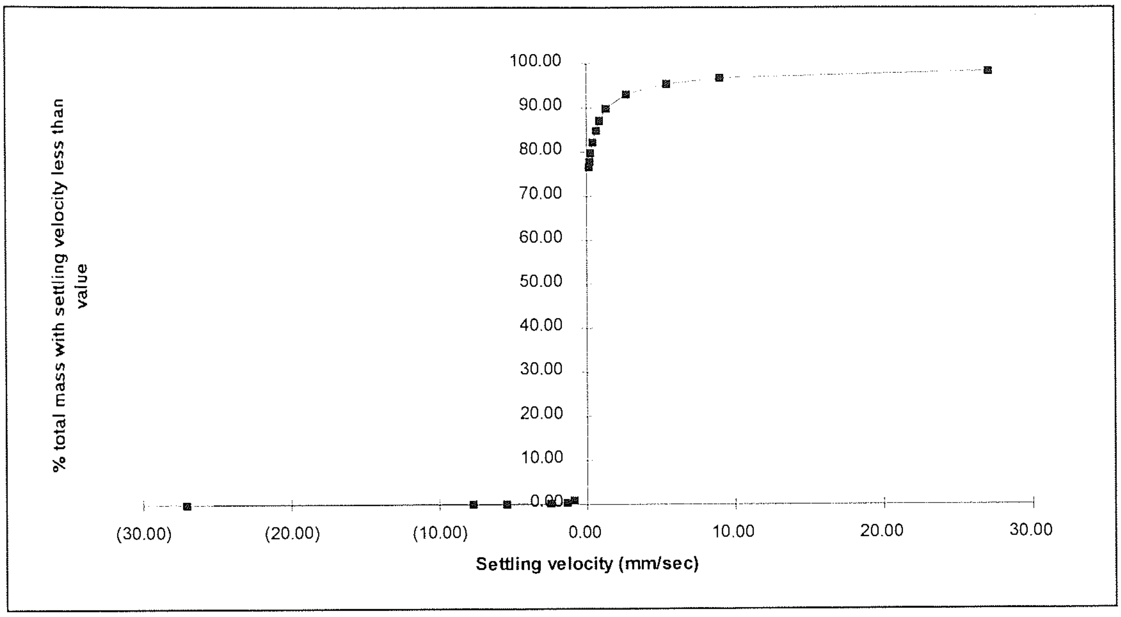

Figure 3.5 Settling velocity distribution illustrating the percentage of particle mass that can enter the sub-sample cell during a test due to turbulence.

In many of the sub-samples taken during the measurement of the floating fraction there did not appear to be any real 'floaters' rising into the top cell. The only movement appeared to be the billowing effect of the transfer of the fine suspended particles from the residue. This is discussed further in section 4.4.1.

One area where people new to the test sometimes had problems was in filling the column with sewage and then purging the valves to avoid air bubbles interfering with the settlement during the test. With practice this problem could be eliminated, but any user should always be careful when re-filling the end cells with clean water to ensure that valves 1 or 4 in figure 3.1 are filled to the top and purged of all air before rotating the column.

The greatest drawback of the test was the turbulence caused within the settlement column when it was rotated to empty and refill the sub-sample cells. With the design of the column it was impossible to reduce the number of 180 degree rotations below two at the end of each time interval. The only way to avoid the rotations would have been to bleed off a volume containing the fallen particles, but this would have had several disadvantages.

i) Human judgement would be involved in determining the volume to be bled off during each sub-sampling event. The volume withdrawn would be dependent on the volume of solids collected at the base of the column, as in Michelbach and Wöhrle's settling velocity measurement method (see section 3.4.2).

ii) By continually shortening the settling distance, the conditions under which all the particles settle would vary from the recommended length of 1.5 to 2.0m. This would not allow full flocculating settling to occur for the suspended solid flocs.

iii) A calculation would have to be made to determine the residual concentration and this value would have to be deducted from the measured mass to obtain a true mass value for each sub-sample taken. This is not satisfactory because a large percentage of the total mass is contributed by the residue and any uncertainties in the procedure would result in larger errors being introduced. This percentage needs to be accurately determined in order to obtain a true representation of the distribution of settling velocities.

v) The settling velocity of the floating fraction could not be measured because there would be very little or no residue remaining at the end of the test and samples could not be removed from the top by gravity, although siphoning could be used with care.

3.4 COMPARISON OF THE TEST WITH ALTERNATIVE SETTLING VELOCITY MEASUREMENT METHODS

During the review of research into the settlement velocity measurement of sewage particles, several alternative methods of measurement came to light, as discussed in Chapter 2. As part of the test development as many of the good features of the alternative methods were taken into consideration and incorporated where possible into the revised test.

Before the form of the test was finalised, comparisons with two of the alternative settling velocity measurement methods were carried out. The main aim of this was to determine whether the results from the three different methods were comparable, suitable for the project application, and to compare their ease of use. The tests chosen were the settling velocity measurement technique developed by Michelbach and Wöhrle (Institute für Siedlungswasserwirtshaft Universität Karlsruhe, 1990) and the HRS, Wallingford bottom withdrawal method (Owen, 1976). These two were selected because they most closely resemble the Aston method, details of the procedure were available, and both were currently in use. The details of both methods are provided in chapter 2, sections 2.8.2.5 and 2.8.2.2.

Full details of the bottom withdrawal method were available to the author at the time of the comparison test, but unfortunately only partial details of Michelbach and Wöhrle's method had been obtained. It was not realised that the sample of sewage was preconcentrated and only the settled solids used in the test. In the comparison tests at Aston University, a 75 ml sample of raw sewage was used. Due to the use of an incorrect method, it has been decided not to use the authors results for this comparison, other than for qualitative evaluation. Instead, the results of subsequent work by Baker (1994), undertaken with the guidance of the author, using the corrected test method will be used.

3.4.1 The bottom withdrawal method

Having carried out a test using the bottom withdrawal method (Owen, 1976), several comments on its use and accuracy can be made.

i) There was a considerable amount of turbulence within the column as the test started. This was because the test began as soon as the column was filled with the well mixed sewage and the filling action caused a considerable amount of turbulence.

ii) The turbulence within the column was observed to have calmed down 10 minutes into the test, with most of the particles then sinking. This would have distorted the earliest, and perhaps the more important sub-samples taken.

iii) As the samples were withdrawn, there was a certain amount of deposition on the sides of the column above the new reduced water level. It may be that the deposits were the floating particles that rose to the top of the column. These could only be removed by flushing with clean water after the test had been completed.

iv) There did not appear to be any deposition on the sides of the glass column within the column of sewage.

The results of the test are shown in table 3.2. As can be seen the cumulative percentage of mass does not make any sense. Errors are incurred at each stage of sub-sampling because a proportion of the particles with lower settling velocities than those having fully settled to the bottom of the column are included. This is due to there being a mixture of particles with different settling velocities throughout the length of the column. With the shortening of the settlement distance as the sub-samples are taken, some particles fall through a shorter length and therefore some of the particles with low settling velocities reach the bottom of the column in the same time that it takes the heavier particles to fall from the top of the column. A corrective procedure is employed based on the 'Depth factor', which is applied, by multiplication, to the cumulative weight to produce the cumulative weight in 1.0 m suspension, and to the time to produce a corrected time of sampling for 1.0 m suspension. In this case it is the application of the 'Depth factor' which distorts the results. The values are no longer cumulative: errors can be incurred by correcting for a reduced settlement distance.

Tube No.	Height	Time (min)	Weight of sample (g)	Cumulative weight (g)	Depth factor (1/Height)	Weight in 1.00 m suspension (g)	Corrected time (min)	Cum. mass (%)	Settling velocity (mm/sec)
				0.100	1.000	0.1000		100	
1	0.86	1.5	0.010	0.090	1.163	0.1047	1.7445	104.7	9.554
2	0.72	3	0.019	0.071	1.389	0.0986	4.167	98.6	4.000
3	0.58	6	0.019	0.052	1.724	0.0896	10.344	89.6	1.611
4	0.44	12	0.017	0.035	2.273	0.0796	27.276	79.6	0.611
5	0.3	30	0.013	0.022	3.333	0.0733	99.99	73.3	0.167
6	0.15	96	0.009	0.013	6.667	0.0867	640.032	86.7	0.026
7	0.05	180	0.004	0.009	20	0.1800	3600	180	0.005
8		+180	0.009						

Table 3.2 Calculation of the cumulative mass values for the bottom withdrawal test (after Owen, 1976).

From the bottom withdrawal test carried out by the author, the following conclusions have been drawn.

i) There is a large amount of turbulence in the column at the start of the test. Although this turbulence reduces with time, it has no great advantage over the turbulence caused in the Aston method.

ii) The method of calculating the cumulative grading distribution does not always correctly compensate for the masses in each sub-sample.

iii) In the author's opinion, this is an unsuitable method for measuring the settling velocity distribution of the particulate matter in sewage because of the inaccuracy in compensating for the reduced settlement depth.

3.4.2 The Umwelt-und Fluid Technik (UFT) settling velocity measurement method

It should be noted that after the completion of settling velocity measurement tests by the author, and subsequently Baker (1994), using the UFT method, it was disclosed that the main column was too wide. Later work by Hasselt (1995) showed that having had a larger column diameter did not have any observable effect on the results. On the basis of observations made during the three settling velocity measurement tests undertaken by the author and the tests by Baker (1994) using the apparatus developed by UFT (see section 2.8.2.5 for details), the following comments on the procedure can be made.

i) As the sample was moved over the top of the settling tube (see figure 2.5) there was a rush of the solids down into the water which created a lot of turbulence in the whole of the column, especially in the straight section. This turbulence had died away after 20 minutes.

ii) As the solids settled there was a rising motion of fluid up the sides of the column and the cone.

iii) The fluid levels in the top box section of the apparatus and the cylinder containing the sample were different at the start of the test. After approximately 10 minutes these levels equalised. The level in the cylinder dropping to that in the box section. Some of the solids may be lost from the test by the seeping of solids and liquid underneath the cylinder into the top box.

iv) There was a lot of deposition of particles on the sloping sides of the conical section during the test. This deposition could not be removed during the test itself.

v) Very little flocculation of the particles was observed during the test. This may be because there was a low concentration of particles, so that the settling mechanism could be considered to be type-1, discrete (see section 2.7.2). The lack of flocculation may also be because the solids pass through water, and not sewage residue which contains dissolved and very fine flocculating particles.

vi) As the sub-samples were taken from the base of the Imhoff cone, disturbance was caused above the sampling point. This may have broken up any flocs that were forming farther up the cone.

vii) The 1 litre sample of raw sewage was prepared by allowing the solids to settle for 2 hours. The settled solids were then drawn off and the volume made up to 75 ml with distilled water. This sample was then poured into the sample cylinder in the top box section of the column. If a sewage sample had a particularly high solids concentration, only a small amount of distilled water would be needed to make the solids sample up to 75 ml. When the quantity of solids in the sample was high they fall densely through the settlement column and occasionally blocked the sub-sampling tube at the bottom of the Imhoff cone.

viii) Enough liquid had to be withdrawn from the bottom of the column to remove all the particles that had settled there. This removal had a draw-down effect on the rest of the column contents. This was not a problem in the cylindrical section of the column, but was quite severe at the base of the cone which had a much smaller cross sectional area. A small volume could remove a large height of liquid at the base of the cone, whilst not significantly affecting the height of the total column. This affected the settling velocity measurements for particles nearing the base of the column by reducing the distance over which they travelled.

ix) Occasionally, if the valve was opened too quickly, a jet of liquid would pass through the collected solids and the total mass might not be withdrawn effectively, even though a large volume of liquid was sampled.

x) In the method described by Michelbach and Wöhrle only the sub-samples taken from the base of the Imhoff cone were used to calculate the settling velocity distribution. The solids left as residue in the apparatus and those discarded after the initial 2 hour settlement period were not included in the settling velocity distribution. Therefore, a picture of the complete sewage was not obtained.

Four comparative tests of the method developed by the author in this project with the UFT apparatus and test method were carried out (Baker, 1994). The results are provided in tables 3.3 and 3.4 and graphically in figure 3.6.

Settling velocity (mm/sec)	% mass with settling velocity less than the value			
	Experiment 3	Experiment 5	Experiment 6	Experiment 7
27.08	97.469	95.536	96.473	94.928
9.03	83.129	90.261	94.709	89.857
5.42	73.175	85.797	85.009	84.785
2.71	62.547	79.304	71.781	77.459
1.35	56.642	72.405	64.727	73.434
0.9	52.93	65.912	59.436	70.053
0.68	50.231	59.825	51.499	67.075
0.45	47.363	52.926	43.563	61.278
0.3	45.507	50.491	35.626	54.194
0.23	43.145	46.027	32.981	50.652
0.18	41.796	43.592	29.453	48.64

Table 3.3 Results of settling velocity measurement test using the Aston column in comparison tests with the UFT apparatus (Baker, 1994).

Settling velocity (mm/sec)	% mass with settling velocity less than value			
	Experiment 3	Experiment 5	Experiment 6	Experiment 7
25.93	98.925	100	99.827	100
7	72.043	72.816	94.983	89.632
2.58	45.161	45.631	68.685	49.164
1.14	23.656	24.272	25.779	29.431
0.54	12.903	11.65	14.187	16.165
0.26	3.226	2.913	5.363	11.371
0.14	1.075	0	1.557	6.355
0.06	0	0	0	0

Table 3.4 Results of settling velocity measurement test using the UFT apparatus in comparison tests with the Aston column (Baker, 1994).

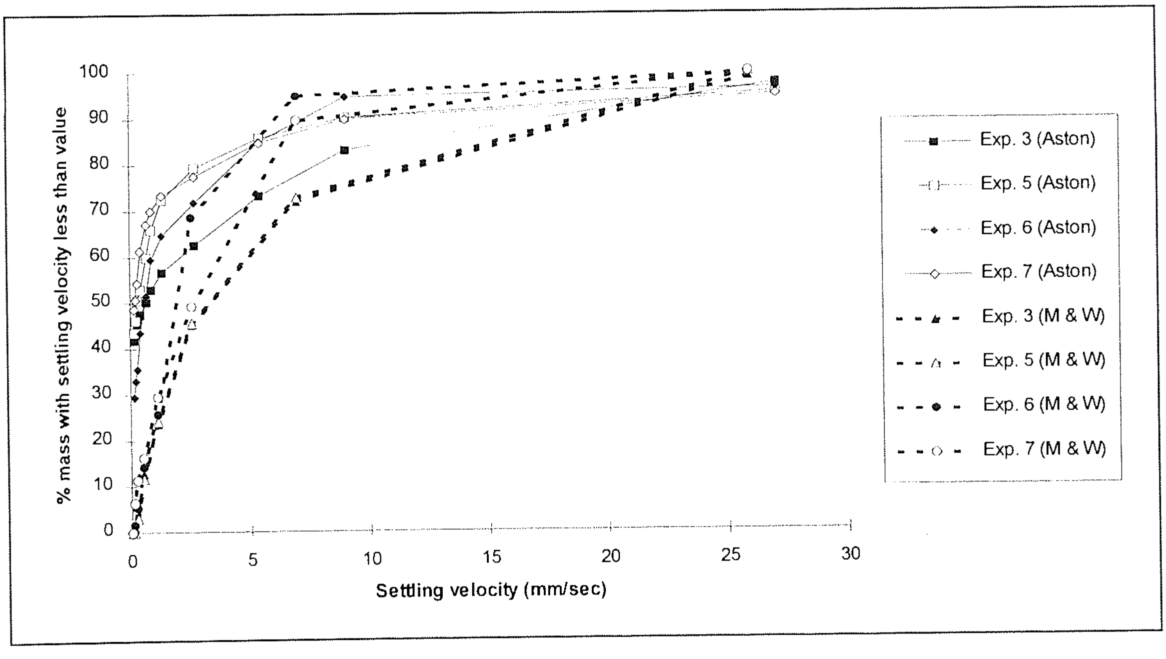

Figure 3.6 Settling velocity gradings using the Aston column and the UFT apparatus in comparison tests on the same sewage samples.

It can be seen clearly from the results in tables 3.3 and 3.4 and the settling velocity gradings in figure 3.6 that the two methods produce different results. The UFT test does not take into account the residual solids or the initial concentration of the raw sewage. As a consequence the results for these tests have a zero value for the percentage of mass with a settling velocity less than a particular value. This means that the graphs for the two methods have different starting points, with the settling velocity grading curve determined using the Aston method having an initial measured value of approximately 30 to 50 % of the total sample mass. The results of the sub-sample masses collected during the test are therefore spread over 100 % of the vertical axis for the UFT method and approximately 50 to 70% of the vertical axis for the Aston method.

For a fairer comparison to be made between the Aston method and the UFT method, all of the solids in the original sample should be included in the graphical results when applying the UFT method. The results from the revised UFT method, recalculated to include the total suspended solids in the sample, are provided in table 3.5 and figure 3.7

Settling velocity (mm/sec)	% mass with settling velocity less than value		
	Experiment 3	Experiment 5	Experiment 6
25.93	99.444	100	100
7	85.555	88.333	97.692
2.58	71.666	76.666	86.154
1.14	60.555	67.499	66.923
0.54	54.999	62.082	61.538
0.26	49.999	58.332	57.692
0.14	48.888	57.082	56.154
0.06	48.332	57.082	55.385

Table 3.5 Results of settling velocity measurement test using the UFT apparatus, adjusting the results to include the total mass of suspended solids in the sample.

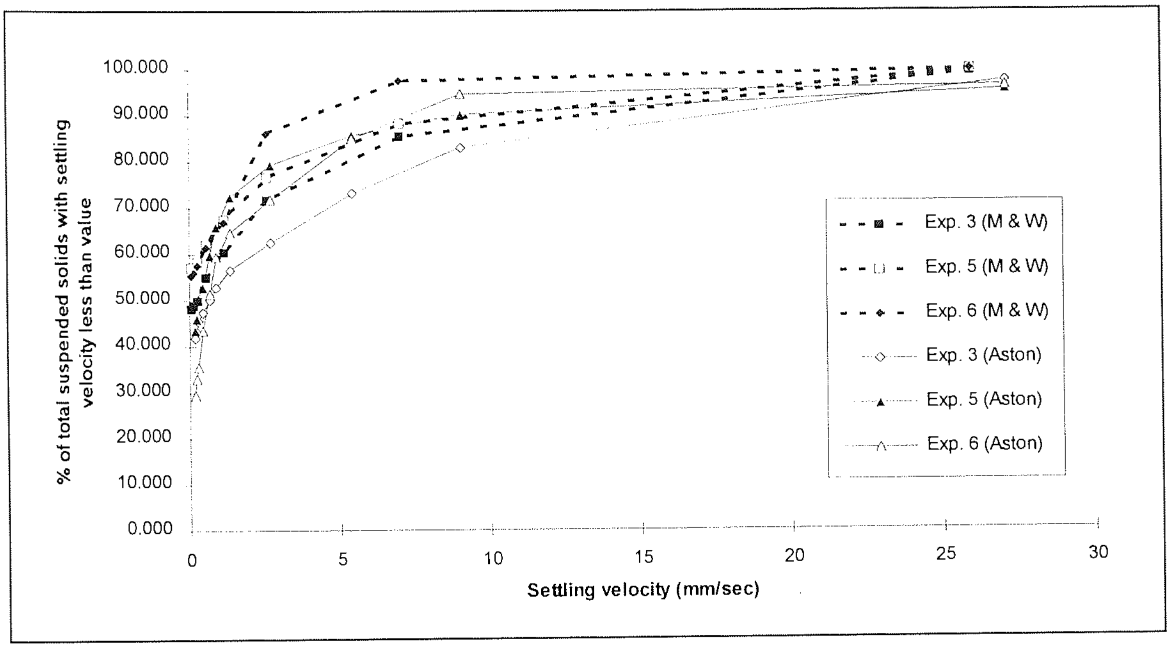

Figure 3.7 Plot to show the comparison between settling velocity measurement test using the UFT apparatus and the Aston method adjusting the results of the UFT test to include the total mass of suspended solids in the sample.

Figure 3.7 clearly shows that the inclusion of all the solids in the sample produces a similarly shaped settling velocity grading for both the revised UFT method and the Aston method. Although this is a very small sample upon which to draw any conclusions, it is interesting to note that for all three samples the UFT method underestimates the mass of suspended solids settling at the higher velocities. These findings are contrary to those reported by Aiguier et al. (1995), who found that the settled solids appeared to settle out more quickly with the UFT method than with the Aston method. It should be noted that not all the suspended solids were used by Aiguier in her comparisons with the UFT device and therefore the values are overestimated by approximately 40% to 77% of the total mass.

As discussed previously, when the testing programme began the correct UFT test method, as employed by Michelbach and Wöhrle, was unavailable. The comparative studies carried out by the author indicated that the UFT method was unsuitable for measuring the settling velocity distribution of sewage. It should be remembered that the UFT method was developed to measure the settling velocity grading of storm sewage and sewer sediments. On this basis it was concluded that for the purposes of this project the test method developed by the author was more suitable for measuring the settling velocity distribution of a complete sewage sample than the method developed by Michelbach and Wöhrle at UFT. With knowledge of the complete UFT test method, the author still considers that the method developed for this research has the following advantages over the UFT method.

i) It is preferential to allow the solids to settle through sewage liquor rather than clean water.

ii) The larger sample size should provide a more representative settling velocity distribution.

iii) The longer settlement length allows the settling velocity of flocculating particles to be obtained. It should be noted that, with the particles in the UFT method settling through clean water, flocculation is unlikely to take place.

iv) Having a vertical settlement length with no tapering sections prevents solids settling onto the sides of the column.

v) It is not possible to determine the floating fraction with the UFT test.

3.5 SUMMARY

For the purposes of experimental analysis a method for measuring the settling velocity of particles within DWF sewage was investigated and developed. In this process, consideration was given to research carried out in the field of settling velocity measurement and comparisons with other currently used procedures were undertaken.

In considering the column dimensions it was decided to retain the Aston column's original size because this allowed both the discrete and flocculating particles to reach their appropriate terminal velocities without any significant influence from the walls. However, the test method was changed considerably to mimic, as far as practical, the settling action in conventional sedimentation devices.

To fully appreciate the test method it was compared under experimental conditions with two other currently used methods. Their methodology, ease of use and suitability for measuring settling velocity distributions of sewage was considered. It was concluded by the author that the method of settling velocity measurement developed in this project was suitable for the analysis described in Chapter 4.

CHAPTER 4

EXPERIMENTAL PROCEDURES AND DATA PRESENTATION

4.1 INTRODUCTION

This chapter is concerned with the experimental procedures used for both sampling sewage at the wastewater treatment works and the laboratory testing to obtain a settling velocity distribution. Included in the procedural section are explanations for the methods used in terms of practical considerations, such as returning the sample back to the laboratory by the end of the day for overnight refrigeration, and the characteristics of the flow to the wastewater treatment works.

A discussion of the methods for presenting the settling velocity grading data is provided. This considers factors associated with the test method, such as the measurement of the floating fraction, and the practicality of being able to use and compare as many of the collected settling velocity data sets as possible.

4.2 SAMPLING

Consideration was given to the problems associated with sampling the sewage. The main areas considered were:

- time of sampling;
- time of concentration;
- weather, mainly rainfall;
- journey time;

- time between sampling and testing;
- sampling method; and
- repeatability of results for the same site.

4.2.1 Time of sampling

For a typical catchment the flow that reaches the wastewater treatment works includes domestic and industrial discharges and an element of infiltration into the sewer system via leaks at joints and broken pipes. For a well maintained sewer system, the infiltration is minimal. The infiltration rate does vary with the water table level, the pipe materials and the condition of the sewer system (Metcalf and Eddy, 1991), but it will be considered constant for the purposes of this project.

The main factors that cause diurnal variations, that is changes in flow rates during the 24 hour daily period, are the varying water use patterns from residential and industrial properties. This diurnal variation for a typical dry day from a gravity fed sewerage system is shown in figure 4.1 (Institute of Water Pollution Control, 1984). Hourly flow rates vary from 20 to 250 percent of the average daily flow for small catchments, to 50 to 200 percent for larger cities. The greater the number of connections to the sewer system, the less pronounced are the peaks relative to the average daily flows (Hammer, 1991). If pumping stations are present within the sewerage system, the flow pattern may be very different (Institute of Water Pollution Control, 1984).

The strength of sewage varies throughout the day. The greatest concentrations of pollutants occur during the day when both domestic and industrial activities and discharges are greatest. At night, flow decreases to a minimum along with human activity (Hammer, 1991). At the lowest flows the main component of the sewage is made up from infiltration into the sewer system.

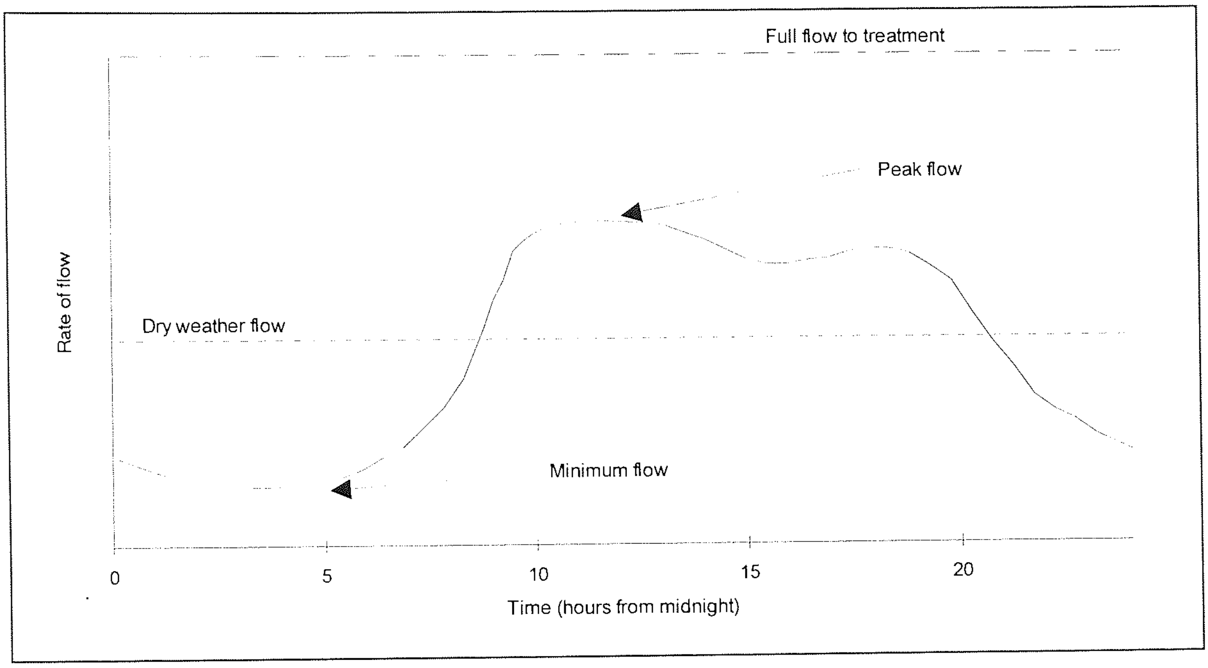

Figure 4.1 Schematic diagram of the diurnal flow pattern for a gravity fed sewerage system (after Institute of Water Pollution Control, 1984).

Although it was recognised that the time of concentration varied between catchments of different area (see section 4.2.2), to minimise variations in the composition of the sewage it was important that the time of sampling was kept as consistent as possible throughout the project. It was decided that samples should be taken between 10 am and 11 am. This specific time was chosen mainly for practical reasons. It allowed the operator time to travel to a site in the morning, even if an overnight stop was necessary, and still be able to return the sample to the laboratory the same day for overnight refrigeration. The full test could then be carried out the following day. In addition, between 10 am and 11 am the flow to the wastewater treatment works was at approximately the average daily flow level according to typical diurnal flow patterns (see figure 4.1).

It was recognised that in an ideal situation the test would be carried out on the same day that the sample was taken to ensure that the sewage was fresh. Unfortunately, as the test catchments were located all over England and Wales (see chapter 5), same day sampling and testing was not possible without a mobile laboratory, and the costs of which was outside the budget for the project.

4.2.2 Time of concentration

In general terms the greater the size and area of a catchment, the greater the length of the sewers from the periphery of the catchment to the wastewater treatment works and therefore the greater the time of concentration. The time of concentration is the time it takes for the sewage that enters the sewer system to reach the outfall or point of interest - in this case the wastewater treatment works. A large catchment usually has a greater number of connections to the sewerage system than a small catchment due to the larger number of users of the system. The time of concentration of a large catchment, along with the greater number of connections at various points along the sewer system, means that the peaks and troughs in the daily flow rates are reduced and become closer to the average daily flow rate. This is because there is a greater variation in the times the sewage from different discharge points takes to reach the main trunk sewer and therefore the flow rates through the trunk sewer have a smaller range. As a result of this not only is the flow rate more uniform, but the composition of the sewage is more consistent throughout the day. Furthermore, the industrial and commercial activities in a large city are greater than in a small town. This increase in activity reduces the chances of peaks in pollutant concentration that could occur in small, mainly residential towns.

The potential change in the composition of the sewage due to the different times of concentration in different catchments could not be allowed for in sampling. Indeed, the time of concentration was one of the catchment characteristics that was thought might affect the settling velocity grading of the sewage (see chapter 5). With the daily peaks in discharge occurring at about the same time of day, it was considered important to ensure that the time of sampling the sewage remained the same for each catchment, irrespective of size.

4.2.3 Weather conditions

For combined and partially separate sewer systems the composition of sewage is affected by weather conditions. In periods of dry weather, flows in sewers are low, sediments may build up on the pipe beds and slime on the walls. When rainfall occurs, in addition to wash off from impermeable surfaces, velocities within storm sewers and combined sewers are increased and some or all of the deposited sediments and slime layer are re-suspended in the flow and carried to the wastewater treatment works. This process has been well documented and is discussed in chapter 2. In periods of dry weather, or in some countries where snow builds up for long periods alongside roads, pollutants are able to accumulate and are then washed into the sewers when rainfall occurs or the snow melts in spring (Lygren and Damhaug, 1986; Viklander and Malmqvist 1993).

The flow at which storm overflows start to operate in Britain is determined using Formula 'A':

$$\text{Storm overflow setting} = (PG + I + E) + 1.36P + 2E \text{ m}^3 \text{ per day} \qquad \text{eqn 4.1}$$

where:

P = population
G = average domestic water consumption (m^3 /hd/d)
I = infiltration (m^3 /d)
E = industrial effluent (m^3 /d)

DWF is represented in the formula by (PG + I + E), (Institute of Water Pollution Control, 1984). The Formula 'A' storm setting value roughly equates to 6 DWF. Within the sewer system, flows in excess of the Formula 'A' setting are diverted to a watercourse at combined sewer overflows (see figure 4.2).

During periods of wet weather, incoming sewage will continue through the works for full treatment until a flow of approximately 3 DWF (3PG + I + 3E) has been reached. During storms, the flows in excess of 3 DWF are either discharged straight into the receiving watercourse, or they may receive some treatment in the form of a solids/liquid separation device. Where wastewater treatment works have a storm tank capacity, flows between full flow to treatment (3 DWF) and approximately 6 DWF (or Formula 'A' value) are diverted to receiving tanks, where they receive treatment in the form of sedimentation, before being discharged to the watercourse or returned to the main stream for treatment when the flow to the works subsides. This allows a range of flows between approximately 3 and 6 DWF to be passed through to the wastewater treatment works for at least some form of treatment before flow is considered to be of a suitable dilution to be diverted, via a storm overflow, into a receiving water course.

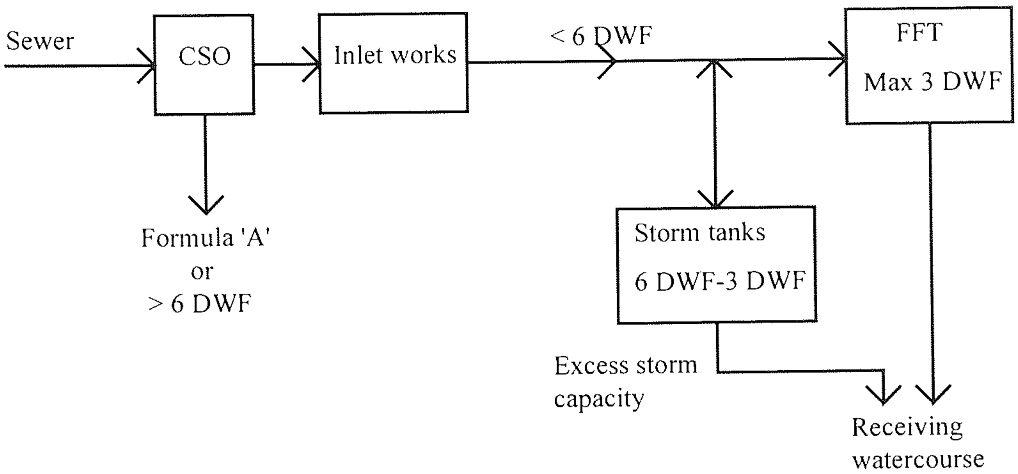

Figure 4.2 Flow settings for UK wastewater treatment works.

In some cases infiltration levels are so great that for long periods of the year the wastewater treatment works will operate as if under storm flow conditions unless this is accounted for in Formula 'A' during design.

The aim of this project was such that the settling velocity grading of DWF sewage was required. Ideally, samples for testing should all have been taken during periods of DWF. However, due to the unpredictable and varied nature of the British weather, it was not always possible to find DWF conditions at the treatment works to be sampled during the testing programme. Instead, where possible, the flow through the works at the time of sampling was taken and then converted to a multiple of DWF for inclusion in the analysis of the results. Local knowledge was also gained by talking to the site operatives about weather conditions prior to sampling.

4.2.4 Time after sampling

4.2.4.1 Journey back to the laboratory

The effect of the delay in returning the sample back to the laboratory for refrigeration may well have had an effect on the settling velocity of the particles. In the original programme for the development of the test method, the journey time and mode of transport were two factors that were to be considered. However, due to time constraints, a priority list of factors to investigate was drawn up. The effects of both journey time and mode of transport are likely to be influenced by the delay between sampling and testing, which was investigated, as discussed in section 4.2.4.2. These journey parameters were noted as possible influences on the results, but were not studied further.

4.2.4.2 The effect of sample ageing

Any delay between sampling the sewage and testing it to determine the settling velocity distribution is likely to change the sewage by a number of mechanisms, some of which are given below (Nielsen et al., 1992);

- change in temperature increasing or inhibiting chemical and microbial actions;
- microbial action altering the organic component of the sewage;
- standing of the sample causing flocculation of the particles.

Reducing the temperature by refrigeration helped to retard the chemical and microbial changes. The chemicals within sewage could be preserved over time using additives, but their use is not appropriate for periods less than 24 hours (American Public Health Association, 1992), and so were not considered for this project.

Flocculation caused by standing was unavoidable. The samples were well shaken before being poured into the test column in an attempt to break down the bonds between the flocs that had resulted from standing, without damaging the particles themselves. Some researchers, particularly in the field of bed sediment analysis, process the particles in a blender (for example Chebbo, 1992). This was considered to be too severe in this case because it would have destroyed the structure of the organic molecules within the sewage.

There was insufficient time within the development phase of the project to investigate fully the effects of ageing on the sample. Some research was undertaken at Aston University, under the author's guidance, using the test method developed in this project (Baker, 1994). As part of that research a test was carried out on a 48 hour old sample. In order to study the effect of ageing the results of two other tests from the same treatment works have been

	Percentage of total sample mass with a settling velocity less than the corresponding value			
Settling velocity (mm/s)	Test ref. 2s (tested day of sampling)	Test ref. 3s (tested day of sampling)	Test ref. 4s (tested 48 hour after sampling)	Average of all 3 tests
27.08	94.107	97.469	94.734	96.102
9.03	82.523	83.128	84.655	83.892
5.42	74.801	73.175	76.531	74.853
2.71	66.062	62.547	67.805	65.176
1.35	58.950	56.642	59.531	58.086
0.90	55.292	52.930	54.115	53.523
0.68	52.650	50.231	50.203	50.217
0.45	50.008	47.363	45.389	46.376
0.30	46.553	45.507	41.778	43.643
0.23	44.928	43.145	38.619	40.882
0.18	43.505	41.796	36.513	39.154
0.15	24.809	28.637	16.654	22.645

Table 4.1 Comparison of results from tests with the same sample variables, but of different ages on testing (Baker, 1994).

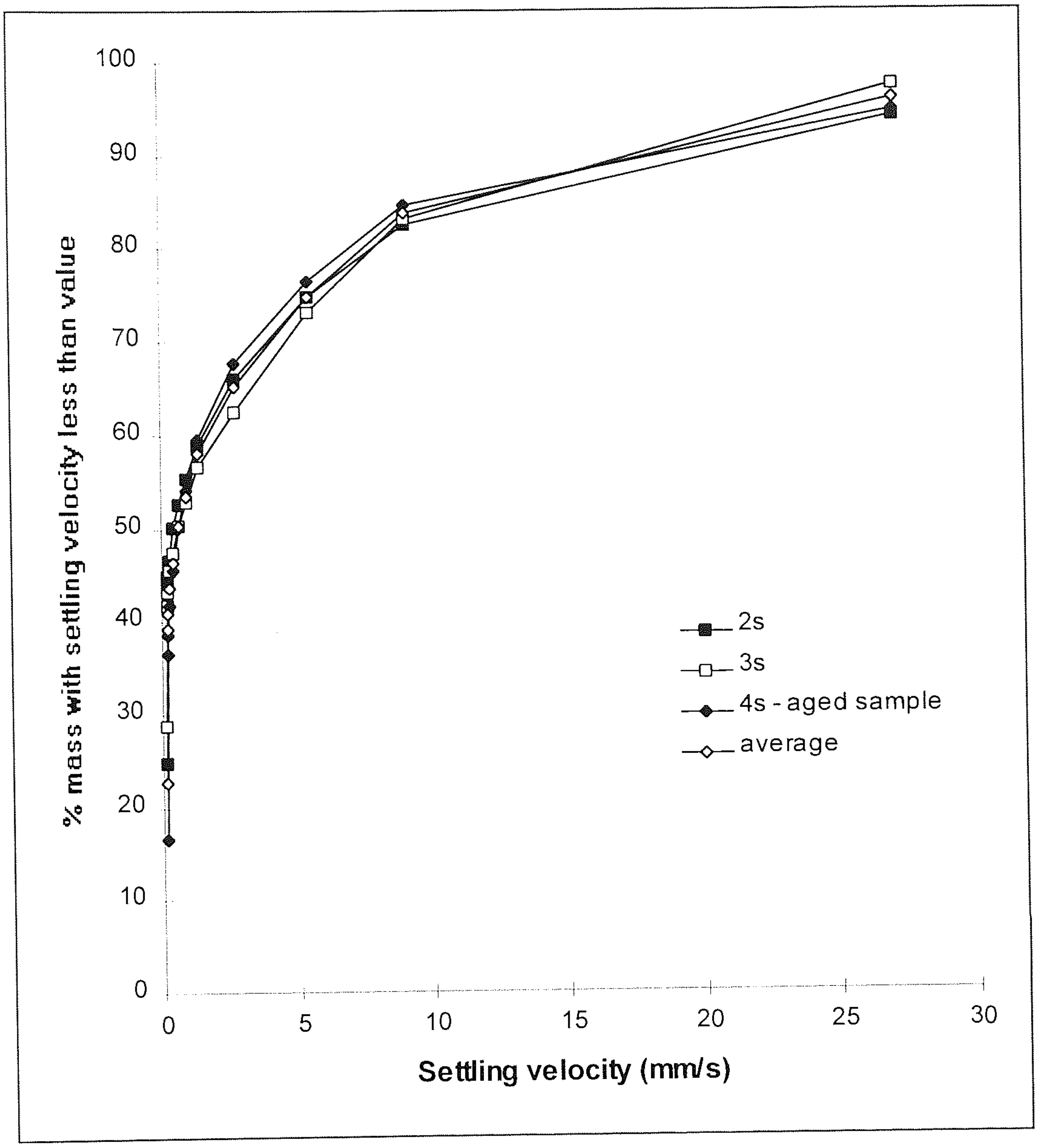

Figure 4.3 Comparison of results from tests with the same sample variables, but of different ages on testing (Baker, 1994). For details of tests see table 4.1.

selected. All three samples had the same variables: time of sampling (7.50 am) and flow rates through the works. The settling velocity gradings for each are shown in table 4.1 and figure 4.3.

These results are very similar for all three separate samples. This suggests that delaying the testing from 24 to 48 hours has very little effect on the settling velocity grading for similar sewage samples. This is a good initial result and agrees with a limited study undertaken using the UFT device by Aiguier (Aiguier et al., 1995), but further study is need to investigate sample ageing, particularly for the interval up to 24 hours. From the work undertaken to date it can be concluded that a delay of up to 48 hours from sampling to testing for settling velocity distribution may not be significant if the testing procedure is strictly adhered to. It may also be concluded that if all samples are treated in a similar way before testing there should be no effect on their composition.

4.2.5 Sampling method

It was of great importance to obtain a sewage sample that was representative of the flow to the wastewater treatment works (see section 2.8.4). This was especially the case because the samples were single samples that were to be used for a comparative study. In this project there was insufficient time to repeat tests for samples from the same catchments. Samples could have been taken either as a composite sample made up of a series of small samples taken over time, or a spot sample - an instantaneous specimen. The use of a composite sampler was considered to have no advantage over a spot sampler for three reasons.

i) Flow records for each small sample would have to have been obtained and then analysed to produce a representative value. This would have involved extra equipment that was not available without extra cost. With a spot sample an instantaneous reading of the flow to the works could usually be obtained.

ii) The installation of a sampler and flow recorder on every site to obtain a history of flows prior to sampling would have taken time to set up which was not available with the large number of sites to be tested. This approach would only be possible with say 4 sites which were to be sampled frequently over a long period and could be visited regularly to obtain data and reset the flow recorder.

iii) Composite samples are taken using a small bore pipe placed in the flow. This was not an ideal method of sampling for use in settling velocity measurement tests, and is discussed further below.

Having decided to use spot samples for the test programme, the type of sampler had to be decided upon. The sampler had to be mobile, light enough to be managed by one person and suitable for use at a large variety of inlet works and flow rates. The two suitable alternatives were a battery powered sampler and a dip bucket.

A battery powered sampler works by pumping the sewage into a container via a small bore plastic pipe that is lowered into the flow. The advantage of this method was:

- the suction pipe could be lowered into the flow at marked depths so that samples could be taken from a range of depths within the channel.

The disadvantages of this method were as given below.

- Without a rod attached to the suction pipe, or a rigid pipe at the suction end, the pipe tended to float on the surface of the water, especially where the velocities were quite high. This made sampling awkward.

- No particles larger than the pipe bore are collected.

- No particles which have a settling velocity greater than the suction velocity are collected.

The dip bucket worked by being lowered manually into the flow to collect a sample. The advantages of this method are listed below.

- An instant sample could be collected that contained all the particles that flowed into the bucket, both heavy and light.

- It was very quick to carry out.

The disadvantage of this method was:

- where the channel was deep it was only possible to obtain a sample from the top of the flow using the 5 litre bucket that was employed for this test.

A qualitative comparison of the sampling methods was carried out. Of the two sewage samples collected, the one obtained using a battery powered sampler contained very few floating or coarse particles. The dip bucket sample contained a far greater range of particles sizes and weights. Consequently it was decided that a dip bucket should be used for all the sampling to be carried out in the test programme. It was recognised that only the suspended solids near to the surface were sampled, no bed solids were collected. As discussed in section 2.8.4, it is recommended that samples are taken between 0.4 and 0.6 of the total depth of flow to obtain the most homogeneous sample, and in many cases samples would have been taken within this range of depths. With the limited time and equipment available, the assumption had to be made that a representative sample was obtained

4.2.5.1 Riffle box

To ensure that the sewage used for each procedure was well mixed and in comparison tests was the same, a riffle box was devised and constructed using welded plastic sheets (see figure 4.4). The riffle box was based on those used to divide soil samples, but was adapted so that the slots were closer together and the receiving boxes were made larger to hold large liquid samples. This method of splitting samples proved to be quite accurate, as was shown by the improved concentration comparisons between the test sample and the filtered crude sample.

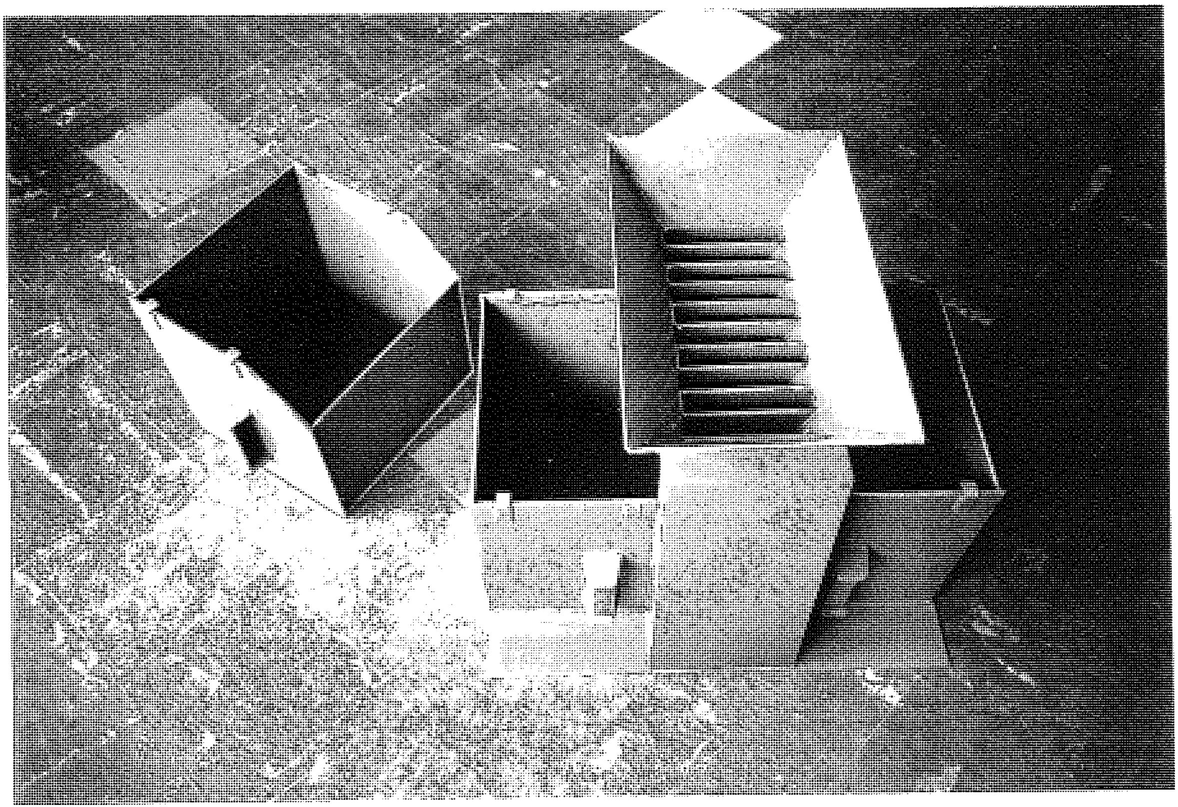

Figure 4.4 The riffle box.

4.2.6 Repeatability of results

Having shown in section 4.2.4.2 that the effect of delaying the testing of a single sample from 24 and 48 hours are minimal for this test method, it is necessary to show that the test results are repeatable for the same site using different test samples.

Due to time restrainsts it was not possible to carry out a complete analysis of repeatability, but by considering samples taken from the same site on different days it is possible to see that there are similarities between the settling velocity gradings, proving an acceptable degree of repeatability. Figure 4.3 shows very clearly that for samples 2s and 3s, obtained on different days from site reference 1, the settling velocity gradings are almost coincident. Figure 4.5 shows the settling velocity grading curves for the three samples taken from site reference 4. It clearly shows that the three samples are not only similar in shape, but in their position on the y-axis.

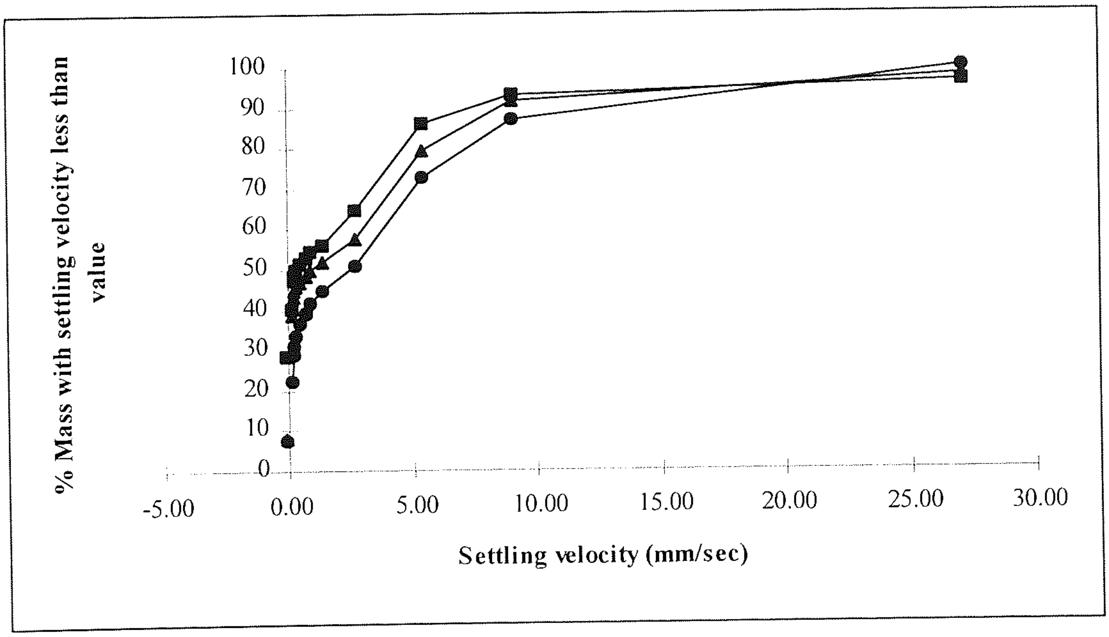

Figure 4.5 Comparison of results for three test samples from site reference 4.

These two results indicate that for the same site, samples taken on different days will exhibit the same characteristics in terms of shape and position on a settling velocity grading curve, that is, the results are repeatable for the same site. It is likely that the closer the conditions in the sewage at the time of sampling, the closer the similarity in the resultant settling velocity grading curves.

4.3 LABORATORY ANALYSIS OF TEST SUB-SAMPLES

The laboratory analysis of the sub-samples collected during the test procedure was carried out according to the HMSO Blue Book on Suspended, Settleable, and Total Dissolved Solids in Waters and Effluents (HMSO, 1980). The sub-samples were filtered in Whatman filter funnels onto grade C glass fibre filter papers. Before use the filter papers were washed in distilled water, dried in the oven at 105°C, allowed to cool in a desiccator and were weighed on a balance accurate to ± 0.0001 g. After filtering the papers were dried, cooled and re-weighed to determine the mass of the suspended solids on each.

In order to determine the split between organic and inorganic material, the filter papers were subsequently dried in a furnace to 500° ± 50°C. The papers were allowed to cool and were re-weighed. The organic element was burnt off leaving only the inorganic particles to be weighed.

The higher temperature required for burning off the organic matter also led to more of the moisture held within the filter papers being released. To calculate the amount of additional water released 51 No. cleaned, dried and weighed filter papers were heated in the furnace to 500° ± 50°C. On cooling, the papers were re-weighed and an average loss of moisture of 3 mg per filter paper was obtained. This loss was added back to the samples to obtain a true value of the inorganic/organic ratio at the standard drying temperature of 105°C.

4.4 PRESENTATION OF DATA

Once the settling velocity grading data had been collected a suitable method of presentation was required for its analysis. Table 4.2 gives a summary of the data acquired for site reference 26. There are three main methods possible to graphically present this data:

- cumulative sewage grading curve
- histogram or bar chart
- scatter/linear plot

A cumulative settling velocity grading curve is the traditional method of presenting the data and it produces a plot of the percentage of particle mass with a settling velocity less than a particular settling velocity, as shown in figure 4.6. Table 4.2 columns (1) and (4) contain the data for the plot.

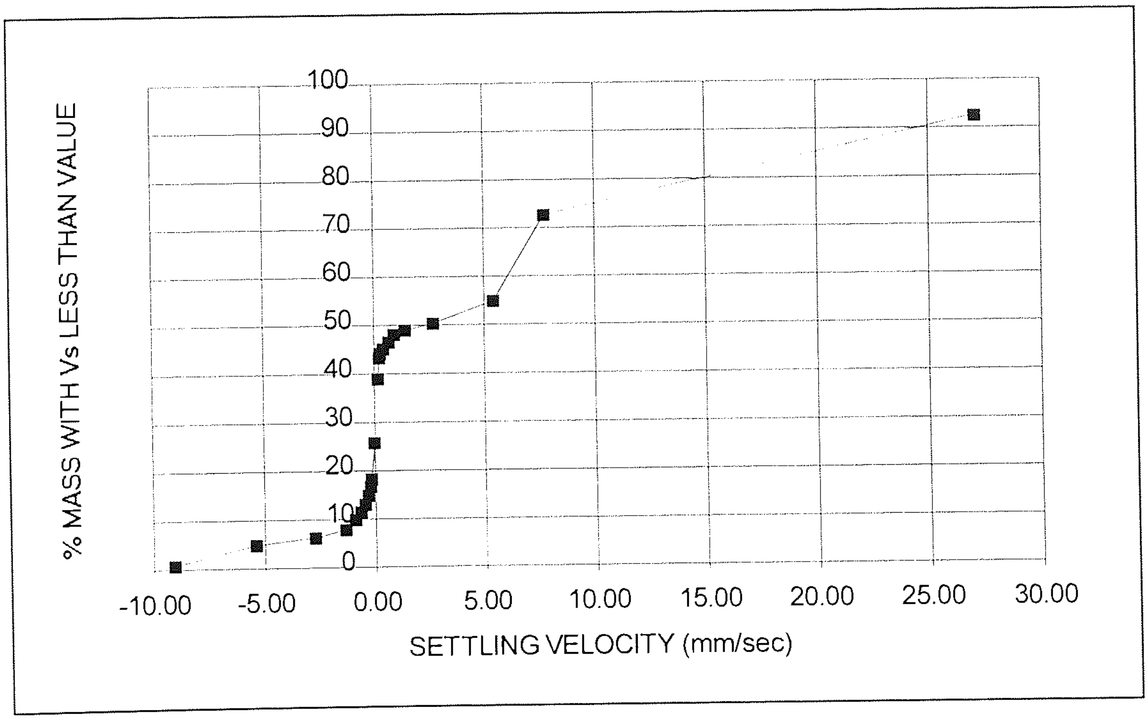

Figure 4.6 Settling velocity grading curve for site reference 26.

(1) Settling velocity (mm/sec)	(2) Mass of suspended solids captured (g)	(3) Mass expressed as % of total sample mass	(4) % of total mass with settling velocity less than value
-27.08	0.011	0.76	0.76
-9.03	0.059	4.07	4.83
-5.42	0.020	1.38	6.21
-2.71	0.024	1.66	7.87
-1.35	0.028	1.93	9.80
-0.90	0.024	1.66	11.46
-0.66	0.022	1.52	12.98
-0.45	0.026	1.79	14.77
-0.30	0.026	1.79	16.56
-0.23	0.024	1.66	18.22
floaters at test end	0.111	7.66	
residue at test end	0.189	13.03	
sinkers at test end	0.064	4.41	
0.18	0.011	076	43.35
0.23	0.014	097	44.11
0.30	0.020	1.38	45.08
0.45	0.022	1.52	46.46
0.68	0.013	0.90	47.98
0.90	0.022	1.52	48.88
1.43	0.066	4.55	50.40
2.71	0.257	17.72	54.95
5.42	0.288	19.86	72.67
7.74	0.099	6.83	92.53
27.08	0.010	0.69	99.36

Table 4.2 Summary of settling velocity grading test data for site reference 26.

The sign convention for use in settling velocity measurement is that a positive settling velocity is given to a sinking particle and a negative settling velocity to a floating particle.

The choice of using either a linear or a logarithmic scale for settling velocity is not set by convention and can be chosen either to illustrate a particular point or for personal preference. In this case a linear scale has been chosen because, in the author's opinion it clearly shows the S-shaped curve of a settling velocity distribution. Other workers argue that the settling velocity grading is analogous to a particle size distribution and should therefore be given a logarithmic scale. Whatever the choice, the mode chosen would not alter the results of the analysis in this study.

The choice of units for describing the settling velocity varies widely from m/sec, cm/sec, mm/sec to m/hour, and there is no strict convention. The author has chosen to use SI units in the form of mm/sec because they fall in a convenient range about unity.

To compare the results from different tests it was necessary to calculate masses as a percentage of the total sample mass (see section 4.4.1 and chapter 6), as shown in table 4.2 column (3). These results could then be presented as a bar chart, histogram, scatter plot or linear plot as shown in figures 4.7a, 4.7b and 4.8 depending on what type of analysis was required. These different methods of presentation were used in the analysis of the data described in chapter 6.

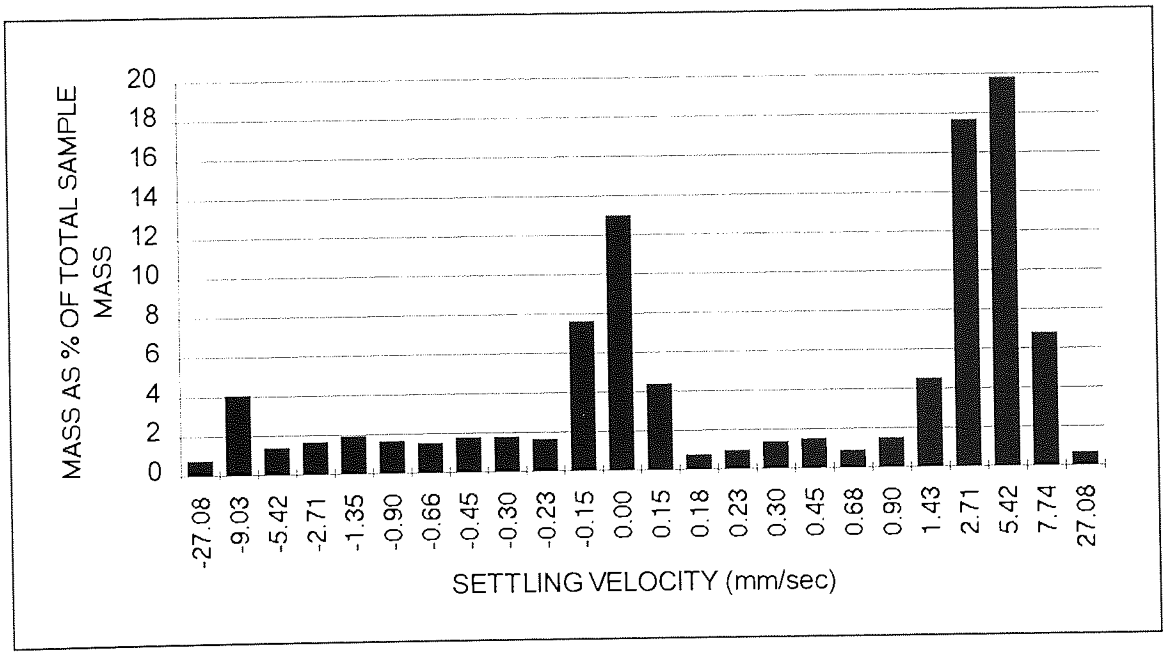

Figure 4.7a Bar chart of percentage of total sample mass against settling velocity for site reference 26.

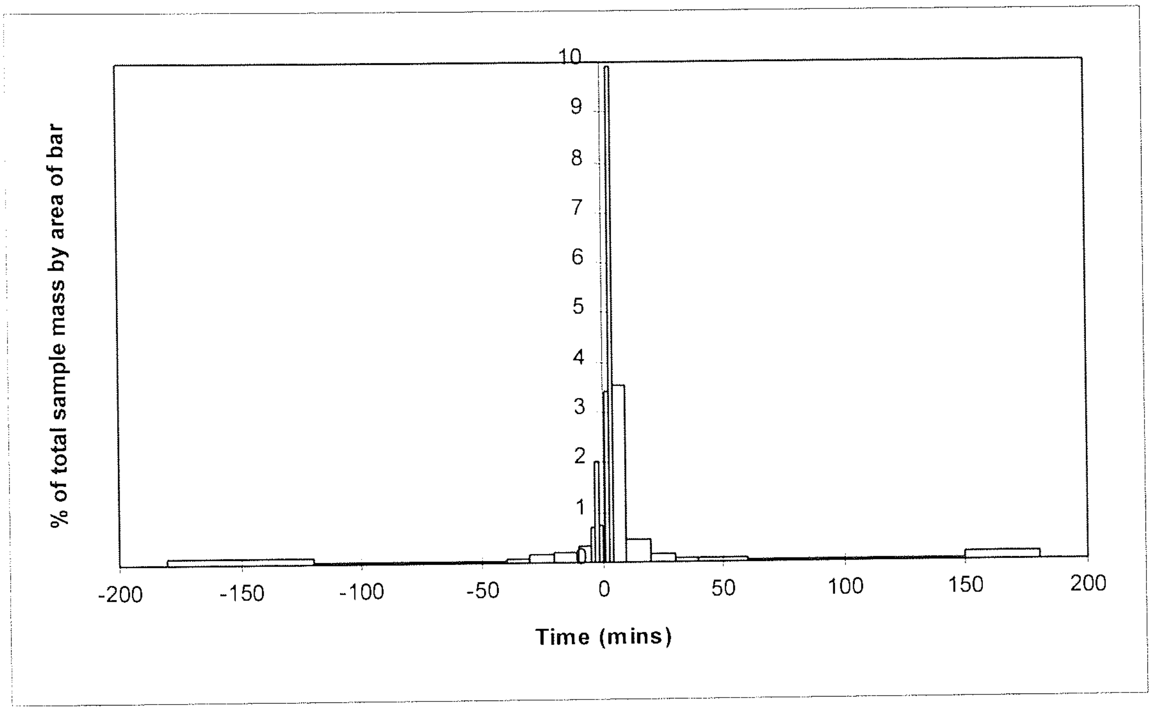

Figure 4.7b Histogram of percentage of total sample mass against settling velocity for site reference 26.

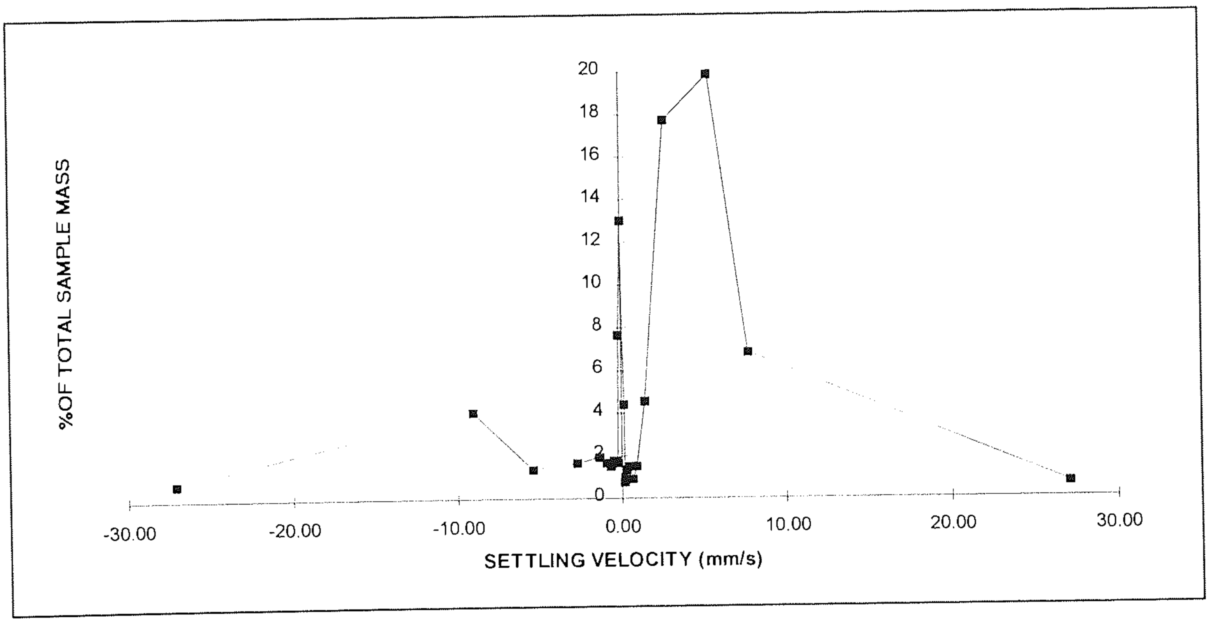

Figure 4.8 Plot of percentage of total sample mass against settling velocity for site reference 26.

4.4.1 Measurement of the floating fraction

During the tests with the synthetic sewage media, particularly the irregularly shaped nylon extrusions, a phenomenon was repeatedly observed. When the particles were separated by settlement before the test started, nylon extrusions with a positive settling velocity were present in the floating fraction at the top of the column. When the test was started on rotating the column, these "floating" nylon extrusions stayed in the bottom cell. Likewise, if there was turbulence in the top cell before the column was rotated to start the test, some of the nylon extrusions at the top of the column would settle to the bottom cell. It is probable that the sinking nylon extrusions either became attached to air bubbles released from the water or formed flocs with other extrusions, floating or sinking, by means of the air bubbles as discussed in section 3.2.3.3. The air bubbles would effectively reduce the density of the individual particles or flocs, which were already at near neutral buoyancy and which would then rise to the top cell. Once in the top cell they would be trapped - either the air bubbles would hold them in place or other floating particles would form a barrier to their sinking to the bottom cell. The movement created by turbulence often either detached the air bubbles or released trapped nylon extrusions and allowed them to settle freely.

In the tests with the nylon extrusions and the other synthetic sewage media, roughly equal numbers of floating and sinking particles were introduced into the column, usually with slightly more sinkers. The smaller the diameter of the column and the larger the particles the more this "trapping" behaviour was observed.

It was considered unlikely that the above phenomenon would occur with sewage where there was less air released from the sewage liquor, a much smaller proportion of floating particles and a far smaller particle volume to column diameter ratio. In subsequent tests with sewage this phenomenon was indeed not observed. Having said this, in many of the tests using sewage the majority of particles that collected in the top cell after the initial settlement period were not floaters. When the contents of the cell that should have contained only floaters plus a proportion of the residue were introduced into the column in order to measure their settling velocity distribution, the majority of the particles acted as sinkers. This can be clearly seen in figure 4.9 which is a bar chart of the masses of solids in DWF sewage expressed as a percentage of the total sample weight.

In the initial settlement phase of the test procedure the complete sewage sample is introduced into the settlement column and the floating and sinking fractions are allowed to separate into the two opposite end cells (see figure 3.1, section 3.2.5 and appendix A.2). The sinking and floating fractions are then withdrawn from the column by closing the two central valves (2 and 3). These separated fractions represent the "sinkers at the start" and the "floaters at the start" of the test, S_S and F_S respectively. For the main phase of the test, these sinkers start and floaters start fractions are introduced into cell A and the particles are allowed to travel into cell B, where they are removed as sub-samples after each timed period. The sum of the sub-samples collected form the "sinkers" (S) and "floaters" (F). The contents of cell A at the end of the test become the "sinkers end" (Se) and the "floaters end" (Fe). The "residue" (R) is the residual fraction remaining in the central section of the column at the end of the test.

Normally the particles in the floaters cell at the end of the test (floaters end) are added to the residue along with the sinkers cell at the end of the test (sinkers end) for the purposes of plotting histograms and settling velocity grading curves (see section 4.4.2). However, in figure 4.9 the "sinkers end", "residue" and "floaters end" have been plotted separately to show the discrepancy in the masses. The high percentage of particles (14.99%) in the floaters cell at the end of the test ("floaters end") represent particles with a positive settling velocity that remained in the bottom cell when the measurement of the floating fraction was completed. For more representative comparative purposes the masses of the solids have been converted into concentrations (g/l), as illustrated in figure 4.10. Figure 4.10 shows quite clearly the extremely high concentration of solids in the "floaters end" compared with the residue at the end of the test. The "sinkers end" has a higher concentration of solids compared with the residue, as it did for all the samples tested for floaters and sinkers. This is because the concentration of solids in the residue is reduced further during the second half of the test when the settling velocities of the floaters are obtained.

An alternative way of presenting this data graphically is to draw a bar chart (figure 4.11) where the area of the graph represents the percentage of the total sample mass. Figure 4.11 indicates the rate of settlement of the particles with time. The apparent peaks in settlement rate between 150 and 180 minutes (for the sinkers) and -120 and -180 minutes (for the floaters) represents the mass of suspended solids in the sinkers end and floaters end respectively. It should be noted that figure 4.11 does not include the residue at the end of the test.

The collection of particles with positive settling velocity in the floaters end cell is difficult to explain. It does not mimic natural settlement where flocs tend to form and increase the density of the agglomeration and then settle more quickly. One possible explanation could be that air bubbles, either introduced into the sample when it was poured into the column or released from the water, became attached to sinking particles and caused them to rise. However, even this is not a good explanation because there was no visible physical evidence that this occurred. It has been suggested that because the floaters were entered into the same end cell as the sinkers for the test, some of the solids could have been left behind and so increased the value of the mass of "floaters end". This may sound plausible, but very few deposits are left in the end cell after the "sinkers end" are withdrawn, and if any were left they could not possibly be of such a mass as to cause the measured discrepancy.

Figure 4.9 also demonstrates another feature of the floating fraction. Only a small fraction (3.55%) of the total sample mass make up the floaters, as determined from the experiments. In many cases, the mass of particles measured as floaters is composed of particles entering the end cell due to turbulence as discussed in section 3.3. In most cases this does not alter the results significantly, it can form the majority measured mass of floaters. The small proportion of floating particles compared with sinking particles was an important finding that was common to all the samples taken.

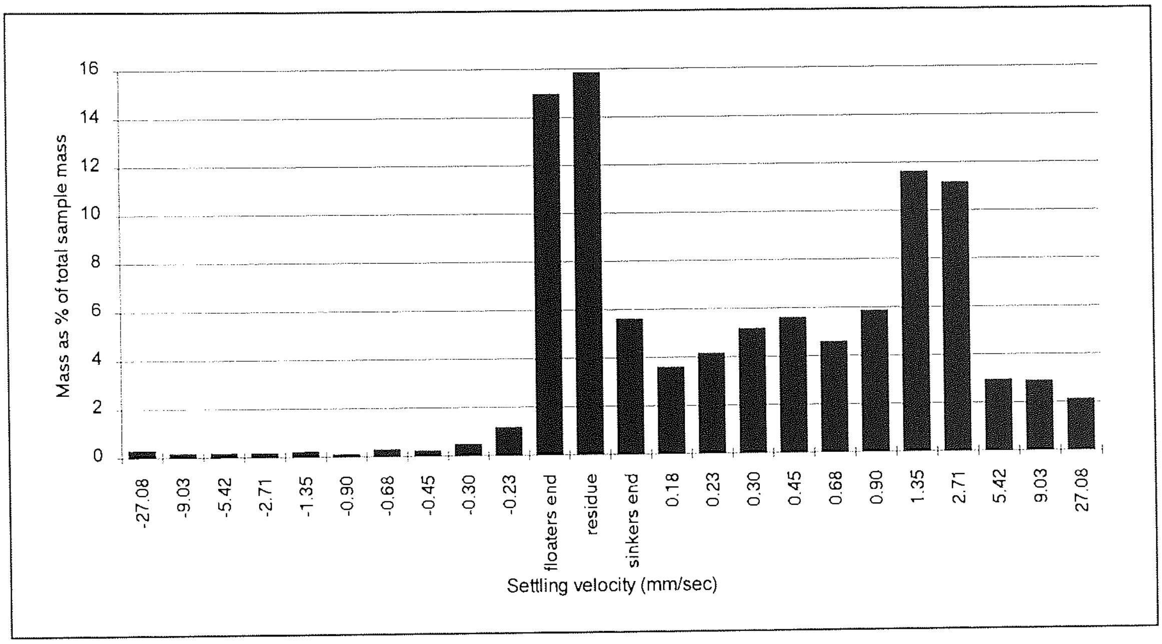

Figure 4.9 Bar chart of sub-sample mass expressed as a percentage of the total sample mass for site reference 21, which is an example of DWF sewage.

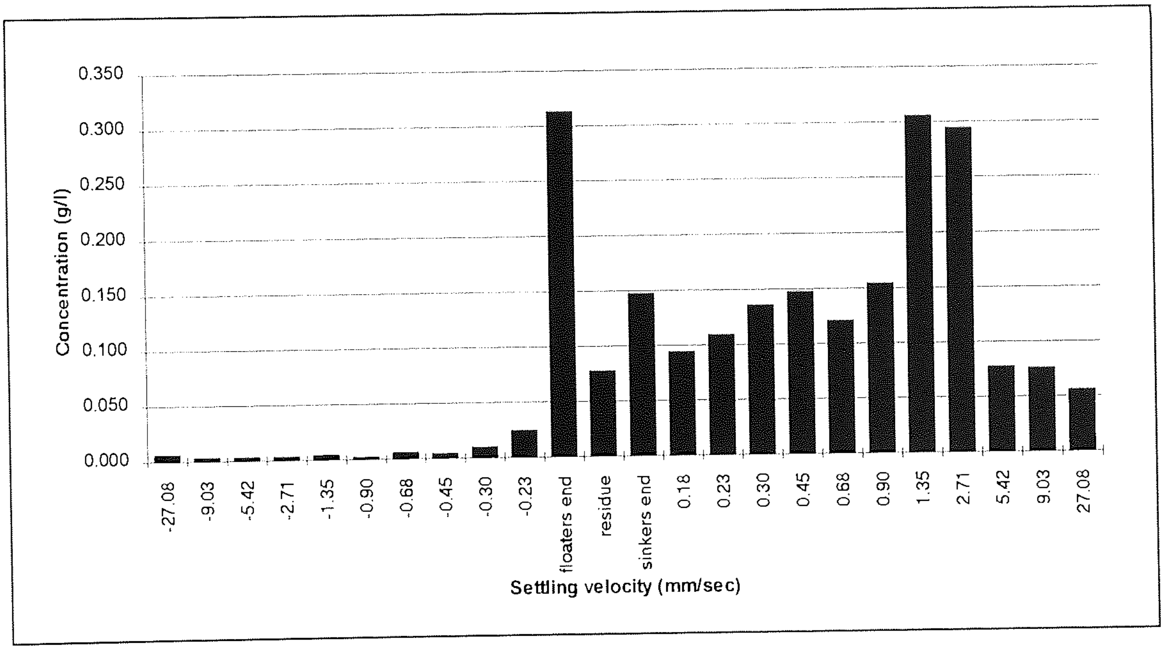

Figure 4.10 Bar chart of sub-sample mass expressed in terms of concentration for site reference 21.

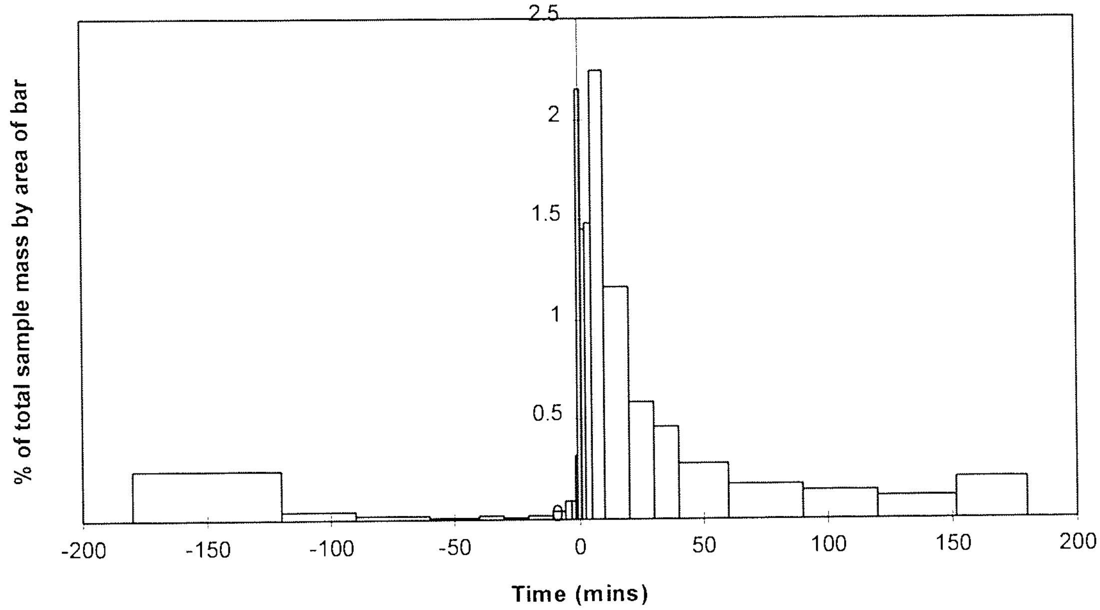

Figure 4.11 Bar chart of sub-sample mass with the area of the bars representing the proportion of mass in each sub-sample for site reference 21.

The unrepresentative measurement of the floating fraction was not fully appreciated until the sampling and testing programme was underway. In order not to interrupt the experimental data collection a comparative study was undertaken in a second settlement column of the same dimensions as the clear one, but constructed in grey plastic. The aim of the study was to determine whether there was a relationship between the concentrations of the separated floating, sinking and residual fractions after the initial three hour settlement period and their concentrations at the end of the full test.

For each of the eight comparison experiments an extra 5 litres of sewage was sampled at the wastewater treatment works and was riffled down with the usual 10 litre sample. In this way a similar homogeneous sample was placed into the two columns. In the clear column the normal settlement velocity measurement test was carried out as part of the data collection programme. In the second, grey column, the comparison experiment was terminated after the three hour settlement period. The samples of 'floaters', 'sinkers' and 'residue' were drained from the column and filtered, dried and weighed in the normal way (see section 4.3). The full results of the comparison study can be found in Appendix B.

TEST	TEST FRACTION	MEAN % OF TOTAL SAMPLE MASS
FULL TEST	Floaters at end (Fe)	12.9
	Floaters (F)	10.3
	Residue at end (R)	12.3
	Sinkers at end (S_e)	6.4
	Sinkers (S)	58.1
COMPARISON	Floaters at start (F_s)	11.7
	Residue at start (R_s)	37.7
	Sinkers at start (S_s)	50.6

Table 4.3 Mean values for all the test fractions from the comparison tests.

On inspection there was no clear relationship in the results. The only fact that was consistent through all the results was that the percentage by mass of the floaters in the full test was always greater than that in the comparison experiment. By inspecting the mean values in each class, a picture began to emerge that confirmed the observations made during the tests. Table 4.3 shows the mean values of each of the fractions in the comparison tests. By considering what was thought to happen during the test, i.e. the effect of turbulence carrying particles in the residue into the end cells, a process of adjustment was applied as follows.

1) Assume that all, or most of the floaters collected in the sub-sample cell during the period of floater measurement in the test are present due to turbulence and are therefore, in reality, part of the residue.

2) By the same assumption, an equal percentage of the sinkers in the test have been trapped in the sub-sample cell during the period of sinker measurement.

3) True residue at the start of the test = R + F + F   eqn 4.2

$$= 12.3 + 10.3 + 10.3$$

$$= \mathbf{32.9\%}$$

where:

R = residue in the central section of the column at the end of the test

F = the floating fraction, not including F_e

F_e = floaters remaining in the floaters end cell A at the end of the test

4) True floaters at the start of the test = F_e eqn 4.3

$$= \mathbf{12.9\%}$$

5) True sinkers at the start of the test = $S + S_e - F$ eqn 4.4

$$= 58.1 + 6.4 - 10.3$$

$$= \mathbf{54.2\%}$$

where:

S = the sinking fraction, not including Se

S_e = sinkers in the sinkers end cell A at the end of the test

The averaged results of all the tests used in the comparison study together with the above adjustments to the averaged test results and the averaged results of the comparison experiments are tabulated in table 4.4. It can be seen that, by allowing for the transfer of particles from the residue into the end cells during the test, a much closer relationship to the masses at the start of the test can be obtained.

Assuming that conditions at the start of both the full test and the comparison experiment were identical, the adjusted values of the residual and the sinking fractions could be brought closer to the start values by considering that the concentration of the residue during the sinking part of the test would be stronger than that remaining after the full test due the lesser amount of turbulence that would have been experienced. In addition, the longer test period for the sinking fraction, 2.5 hours as opposed to 2 hours for the floaters, would lead to a greater amount of turbulence during measurement of the velocities of the sinking fraction. However, with the method of measurement employed it would be difficult to quantify the necessary extra adjustment accurately without further investigation.

FRACTION	PERCENTAGE OF TOTAL SAMPLE MASS		
	FULL TEST	COMPARISON	ADJUSTED FULL TEST
FLOATERS	23.2	11.7	12.9
RESIDUE	12.3	37.7	32.9
SINKERS	64.5	50.6	54.2

Table 4.4 Mean values of the comparison test results and the adjusted means for the full test results.

To be able to quantify the effects of this adjustment for transfer of the residue into the end cells during the test, the data for each of the experiments carried out in the comparison study have been adjusted using equations 4.2 to 4.4. The results of this adjustment are tabulated in table 4.5. As can be seen, the adjusted results in each case bring the full test results closer to the values at the end of the initial separation phase.

In all but test reference 18, the error in the floating fraction in the full test when compared with the comparison experiment has a large positive value and in all cases the error in the percentage of total suspended solids mass in the residue is between 62 and 79% less than those measured in the comparison experiment. The sinking fraction is on average least effected by the full test, with all measurements of the total sinkers mass being greater than in the comparison experiment. It is therefore concluded that accurate measurement of both the sinking and the floating fraction has not taken place and that there has been some transfer of suspended solids from the residue into the end cells during the measurement of the sinking and floating fractions. The section of the grading curve for the floating fraction is more significantly distorted than for the sinking fraction because of the relatively small mass of particles collected during the measurement process.

As a result of this it is recommended that in all future studies the measurement of the settling velocity distribution of the floating fraction is not carried out.

The only justification for undertaking the last stage of the test would be if an accurate measurement of the likely transfer due to turbulence of the residue into the sinking sub-samples is required. Even if this were the case it would be difficult to calculate the particle transfer into each sub-sample without a parallel experiment being conducted (see section 3.3, table 3.1 and figure 3.4), because the time interval between each sub-sample varies throughout the test. Without a parallel experiment to calculate the particle transfer, the best method would be to assume that most of the particle transfer takes place when the column has just been turned because this is when there would be maximum turbulence within the column. From this, divide the total amount of particle transfer measured by the number of sub-samples, subtract the amount from each value measured at the end of a timed interval and add it to the residue.

TEST REF.	PERCENTAGE OF TOTAL SAMPLE MASS				% ERROR IN FULL TEST	% ERROR IN ADJUST. TEST
	TEST FRACTION	FULL TEST (FT)	COMPARISON TEST (CT)	ADJUSTED FULL TEST (AT)	$\frac{FT-CT}{CT} \times 100$	$\frac{AT-CT}{CT} \times 100$
26	Floaters	25.88	7.48	7.66	246	2
	Residue	13.01	34.25	49.47	-62	44
	Sinkers	61.11	58.27	42.89	5	-26
21	Floaters	18.54	16.98	14.99	9	-12
	Residue	15.88	43.79	22.98	-64	-48
	Sinkers	65.60	39.23	62.05	67	58
24	Floaters	31.14	13.63	16.51	128	21
	Residue	14.19	44.05	43.45	-68	-1
	Sinkers	54.68	42.32	40.05	29	-5
4i	Floaters	28.33	8.05	15.05	252	87
	Residue	12.05	32.70	38.71	-63	18
	Sinkers	59.54	59.25	46.21	0.5	-22
7	Floaters	15.78	8.86	9.64	78	9
	Residue	4.09	19.81	16.37	-79	-17
	Sinkers	80.14	71.32	74.00	12	4
13	Floaters	17.58	5.92	9.46	197	60
	Residue	9.79	38.55	26.03	-75	-32
	Sinkers	72.65	55.53	64.53	31	16
18	Floaters	11.88	14.71	11.25	-19	-24
	Residue	12.78	42.41	14.04	-70	-67
	Sinkers	75.35	42.88	74.72	76	74
17	Floaters	36.16	17.91	18.53	102	3
	Residue	16.95	45.85	52.21	-63	14
	Sinkers	46.91	36.23	29.28	29	-19

Table 4.5 Tabulation of the eight tests used in the comparison study showing the full test, comparison test and adjusted full test results.

4.4.2 Presentation of the results for analysis

Having been satisfied that there was a measurable quantity of solids entering the end cells due to turbulence, as discussed in section 4.4.1, a decision had to be made on how to present the data for analysis. Statistical analysis on the eight sites where the comparison study had been carried out (section 4.4.1) proved that there was no linear association between the floaters that were captured at the end of the settlement period and the fractions captured at the end of the test. No linear associations useful to the data presentation were present.

In the end a graphical comparison of different methods of presenting the data was carried out. Some of the tests did not include measurement of the floating fraction. The floating fraction was not measured when either storm sewage was sampled or the sewage appeared to be very dilute and it was judged that there would be no measurable quantity of floaters produced during the test. The four methods that could have been used to represent the results graphically as sewage grading curves are listed below.

4.4.2.1 Method 1

To leave the results as measured during the test.

Using this method it would not have been possible to relate the tests that had included the floating fraction with those that had not. In addition, where measured, the floating fraction results were not considered to truly represent the floating particles in the sample, as discussed in section 4.4.1.

4.4.2.2 Method 2

i) To leave the sinking fraction as measured during the test.
ii) To sum a lump value for the floaters.
iii) To sum a lump value for the residue that included both the sinkers and floaters that remained in the end cells at the end of the test.

This method allowed the misleading floating fraction to be presented as one value. However, it was not a suitable method for comparing tests that had not determined the floating fraction with those that had. The tail of the curve that crossed the y-axis could not be drawn where the floaters had not been determined. The statistical analysis had not proved a linear association between the floaters captured during the settlement period and the concentration of the residue at the end of the test, and so the mass remaining in the residue and the floaters at the end of the experiment could not be calculated where the floating fraction had not been determined.

4.4.2.3 Method 3

i) To leave the sinking fraction as measured during the experiment.
ii) To add the floaters readings to the residue at the end of the test, which included the floaters and the sinkers left in the end cells after measurement.

This method was acceptable and allowed all the results to be compared because they all have the same base point from which they could be drawn.

4.4.2.4 Method 4

i) To assume the particles in the sinkers end cell due to turbulence were equivalent to those that entered the floaters end cell during the experiment and that the quantity of particles transferred was equal for all sub-samples.

ii) The floaters (F) measured during the test were divided by the number of sinker sub-samples (n)

$$\text{mass entering each sub sample cell} = \frac{F}{n} \qquad \text{eqn 4.5}$$

iii) (F/n) was subtracted from each sinker sub-sample mass and F was added into the residue to compensate. The floaters measured in the test and the floaters in the end cell at the end of the test were also added to the residue.

The assumption made in step (i) was that there were no floaters measured during the test, any particles captured in the floaters sub-sample cell were present due to turbulence within the column. Following from this it was postulated that a maximum mass of particles entered the end cell at the start of the test due to a higher concentration of particles in the residue than at the end of the test. This was taken to balance with the increased chance of particles entering the end cell as the time intervals increased between the sub-samples. This led to the overall assumption that the mass of particles entering the end cell for each sub-sample was equal.

This method took account of the particles in the end cells of the floaters/sinkers which are present due to turbulence in the column and could only be used where the full test had been carried out. This should have given a more accurate picture for experiments where the floaters had been analysed. Sometimes this adjustment produced a curve with fewer data points than before modification, as illustrated by the example in table 4.6 and figure 4.12. For this particular data set the adjustments at the end were greater than the masses obtained by measurement, which led to a flattening of the curve.

Settling velocity (mm/sec)	Actual mass (g)	Adjusted mass (g)	Adjusted % of total SS	% of total sample with V_S less than value
Floaters (F)	0.264	0.000	0.00	
Residue	0.364	0.836	57.65	
0.18	0.011	0.000	0.00	57.65
0.23	0.014	0.000	0.00	57.65
0.30	0.020	0.000	0.00	57.65
0.45	0.022	0.000	0.00	57.65
0.68	0.013	0.000	0.00	57.65
0.90	0.022	0.000	0.00	57.65
1.35	0.066	0.042	2.90	57.65
2.71	0.257	0.233	16.07	60.55
5.42	0.288	0.264	18.21	76.62
9.03	0.099	0.075	5.17	94.83
27.08	0.01	0.000	0.00	100.00
Total	1.450	1.450		100.00

Table 4.6 Tabulated calculations for graphical presentation of the settling velocity data for site reference 26, using presentation method 4 (n = 11 & $F/_n$ = 0.024g).

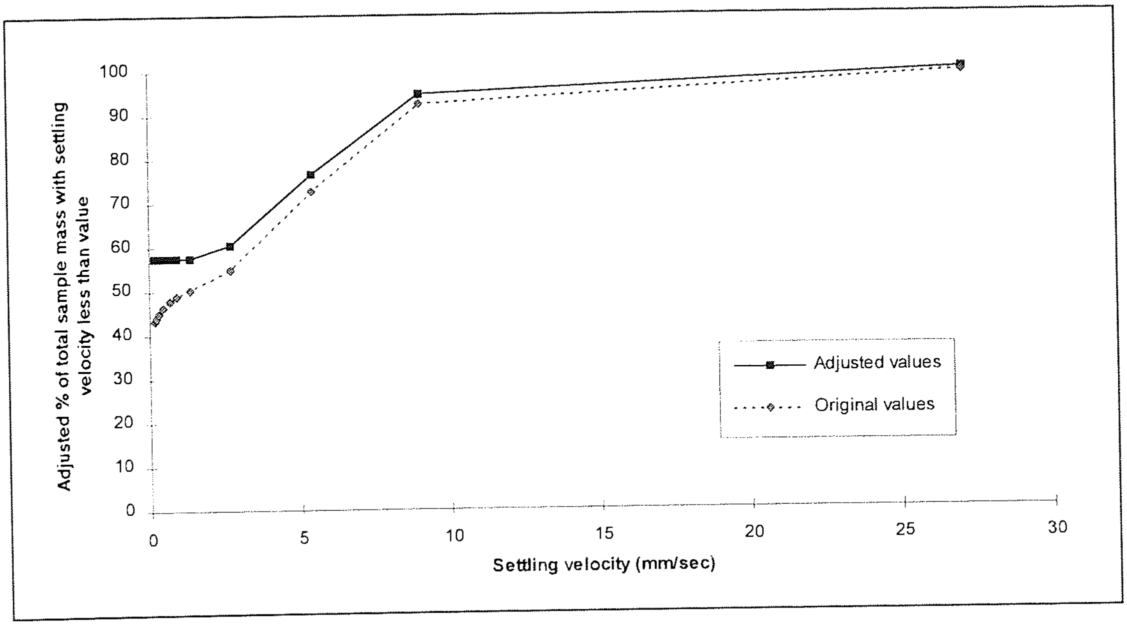

Figure 4.12 Adjusted settling velocity grading curve for site reference 26 using presentation method 4.

4.4.2.5 Selected method for presenting the results

Having considered all the methods of presenting and comparing the data it was decided that method 3 should be adopted for analysing the data. Method 3 was chosen because the results from all the tests carried out could be used and the data was not distorted by any adjustment. It was recognised that analysis of the floating fraction could not be included in any graphical interpretation or analysis of the results if method 3 was used, but it was decided that this outweighed the possibility of using misleading results for the floating fraction. The analysis carried out is discussed in detail in chapter 6.

4.5 SUMMARY

In this chapter the methods adopted for use in sampling and testing sewage from wastewater treatment works in order to produce settling velocity grading curves have been discussed. Where possible, within the limited time and budget, many of the variable factors that were present in the sampling process were designed out of the programme. It was considered that within this project the most representative samples could be obtained using a bucket rather than a sampler. Samples were taken between 10 am and 11 am to account for fluctuations in the diurnal flow pattern. Because of the distances involved in accessing some of the wastewater treatment works across England and Wales it was not possible to sample and test sewage on the same day and so all samples were tested the day after sampling. Initial investigations into the effect of sample ageing showed no significant difference in the settling velocity gradings for samples up to 48 hours old, although further research is needed in this area. The set of results for settling velocity measurement tests on samples collected from the same sites appear to show that the grading curves are similar and that the results are repeatable. To ensure consistency between samples used in comparative tests a riffle box was designed to split the large samples down to the correct size for analysis.

Once the settling velocity distribution data had been obtained from the tests, the results had to be presented in a format suitable for analysis. Some of the samples were such that the floaters were not analysed, and so a great deal of consideration was given to the most appropriate method of presentation to enable all the results to be compatible. In all the samples tested the proportion of floating particles is small compared to sinking particles. It had been shown that the quantities of solids measured in the floating fraction contain solids that pass into the end cells due to turbulence within the column. Statistical analysis did not reveal any relationships between the quantities of solids in the floating fraction and the solids in any of the other fractions and thus it was not possible to compensate for this effect. It was therefore decided that the best way of presenting the data for analysis was to include all the floating fraction with the residue at the end of the test and not to carry out any adjustment for the turbulence that enters the end cell whilst the sinkers fraction was being tested. The analysis of the data and the conclusions drawn are discussed in detail in chapters 6, 7 and 8.

CHAPTER 5

CATCHMENT DATA: COLLECTION AND DETAILS

5.1 INTRODUCTION

The second objective of this research project was to produce a mathematical model of the settling velocity grading curve using catchment characteristics as the predictors (see section 1.2). To achieve this it was necessary to obtain reliable and up to date information from which the model could be calibrated.

The data required for this research project related to the characteristics of the influent to wastewater treatment works and those of the contributing catchments. Ideally, data from a large number of treatment works' catchments would have been obtained, from which the requisite number of sites for a representative sample would have been carefully selected. In the process, sites with peculiar or inconsistent characteristics would have been removed from the test programme. If a relationship between catchment characteristics and the settling velocity grading was proved, it might then be possible to return to study sites with more diverse characteristics to calculate their influence on the model. The methods employed for the data collection process and the problems incurred are discussed in this chapter.

5.2 DATA COLLECTION METHODS

5.2.1 Catchment characteristics

Before approaching the privatised water companies for their assistance, the catchment characteristics to be used in the study had to be decided upon. It was not known at this stage what factors, if any, may have had an influence on the settling velocity grading of the sewage, and therefore as many characteristics as believed to be obtainable were chosen. Table 5.1 shows the catchment characteristics that were judged to be desirable.

Data field	Detailed characteristics
Flow rates	Connected population Equivalent population Dry weather flow Diurnal variation Maximum flow Minimum flow
Catchment data	Gross area Longitudinal fall across the catchment Predominant geology Approximate age of development in the catchment Catchment shape
Land use	Impermeable area Area used for commerce Area used for industrial use and the main industries Residential area Area used for farmland Area used for parkland or recreation
Main sewer details	Length Fall/gradient Sewer shape Time of concentration Type of system, i.e. combined, separate or partially separate Pumped or gravity fed sewerage system Number of pumping stations in the system
Miscellaneous	Are there large seasonal population fluctuations? Has the population or industry changed significantly since the wastewater treatment works was commissioned?

Table 5.1 Catchment characteristics requested from the privatised water companies.

At the time the catchment data collection for this project was to start, two sister projects were commencing within the research group at Aston University. Both of these projects also required information from the ten privatised water companies relating to wastewater treatment works and water quality (Withams, 1993). A Catchment Data Sheet was produced that incorporated information for all three projects, some of which was common. A copy of the form is provided in Appendix C.

5.2.2 Catchment data collection

When the information required had been decided upon and the Catchment Data Sheet drawn up, each of the ten privatised water companies in England and Wales was approached and asked if they would cooperate in the data collection exercise. Complete confidentiality as to the location of the wastewater treatment works was assured, as was the provision of a summary of the information for that particular water company, if it was desired. This promise of confidentiality has meant that only the researchers at Aston University have had any knowledge of wastewater treatment works locations. The sites were ranked in terms of the magnitude of DWF into the treatment works and each site was allocated a reference number on this basis (see section 5.3 for details). The response from the water companies varied from enthusiastic and helpful, to declining to help because they were either not interested in the research or concerned at the number of man hours that would be involved.

Once the cooperation of several of the water companies had been obtained, the next task was to collect the information on the Catchment Data Sheets. The details required were not always available, and where they were the data were often held by different offices in different locations or by different organisations. For example, the information on sewers and drainage areas was often held in local council offices, where the sewer systems were managed under agency agreement with the water companies. This made collecting the data an extremely time consuming and laborious process, as a result of both having to find the relevant contact in each organisation, and then having to travel and collect the relevant information. The majority of the data collection was carried out by a research assistant from the research group as part of her project (Withams, 1993).

Problems were experienced in collecting current information. Many of the wastewater treatment works had been redesigned and modified since their initial design. Thus, where it was available, the information that had been collected for the design of the treatment operations and processes was often several years out of date. In addition, many catchments had changed through population increases and changes in land use, such as industry either growing or shrinking, depending on economic conditions and development of manufacturing systems etc. In general it was not possible to ascertain the age or accuracy of the information gathered.

The best source of catchment and treatment works information was in the form of drainage area studies (DAS). The DAS have been produced since privatisation of the water authorities and so were at most two years old. DAS are time consuming to undertake and wearing on manpower and as a consequence only the larger or more sensitive sites had completed DAS at the time the information was required for this project.

Wastewater treatment works are generally designed on the basis of equivalent population and, where relevant, take into account the type of industrial effluent being discharged. Equivalent population not only includes the residential population connected to a particular sewer network, but also equates industrial discharge to a population figure. The split between these two values was often not available and therefore only the total equivalent population has been used.

An indication of the residential/industrial split had to be obtained from area factors. The area factors were percentages of the total catchment area that were measured as being used for a particular purpose, such as residential property, industry, parkland, etc. These area factors, along with many of the sewer lengths acquired, were again of unknown accuracy, often being obtained by other researchers using unknown methods or from plans of differing detail. Although not always accurate, the area factors do give an indication of the land use within a catchment.

It had been intended that the sewer length parameter should be the total length of the main trunk sewer to the wastewater treatment works, but this was not obtained. The sewer length actually recorded was the sum of the lengths of the main sewers in the whole catchment. These lengths were either obtained from the values given in drainage area studies or by physical measurement of drainage layouts. The classification of the 'main sewer' in a catchment when measured by the researcher was subject both to personal judgement and the detail provided on the drainage plans. It is believed that these lengths are subject to significant inaccuracy. The sewer lengths for large catchments were usually estimated by the researcher by measuring pipe lengths for a fraction of the area and then extrapolating to obtain a length for the whole area. As a consequence it was decided that it would be misleading to use them other than as a simple indication of the sewer length within a catchment.

The flow and catchment characteristics that were finally obtained for the sites studied are shown in table 5.2.

Data field	Detailed characteristics
Flow rates	Equivalent population Dry weather flow
Catchment data	Gross area
Land use	Impermeable area Industrial area Area used for commerce Residential area Area used for farmland Area used for parkland or recreation
Main sewer details	Length of the main trunk sewer System type, i.e. combined, separate or partially separate Pumped or gravity fed sewerage system Number of pumping station in the system

Table 5.2 Flow and catchment characteristics obtained for use in this project.

5.3 SITES SELECTED FOR STUDY

Due to the many problems incurred and the time consuming nature of the data collection process, only 77 wastewater treatment works and their contributing catchments were surveyed. Of those 77, only 35 had complete (or almost complete) sets of catchment and flow information. This meant that sites could not be selected to obtain a representative spread of characteristics, as was originally intended. In addition, the limited number of available sites meant that they all had to be included in the sampling programme, and those sites exhibiting atypical characteristics, such as large seasonal variations due to a transient tourist or student population, could not be eliminated.

The sampling programme was constructed around these 35 sites, plus site number 23 which was tested in error. A maximum of two tests per week was possible, dependent on dry weather before and at the time of testing. A summary of the catchments studied, including all of their flow and catchment details, is given in table 5.3. The table shows only 29 sites out of the possible 35, for two main reasons.

i) It was not possible to gain access to some of the wastewater treatment works.

ii) Although samples were taken, unfortunately a mistake was made early on in the test process and the test had to be abandoned. Where possible these sites were sampled again.

The blanks in table 5.3 represent data that was either not available or not confirmed and so cannot be assumed to have a zero value.

At the start of the test programme it was envisaged that only dry weather flows would be sampled. This worked well until November 1993 when a long period of wet weather began. This disrupted the test programme, and it was decided to revise the programme and to collect sewage samples regardless of the weather conditions. This gave an adequate number of test results for a meaningful statistical analysis to be carried out. Within the revised time schedule, flexibility was retained as far as possible in order to utilise regional variations in weather conditions to minimise the number of stormwater samples obtained.

Since not all the sites were sampled with dry weather conditions, a reading of the incoming flow to the treatment works was obtained. For the purpose of analysis, these flows were converted into multiples of DWF. At works where storm flow sewage was sampled, whenever possible, the site was re-sampled under dryer conditions.

At the end of the testing period 33 settling velocity gradings had been produced on the 29 sites, of these 21 were for flows greater than DWF. The results of the settling velocity measurement tests are shown in Appendix D.

Record No.	Equivalent population (No.)	DWF (l/s)	Sewer length (m)	System type	Pumped or Gravity fed	No. pumping stations	Total area (ha)	Impermeable area (ha)	Area of industry (ha)	Area of commerce (ha)	Area of farmland (ha)	Residential area (ha)	Area of parkland (ha)
1	1315325	5208	1198066	P.SEP	PUMPED	47	34754	148	4000	3600	0	26574	706
2	380000	1296	400000	P.SEP	PUMPED	12	9700	15	970	485	300	7445	485
3	118300	485	89536	SEPARATE	PUMPED	13	3270	0	98	392	0	2714	65
4	150000	428	1000000	P.SEP	PUMPED	10	5000	0	500	750	1500	2250	0
5	52165	355	37830	P.SEP	PUMPED	5	1295	0	91	39	0	1165	0
6	90000	270	5300	COMBINED	GRAVITY	0	5500	0	310	50	3710	1300	130
7	123395	270	200000	COMBINED	PUMPED	8	2870	0	57	373	0	2296	144
8	96000	210	9584	P.SEP	PUMPED	8	2485	0	224	224	0	1864	149
9	14250	151	32980	COMBINED	GRAVITY		450	0	36	9	67	338	0
10	12000	99	2340	COMBINED	PUMPED	1	379	0	83	0	0	286	0
11	29000	80.3	157000	P.SEP	PUMPED	6	810	0	0	56.7	0	753	0
12	23000	80	60580	COMBINED	PUMPED	3	750	0	75	75	38	562	0
13	32500	74.1	86810	P.SEP	PUMPED	4	925	0	0	0	0	833	93
14	14200	66.1	1235		PUMPED	3	872	0	12	0	523	282	55
15	21300	53.4	24066	SEPARATE	PUMPED	11	1400	63	67	67	0	1203	0
16	12500	51	3750	COMBINED	PUMPED	2	500	100	0	10	0	90	0
17	15000	47.5	33450	COMBINED	PUMPED	1	630	24	15	14	235	255	88
18	8000	34	27600	P.SEP	GRAVITY		400	0	87.5	0	0	262.5	0
19	12595	33	14309	P.SEP	PUMPED	8	400	0	140	0	20	240	0
20	9000	32	3940	COMBINED	GRAVITY	0	249	49	1	2	0	46	0
21	28255	28	18693	P.SEP	GRAVITY	0	300	0	6	24	0	240	30
22	9414	28	22800	COMBINED	PUMPED	6	230	0	12	11	0	441	126
23	12700	18.9		P.SEP	GRAVITY								
24		14	7720		GRAVITY		265	0	8	0	150	105	2
25	1850	5.8	5100	SEPARATE	PUMPED		500	10	0	0	340	150	0
26	1810	4.36	7330	P.SEP	PUMPED	3	91	0	10	0	31	42	8
28	685	1.06	1520	COMBINED	GRAVITY	0	35	0	0	0	21.9	8.5	4.6
29	685	1.06	8920	COMBINED	GRAVITY	0	220	6	0	0	103	42	69
30	250	0.46	1390	COMBINED	GRAVITY	0	20	0	0	0	9.6	8.8	1.6

Table 5.3 Catchment data for the sites selected for use in the test programme.

5.4 SUMMARY

The ten privatised water companies in England and Wales were approached to assist in the research project by providing access to information relating to wastewater treatment works catchments. Eight of the water companies co-operated, although the information available was severely limited by the accuracy and completeness of records. Information on 77 wastewater treatment works was collected, but of these only 35 had complete sets of catchment information and flow records that could be of use in this project. The accuracy and age of the information was unknown in all cases, with the information obtained from DAS being the most accurate and up to date. Consequently great care was needed when interpreting the results of the statistical analysis, as discussed in chapters 6 and 7.

Problems were encountered with a long period of wet weather. To obtain a large enough sample for a meaningful statistical analysis of the results, samples were taken at flows greater than DWF. At the end of the testing period 33 settling velocity gradings had been produced for the 29 sites, and of these 21 were for flows greater than DWF.

CHAPTER 6

ANALYSIS

6.1 INTRODUCTION

As discussed in chapter 5, on completion of the development of the settling column test method, a series of settling velocity grading tests were carried out on 29 selected catchments. When all the results were collected the data were analysed in terms of the catchment data and then the grading data. The grading data were presented in three different formats for the analysis:

a) bar charts;
b) curve fitting;
c) velocity coefficients.

It had been anticipated at the beginning of the project, based on the settling velocity grading curves collected by Smisson (1990), that the strongest relationship between grading curves and the catchment characteristics would be with respect to the catchment size. The relationship was not immediately apparent and more detailed analysis was required to determine if the relationships were more complex and inter-related.

This chapter includes a description of the analysis undertaken and discussion of the results.

6.2 ANALYSIS OF WASTEWATER TREATMENT WORKS CATCHMENT CHARACTERISTICS

6.2.1 Correlation between catchment variables

To determine whether there was a linear relationship between any two catchment variables the Pearson correlation coefficient was calculated for pairs of data using the SPSS statistical analysis computer programme.

The correlation coefficient is a measure of the linear relationship between a pair of variables. A correlation coefficient of 1, the maximum value, means that there is a true linear relationship, whilst a value of 0 indicates that there is no linear relationship between the two variables under consideration. A correlation coefficient may be negative, indicating that the value of a variable will decrease with a corresponding increase in the value of the second variable.

Care must be taken in interpreting correlation coefficients. Even though analysis may indicate that there is a correlation between two variables, there is no indication that it is a cause and effect relationship. It may be just coincidence that the values of two variables increase or decrease with each other (Owen and Jones, 1994). Judgement must be used to verify the results. This is especially true when a small sample (less than 30) is used to test a relationship (Owen and Jones, 1994), as in this project where only 29 catchments were used in the experimental programme.

An aid to measuring the strength of association between two variables is the coefficient of determination. This measures the proportion of total variation that can be explained by the regression equation. It is calculated by squaring the correlation coefficient (r). If $r = 0.7$, $r^2 = 0.49$, showing that 49% of the variations in the value of a variable can be explained by the regression equation, with 51% being explained by other unknown factors (Owen and Jones, 1994).

The level of significance is a measure of the deviation outside the range of the distribution that cannot be attributed by chance. The level of significance can be altered and should be stated in all cases. Obviously the higher the level of significance the greater the confidence that can be place in the accuracy of a relationship and so it is preferable to use the highest possible significance levels at all times. The significance of the correlation coefficient for small samples can be tested by calculating the test statistic t and comparing it to the t-distribution. The t-distribution assumes that the variables are normally distributed. Although this proves whether the correlation coefficient is significant or not, it cannot prove a causal relationship, that must still be explained by human judgement.

The correlation coefficient and test statistic t for all pairs of catchment variables were calculated using SPSS. The full results are provided in Appendix E.1 and a summary of the correlation coefficients greater than ±0.7071 is given in table 6.1. This value of ± 0.7071 was chosen because the r^2 value (the coefficient of determination) would then be greater than 50%. It was considered that if less than 50% of the results could be explained by the correlation, the relationship would be too weak for any satisfactory conclusions to be drawn.

The level of significance of the correlation coefficients was ascertained by comparing the critical values of the t distribution with the t test values produced by analysis. None of the results are significant at the 99% significance levels. Table 6.1 summarises the correlations between the catchment characteristics at 95% significance.

	Total area	Sewer length	Area of parkland
Area of commerce	0.9777	0.8615	
DWF	0.9913	0.7988	
Industrial area	0.9923	0.8183	
Area of parkland	0.8990		
No. of pumping stns	0.9311	0.8005	0.8101
Residential area	0.9924	0.8018	
Sewer length	0.8219		

Table 6.1 Summary of correlation coefficients greater than ±0.7071 and with at least 95% significance for the catchment characteristics of sites used in the test programme.

Table 6.1 highlights several interesting points.

i) The three catchment parameters: area of farmland; whether the system is pumped or gravity fed; and the system type (combined, separate or partially separate sewers), all have very low correlation coefficients and so are excluded from table 6.1. They must be considered to have a very low degree of linear association.

ii) All the correlation coefficients have positive values. All the variables increase in accord with each other. This result was expected because the main controlling feature is the size of the catchment, which is related to the land use areas, sewer lengths, population etc. for each test site. This is confirmed in table 6.1, which shows that the total catchment area is the most common variable in a significant correlating pair.

iii) Most of the pairs of variables which have correlation coefficients greater than 0.7071 are significant at a level of at least 90%.

6.2.2 Principal component analysis

The aim of a principal component analysis is to take a set of variables and by combining them find another set of variables that are uncorrelated. These uncorrelated variables are called principal components and being uncorrelated can be used to measure different 'dimensions' within the data. The principal components all have different variances and the aim is to find a small number of principal components that will display about 90% of the variance within the data set, and so to reduce the number of variables against which to describe the data (Manly, 1994).

A principal component analysis was carried out on the catchment data using SPSS. The eigenvectors and eigenvalues for the three principal components that make up 88% of the variance are shown in table 6.2. All the remaining principal components have eigenvalues below unity and so their variance is negligible and they can be ignored.

	Principal component 1	Principal component 2	Principal component 3
Eigenvalue	9.00153	1.30808	1.13462
Percentage of total variation	69.2	10.1	8.7
Cumulative percentage	69.2	79.3	88
Area	0.99019	0.11863	-0.03153
Commercial area	0.98477	0.02558	-0.03611
DWF	0.99153	0.02817	-0.04818
Area of farmland	-0.01216	0.84755	0.1399
Impermeable area	0.71365	-0.15252	-0.47291
Industrial area	0.99274	0.06785	-0.01554
Number of pumping stations	0.95605	-0.15993	-0.03001
Area of parkland	0.89361	0.09325	0.02164
Equivalent population	0.99504	0.04827	-0.02253
Pumped or gravity fed system	0.27217	-0.70754	0.29789
Residential area	0.99382	0.01598	-0.04935
Main sewer length	0.84388	0.0943	0.23972
System type	0.31076	-0.00046	0.85792

Table 6.2 Factor matrix showing the eigenvalues and eigenvectors for the three major principal components within the catchment data.

Table 6.2 quite clearly indicates that there is one very dominant principal component that is associated with measures of size of the catchment. The second principle component accounts for far less of the variation within the data and is associated with the farmland within the catchment and whether the sewer system is pumped or gravity fed. The third principle component is associated with the type of system, that is whether the system is combined, separate or partially separate.

To illustrate the effect of the principal components on the variation within the data, the values for all three principal components were calculated for each of the catchments (table 6.3) and principal components 2 and 3 were plotted against principal component 1 for each case (figure 6.1 and 6.2).

Catchment record number	Principal component 1	Principal component 2	Principal component 3
1	41.54156	0.088622	-0.84749
2	9.404841	0.019971	1.165859
3	0.305975	-0.87428	-1.32894
4	4.327632	1.12	2.12985
5	-1.50738	-0.86942	1.185246
6	-1.44902	4.918849	-0.00708
8	0.263057	-0.79635	1.152611
9	-3.73623	0.691829	-0.61554
10	-3.20391	-0.85132	-0.04428
11	-1.67226	-0.87658	1.299558
12	-2.62823	-0.81209	-0.00475
14	-3.66813	-0.27043	-2.43453
15	-1.01365	-1.24732	-2.14042
16	-1.28317	-1.29581	-1.35148
17	-2.2395	-0.63479	-0.2773
18	-3.40794	0.613946	0.617794
19	-2.05103	-0.93412	1.193708
20	-3.12267	0.389685	-1.28205
21	-3.28542	0.623923	0.614243
22	-2.12737	-0.86281	-0.0225
23	-3.69927	0.590541	0.602066
24	-5.0054	0.765102	-3.09523
25	-3.79204	-0.50997	-1.3437
26	-2.81677	-0.85987	1.214249
28	-4.1772	0.616444	-0.63383
29	-3.65406	0.723153	-0.68434
30	-4.19812	0.600733	-0.63644

Table 6.3 Summary of principal component values for each catchment.

Figure 6.1 shows that catchments with a large positive values of the first principle component have large sites. The large sites have been plotted with open symbols. The medium and small sites are very closely clustered and do not show much variation in the value of the first principal component.

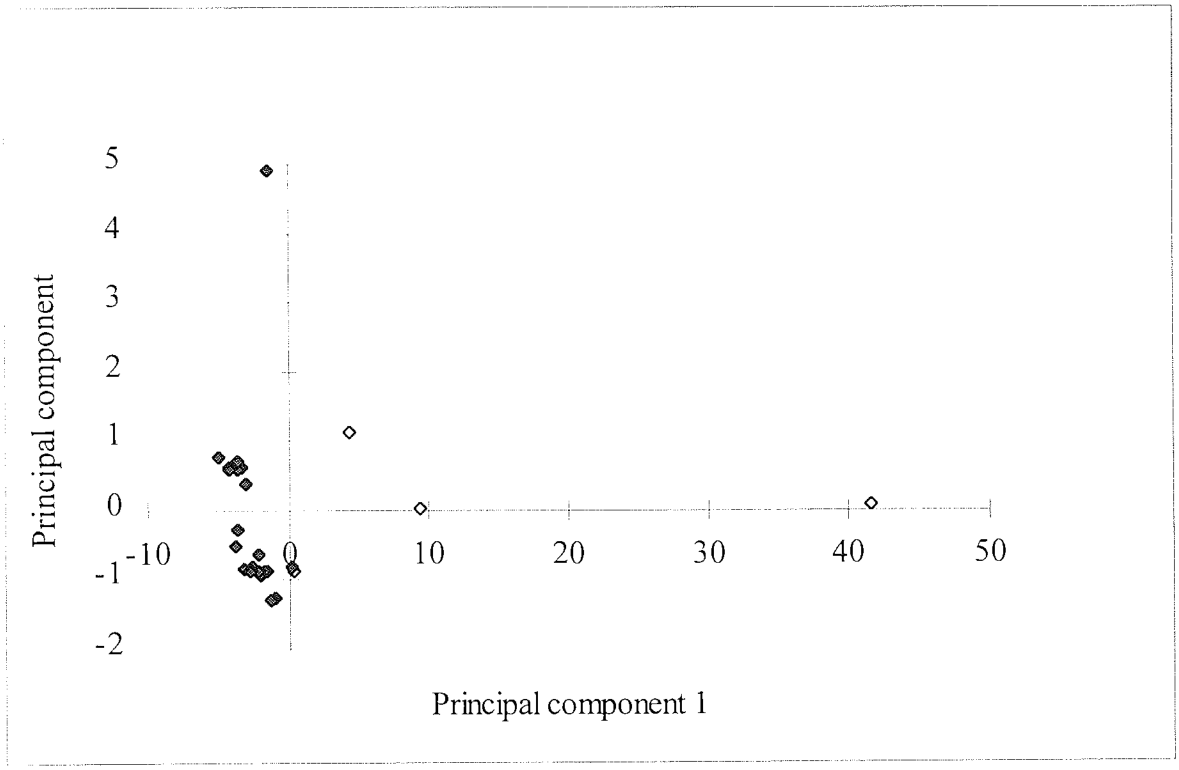

Figure 6.1 Plot of principal component 2 against principal component 1 for the catchment variables. (Open symbols indicate catchments with large DWF.)

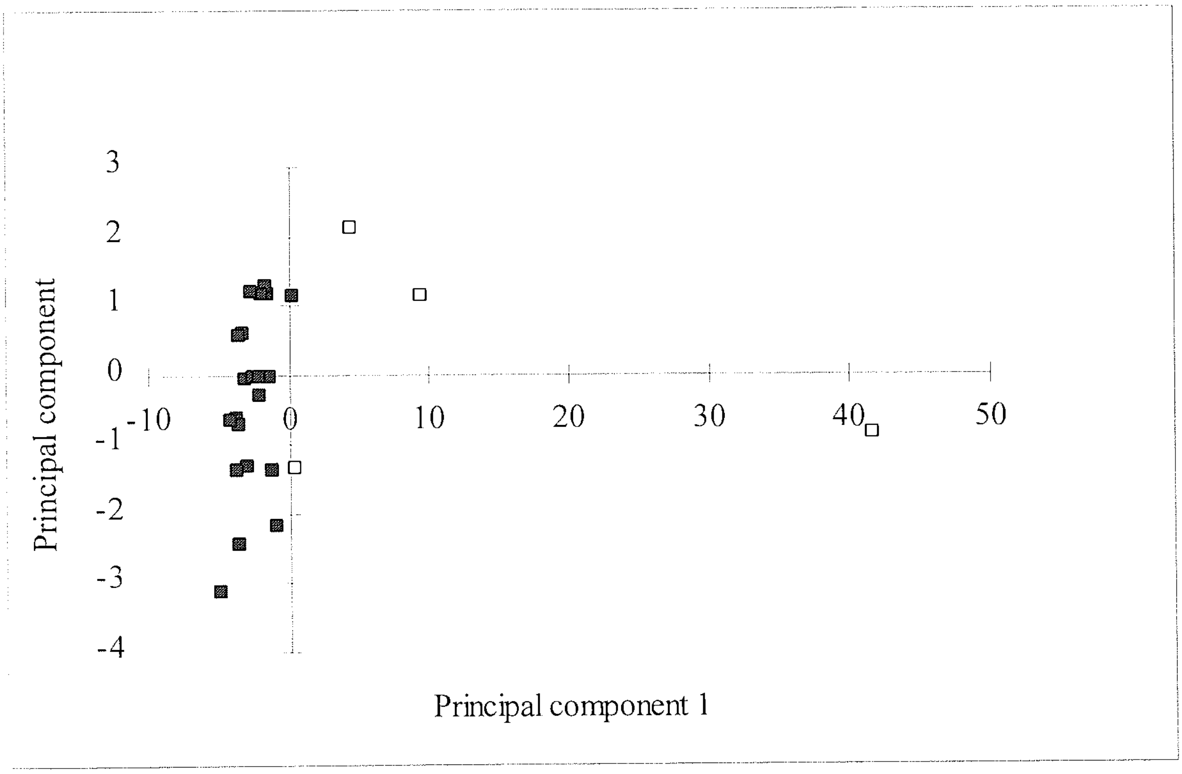

Figure 6.2 Plot of principal component 3 against principal component 1 for the catchment variables. (Open symbols indicate catchments with large DWF.)

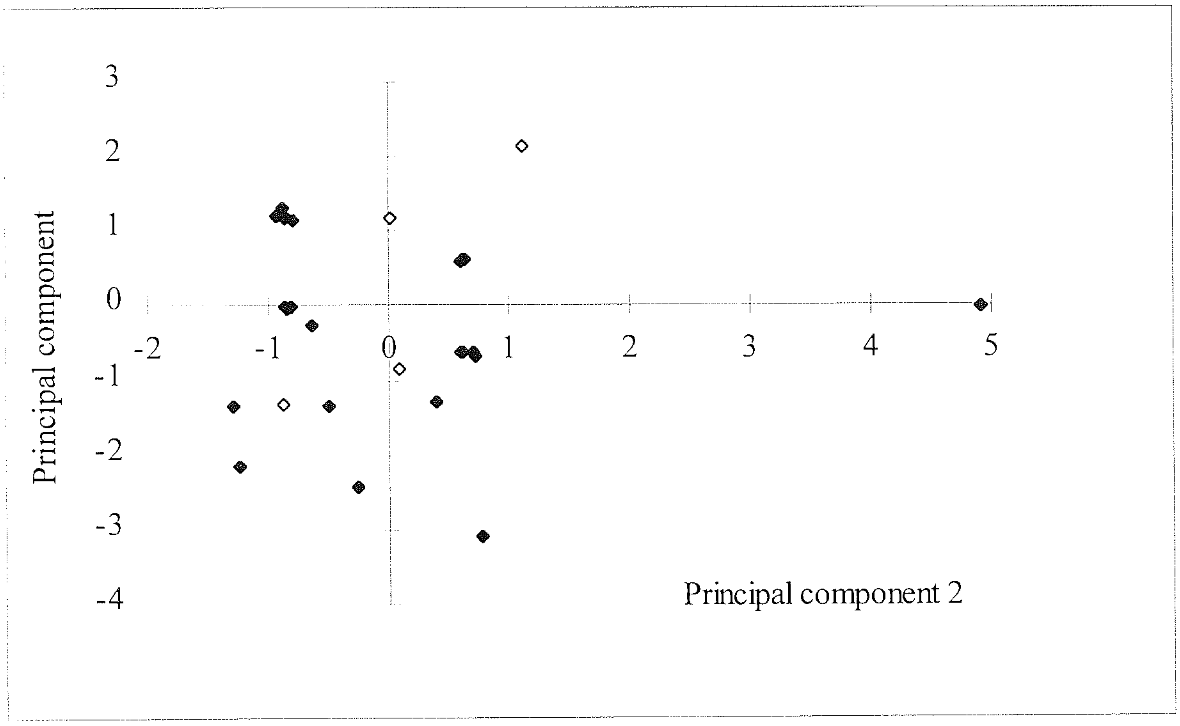

Figure 6.3 Plot of principal component 3 against principal component 2 for the catchment variables. (Open symbols indicate catchments with large DWF.)

Considering the scatter in figure 6.3 with the values of the principal components in table 6.3 for actual sites indicates that there is little variation due to the area of farmland, the type of system or whether the system is pumped or gravity fed. The large positive value in principal component 2 is for catchment reference 6, which has a large proportion of farmland compared with its total area and distorts the results. The large negative values for principal component 3 are for sites with no information provided on the type of system. As would be expected from the eigenvalues for the principal components, the best description of the data is provided by the first principal component.

By removing the three large catchments and analysing the data to produce alternative principle components, an attempt was made to find a first principle component that would produce more spread in the medium and small sites. Table 6.4 contains the eigenvectors and eigenvalues for the four principle components produced. Table 6.5 contains the values of the principal components for each catchment.

	Principal component 1	Principal component 2	Principal component 3	Principal component 4
Eigenvalue	6.78	2.10	1.41	1.13
Percentage of total variation	52.1	16.1	10.8	8.7
Cumulative percentage	52.1	68.3	79.1	87.8
Area	0.90413	-0.35355	0.18724	0.00751
Commercial area	0.88539	0.21489	0.00694	-0.26363
DWF	0.90316	-0.02551	-0.02478	-0.02521
Area of farmland	0.59869	-0.68993	0.16772	-0.05577
Impermeable area	-0.24581	0.20818	0.82735	-0.13288
Industrial area	0.95818	-0.11111	0.03526	-0.06286
Number of pumping stations	0.56132	0.64028	0.17043	0.31281
Area of parkland	0.21573	-0.54194	-0.00347	0.71864
Equivalent population	0.97842	-0.09143	-0.00653	0.00758
Pumped or gravity fed system	0.27375	0.74252	0.11504	0.43377
Residential area	0.93055	0.07784	0.11948	0.2028
Main sewer length	0.78995	0.25887	-0.03219	-0.43499
System type	0.37366	0.24062	-0.77516	0.02269

Table 6.4 Factor matrix showing the eigenvalues and eigenvectors for the four major principal components within the catchment data for the small and medium sites.

Four principal components were produced with the first principal component accounting for 52.1% of the variation within the data and the second for 16.1%. The first principal component is associated with the size of the catchment as when all sites were included in the analysis, but the eigenvectors have lower values. The area of farmland has an influence in the first principal component that was not previously present. The second principal component is different to that for all the catchments because the total area of the catchment and the area of farmland have negative values and the number of pumping stations and whether the system is pumped or gravity fed have high positive values. It could be said that this principal component is associated with the presence or absence of pumping within the sewerage system. The third principal component is associated with the impermeable area and the fourth with the area of parkland. These principal components have been plotted against each other and a selection and are shown in figures 6.4 to 6.7.

Catchment record number	Principal component 1	Principal component 2	Principal component 3	Principal component 4
4	24.27	1.79	0.24	-2.31
5	4.46	1.42	-0.95	0.40
6	10.70	-7.21	1.19	0.77
8	9.36	0.11	-0.46	2.81
9	-2.35	-1.12	-0.44	-1.08
10	-2.09	0.53	-0.17	-0.07
11	0.78	2.04	-1.03	0.17
12	-0.39	0.95	0.03	-0.05
14	-2.76	-0.97	2.46	0.85
15	0.49	2.41	3.84	0.58
16	-4.07	1.57	3.09	-0.54
17	-2.31	-0.39	0.67	1.03
18	-2.72	-0.71	-1.63	-1.04
19	-0.49	2.07	-1.01	0.50
20	-4.93	-0.62	1.07	-1.31
21	-2.73	-0.98	-1.67	-0.58
22	-1.67	0.19	0.06	2.25
23	-4.14	-0.61	-1.75	-1.02
24	-5.71	-1.89	1.92	-1.09
25	-4.43	-0.14	1.36	-0.26
26	-3.26	1.29	-1.34	0.21
28	-5.10	-1.02	-0.54	-0.99
29	-4.62	-1.79	-0.30	-0.08
30	-5.15	-0.98	-0.54	-1.03

Table 6.5 Summary of principal component values for each small and medium sized catchment.

As can be seen from table 6.5 and figures 6.4 to 6.6, there is a trend that the smaller the catchment area the less the value of the first principle component. As with the principal component analysis for all the catchments, the smaller sites have smaller values of the first principal component, with the few larger sites separated out by larger values.

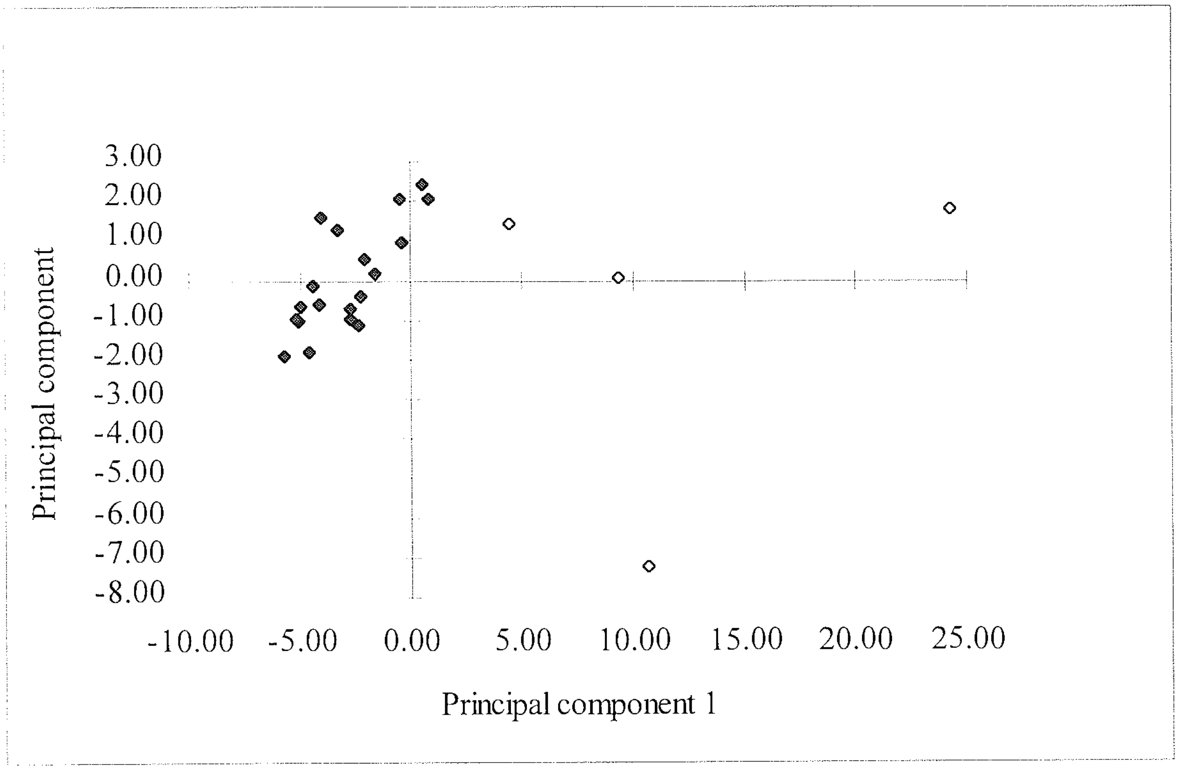

Figure 6.4 Plot of principal component 2 against principal component 1 for the small and medium sites. (Open symbols indicate catchments with largest DWF.)

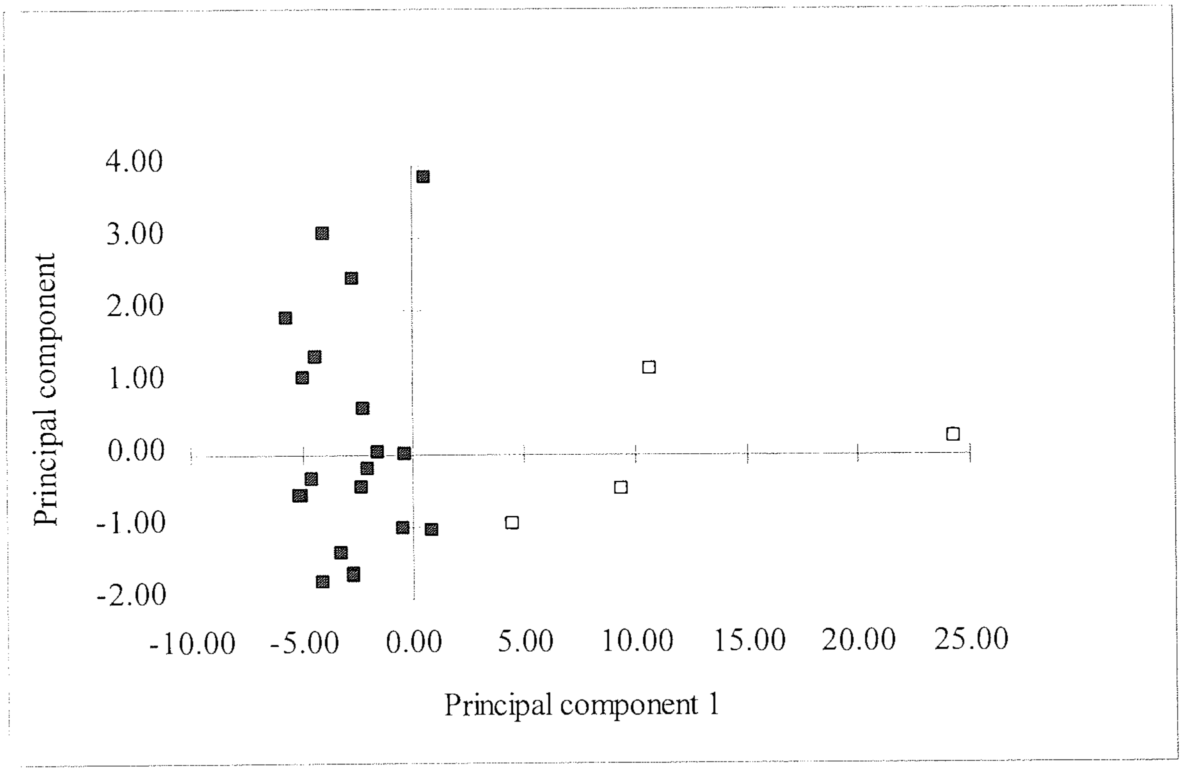

Figure 6.5 Plot of principal component 3 against principal component 1 for the small and medium sites. (Open symbols indicate catchments with largest DWF.)

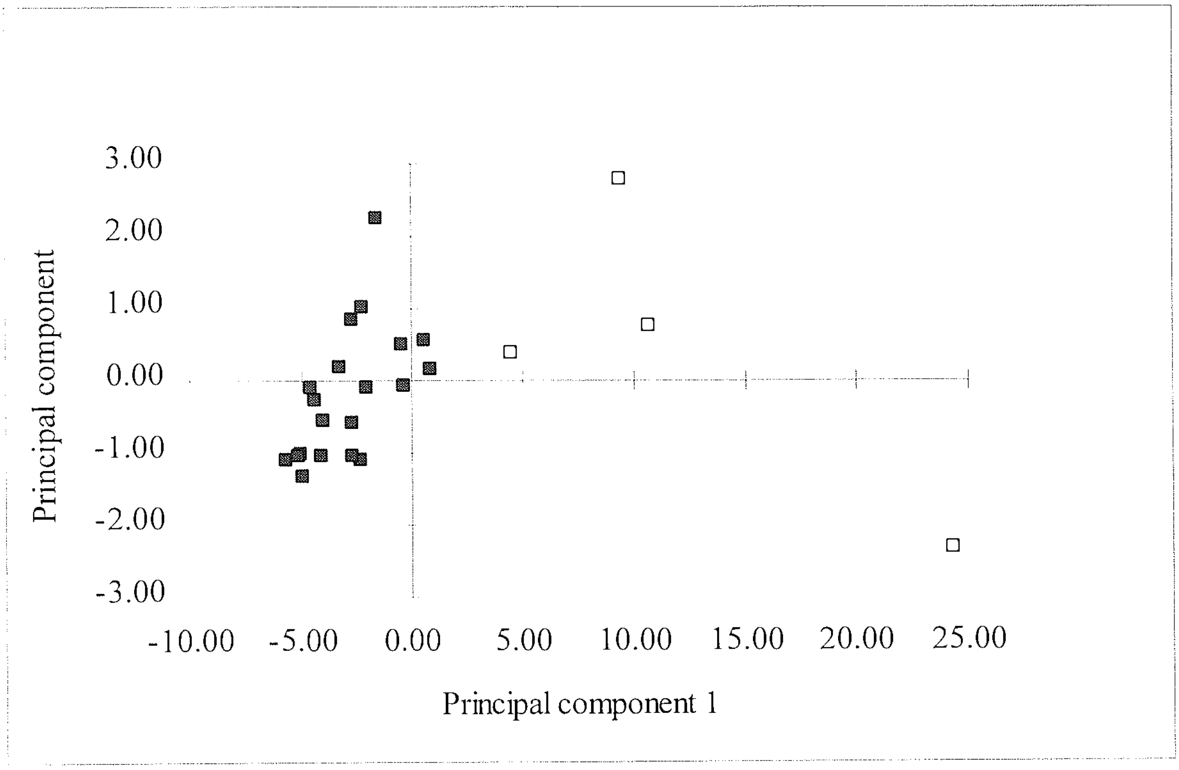

Figure 6.6 Plot of principal component 4 against principal component 1 for the small and medium sites. (Open symbols indicate catchments with largest DWF.)

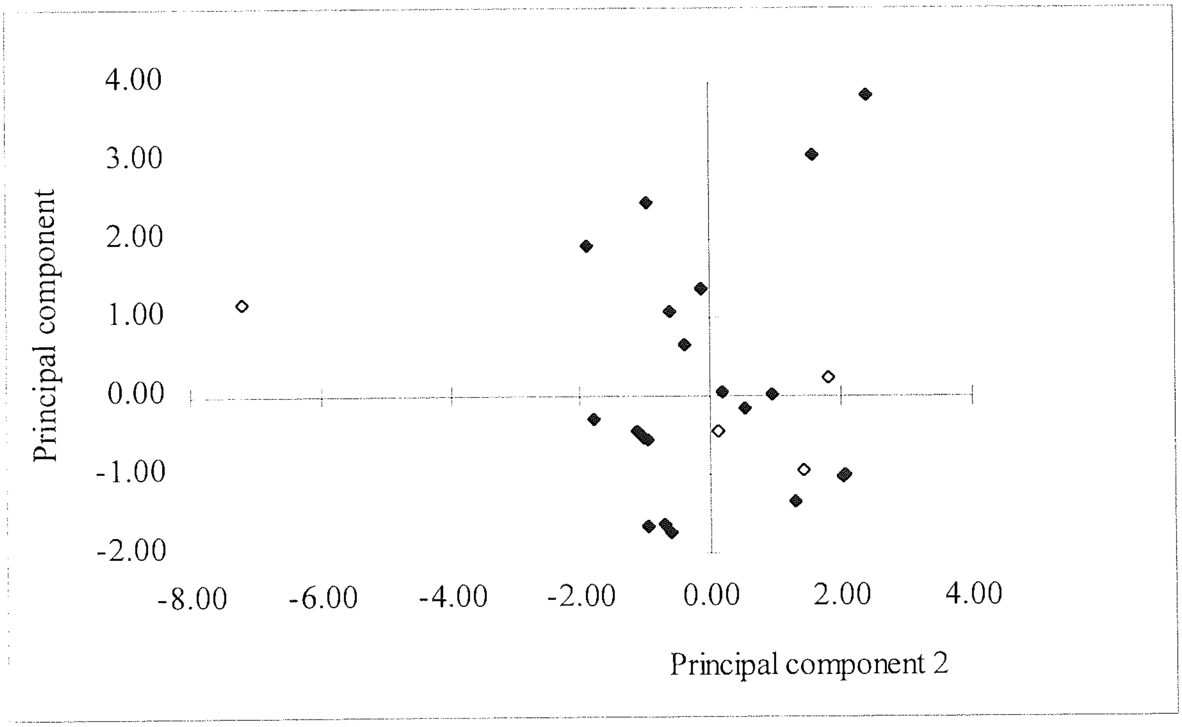

Figure 6.7 Plot of principal component 3 against principal component 2 for the small and medium sites. (Open symbols indicate catchments with largest DWF.)

The positive values of the second principal component are produced for sites with pumping stations: the more pumping stations the larger the value will be. Catchments with a large area of farmland or parkland will have a negative value. Figure 6.4 shows that, as might be expected, the smaller catchments are less likely to have a pumped sewer system than the medium sized catchments and so have a larger negative value with the influence of farmland and parkland.

The influence of the third and fourth principal components is difficult to determine and there is a fairly random scatter in figure 6.6 and 7.7.

The major principal component in analysing both all the catchments and just the small and medium sized sites is associated with a measure of the size of the catchment, which confirms the correlation analysis that size has a major influence on most of the catchment characteristics. It appears that the remaining principal components are composed of eigenvectors that are influence by the more random extremes in catchment parameters.

6.3 ANALYSIS OF SETTLING VELOCITY GRADING TEST RESULTS

6.3.1 Grouping of sub-sample mass

It was considered best to look at the test results in a simple form before going on to the more complex curve fitting procedure. Both settling velocity grading curves and bar charts of the sub-sample mass against the settling velocity were plotted.

The bar charts all appeared to have a similar shape, irrespective of whether storm sewage or DWF sewage were being tested. Due to this similarity, the total mass of suspended solids was subdivided into four groupings:

i) the heavy sinkers with settling velocities greater than 0.68 mm/sec;

ii) the light sinkers with settling velocities between 0.18 and 0.68 mm/sec;

iii) the residual suspended solids; and

iv) the floating fraction, with settling velocities greater than or equal to the absolute value of -0.15 mm/sec.

Figure 6.8 illustrates this breakdown.

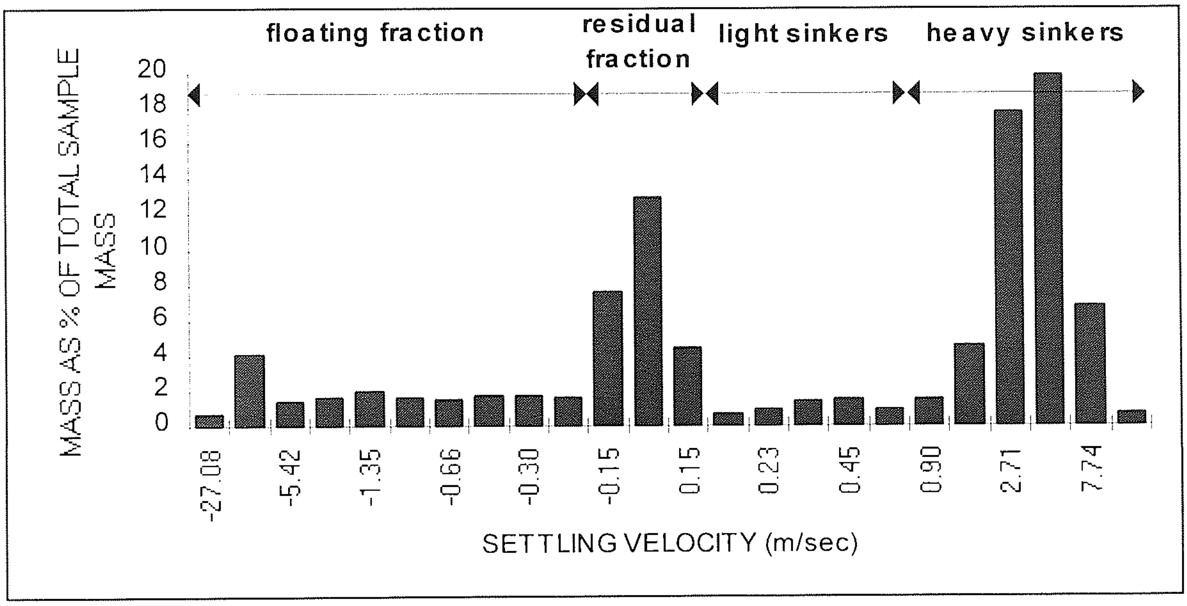

Figure 6.8 A bar chart of sub-sample mass against settling velocity for site reference 26 to show the sub-sample grouping used for analysis.

0.68 mm/sec was chosen as the break point between the light and heavy sinking fractions because this was the point at which the trough between the two groups occurred in all but a few of the tests. The trough can be clearly seen on figure 6.8, other bar charts showing this feature are included in Appendix D. Although the spacing on the bar chart is irregular, that is not linear, the same result is observed with equal spaced classes on a histogram, as illustrated in figure 6.9b.

The following statistical analysis was then carried out on the groupings of the sub-sample masses:

- correlation coefficients of each of the four groupings with the others and with the catchment parameters.

- multiple regression of each group with the other 3 groups and with the catchment parameters;

- when samples were taken at the wastewater treatment works the flow rate at the inlet was noted, when possible. The flow rate was then converted to a multiple of the DWF to the treatment works. The test data were sub-divided in terms of the multiple of DWF and correlation coefficients were then calculated between catchment characteristics and the four groupings within the sub-divisions;

- multiple regression of the groups after sub-division in terms of the multiple of the DWF when sampled (as described above);

- correlation coefficients were calculated between the settling velocities at which the peak and trough mass values occurred for the sinking fraction in each test and the catchment parameters, as illustrated in figure 6.9a and b;

- multiple regression of the settling velocities at which the peak and trough mass values occurred with the catchment parameters.

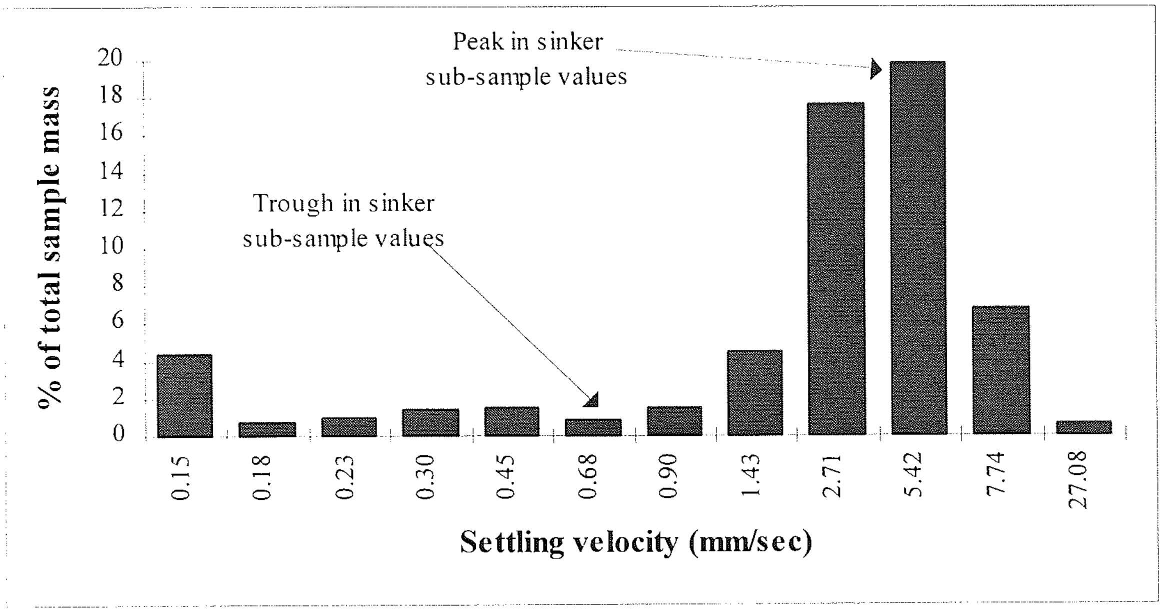

Figure 6.9a A bar chart of sub-sample mass against settling velocity for site reference 26 to illustrate the settling velocities at which the peak and trough values of mass occurred.

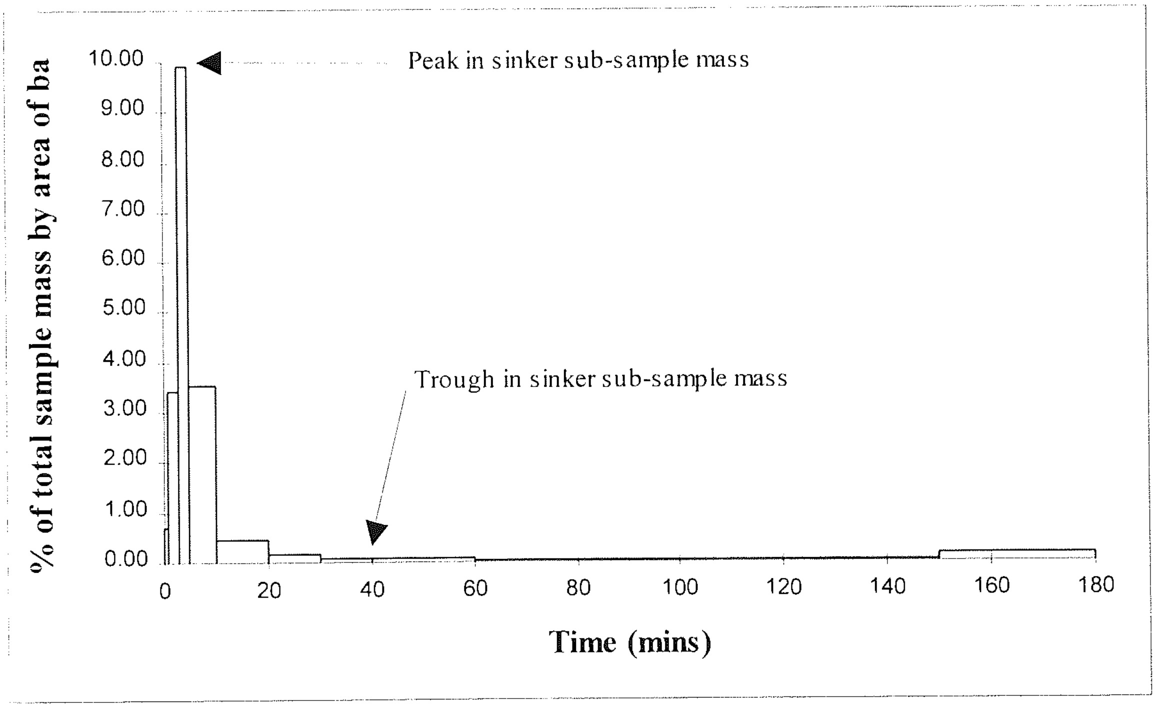

Figure 6.9b A histogram of sub-sample mass against settling velocity for site reference 26 to illustrate the settling velocities at which the peak and trough values of mass occurred.

6.3.1.1 Main grouping analysis

The correlation coefficients of the four main groups of sub-sample mass from all the tests with each other and the catchment characteristics are provided in Appendix E.3. A summary of the correlation coefficients with values greater than 0.5 and more than 95% significance is provided in table 6.6.

	Floaters	Residue
Residue	0.6862	
Light sinkers	0.7933	0.6293
Heavy sinkers	0.5551	
Area of farmland	0.5537	0.6776

Table 6.6 Correlation coefficients of the four main sub-sample groupings and the catchment parameters for all tests at 95% significance.

Table 6.6 is not very conclusive. The highest correlation coefficient is 0.7933 between the floating and light sinking fraction. Using the coefficient of determination this means that 62.9% of the values of the variables can be explained by the linear regression equation, the remaining 37.1% are unexplained by a linear relationship. This is acceptable for this study, but unfortunately, the relationship with the catchment variables is not so strong. In this exercise, no correlation coefficients other than those shown in table 6.6 had a value greater than ±0.5. The significance levels were calculated individually for each pair of variables, and likewise there were no other correlation coefficients with significance levels over 95%.

Having drawn no conclusions when comparing pairs of variables, it was decided to carry out a multiple regression. Each of the four fractions were used in turn as a dependent variable and were tested against each of the remaining variables, in an effort to determine if the linear relationship contained more than one variable at a time. The closer the scatter of results to the line, the stronger the relationship. The significance level for this exercise was set at 95% and the following results were obtained using SPSS.

$$\text{floaters} = (0.569 \times \text{light}) + (0.343 \times \text{farm}) + (0.399 \times \text{heavy}) - 25.8 \qquad \text{eqn 6.1}$$

$$\text{residue} = 23.3 + (0.411 \times \text{farm}) + (0.413 \times \text{light}) \qquad \text{eqn 6.2}$$

$$\text{light} = 10.7 + (0.771 \times \text{floaters}) \qquad \text{eqn 6.3}$$

$$\text{heavy} = 47.6 + (0.650 \times \text{floaters}) - (0.303 \times \text{farm}) \qquad \text{eqn 6.4}$$

where:

floaters = percentage floaters measured by weight;
residue = percentage residual suspended solids by weight;
light = percentage light (slow) sinking fraction measured by weight;
heavy = percentage heavy (fast) sinking fraction measured by weight;
farm = area of farmland as a percentage of the total catchment area.

Although the multiple regression calculations produced relationships between the main groupings, it was disappointing in that farmland was the only catchment characteristic that was included in all relationships. This is made less useful by the fact that in the analysis of the catchment data the area of farmland expressed as a total of the catchment area formed no relationships with any of the other variables (see section 6.2.1), it appeared as an independent variable. It is not then surprising that no other catchment characteristics are related in the multiple regression equation. As discussed in chapter 5, the area factors are of unknown accuracy, however, farmland is most likely to be fairly accurately measured because it shows up clearly on plans, unlike other area factors such as percentage of impermeable area, percentage of total area in commercial use, etc. Fourteen out of the thirty test sites have measured areas of farmland that are included in the analysis, which is not a dissimilar number of sites as the other area factors and so no inference can be drawn from this.

To prove the accuracy of these relationships each main group of suspended solids must be calculated using the catchment characteristics. Being unable to calculate any of the groups of suspended solids from equations 6.1 to 6.4, each main group was analysed by multiple regression with the catchment characteristics only. This produced the following set of relationships.

At 95% significance:

$$\text{floaters} = 1.0 + (0.495 \times \text{farm}) \qquad \text{eqn 6.5}$$

$$\text{residue} = 28.8 + (0.516 \times \text{farm}) \qquad \text{eqn 6.6}$$

At 80% significance:

$$\text{light} = 17.0 - (5.18\times10^{-5} \times \text{sewer}) + (0.024 \times \text{area}) - (0.0006 \times \text{pop}) - (2.37 \times \text{pdwf}) + (1.01 \times \text{comm}) \qquad \text{eqn 6.7}$$

$$\text{heavy} = 51.3 - (0.642 \times \text{park}) \qquad \text{eqn 6.8}$$

Out of interest the equations for the floaters and the residue were also calculated at 80% significance:

$$\text{floaters} = 2.6 + (0.615 \times \text{farm}) - (0.792 \times \text{park}) \qquad \text{eqn 6.9}$$

$$\text{residue} = 20.3 + (0.534 \times \text{farm}) - (0.664 \times \text{park}) + (8.6 \times \text{pumped}) \qquad \text{eqn 6.10}$$

where:

farm = area of farmland as a percentage of the total catchment area;
sewer = length of the main sewers feeding the wastewater treatment works (m);
area = total catchment area (hectares);
pop = equivalent population (number);
pdwf = proportion of DWF reaching the treatment works when a sample was taken;
comm = area of commerce as a percentage of the total catchment area;

park = area of parkland as a percentage of the total catchment area;

pumped = pumped or gravity fed sewer system: 1 = pumped;

2 = gravity fed.

	CALCULATED				OBSERVED			
TEST REF.	FLOATERS	RESIDUE	LIGHT	HEAVY	TRUE FLOATERS	TRUE RESIDUE	TRUE LIGHT	TRUE HEAVY
1	1.0	28.8	11.5	48.2	11.0	30.0	7.8	51.1
1s	1.0	28.8	11.5	48.2	0.0	41.4	10.6	48.0
2	2.5	29.0	12.6	48.3	4.1	27.9	11.4	56.5
3	1.0	28.8	11.5	48.2	1.2	28.1	52.5	18.2
4	15.8	30.3	22.9	48.8	0.0	43.4	6.4	50.2
4i	15.8	30.3	22.9	48.8	13.3	34.2	6.9	45.6
4iii	15.8	30.3	22.9	48.8	0.0	28.9	13.1	58.0
5	1.0	28.8	11.5	48.2	1.1	44.7	15.7	38.6
7	1.0	28.8	11.5	48.2	6.1	19.4	8.0	66.6
8	1.0	28.8	11.5	48.2	13.9	22.3	13.3	50.4
9	8.4	29.6	17.1	48.5	2.2	24.6	7.4	65.9
10s	1.0	28.8	11.5	48.2	0.0	33.5	15.1	51.4
11	1.0	28.8	11.5	48.2	11.5	18.2	14.1	56.2
12	3.5	29.1	13.4	48.3	1.7	41.8	12.2	44.3
13	1.0	28.8	11.5	48.2	8.1	31.8	13.9	46.2
14	30.7	31.9	34.4	49.4	10.9	33.5	7.7	47.9
15	1.0	28.8	11.5	48.2	0.0	31.0	11.1	57.9
16	1.0	28.8	11.5	48.2	0.0	35.4	12.6	52.0
17	19.4	30.7	25.7	48.9	17.6	41.4	12.4	28.6
18	1.0	28.8	11.5	48.2	0.6	27.3	23.1	49.0
19	3.5	29.1	13.4	48.3	0.0	28.0	19.8	52.1
20	1.0	28.8	11.5	48.2	0.0	37.0	18.0	44.9
21	1.0	28.8	11.5	48.2	3.6	36.5	23.2	36.8
22	1.0	28.8	11.5	48.2	0.0	48.6	24.7	26.7
22s	1.0	28.8	11.5	48.2	0.0	49.1	0.0	50.9
23	1.0	28.8	11.5	48.2	11.0	25.1	20.7	43.1
24	29.0	31.7	33.1	49.3	14.6	37.5	17.9	30.0
25	34.6	32.3	37.4	49.5	0.0	36.1	30.7	33.1
26	17.9	30.6	24.5	48.9	18.2	25.1	5.5	51.1
28	32.0	32.0	35.3	49.4	17.6	49.4	14.1	18.9
29	24.1	31.2	29.3	49.1	0.0	41.2	11.5	47.2
30	24.7	31.3	29.8	49.1	0.0	69.3	7.4	23.4

Table 6.7 Comparison of model and test results for samples at all flows.

Obviously using equations 6.9 and 6.10 one is less sure that the results will fall within the acceptable limits of accuracy than using equations 6.5 and 6.6 respectively because the significance levels used to calculate the equations were lower: 80% compared with 95%.

Using equations 6.5 and 6.6 to calculate floaters and residue, it was possible to calculate the light and heavy fractions using equations 6.3 and 6.4. Using equations 6.5 and 6.6 in the calculations was preferable to using equations 6.7 and 6.8 because they were derived at a 95% significance level, rather than at 80% significance. This helped to maintain as high a level of significance in the results as possible.

A comparison of the model results with the actual test results is provided in table 6.7.

The model values of the floaters and the light sub-sample groups have a similar high level of inaccuracy compared with the observed results; the calculated and observed values for the residue and the heavy sub-sample fractions are more accurate. As an illustration of the extreme variation in the predicted value with the actual measured values a scatter plot has been included for the residual values (figure 6.10).

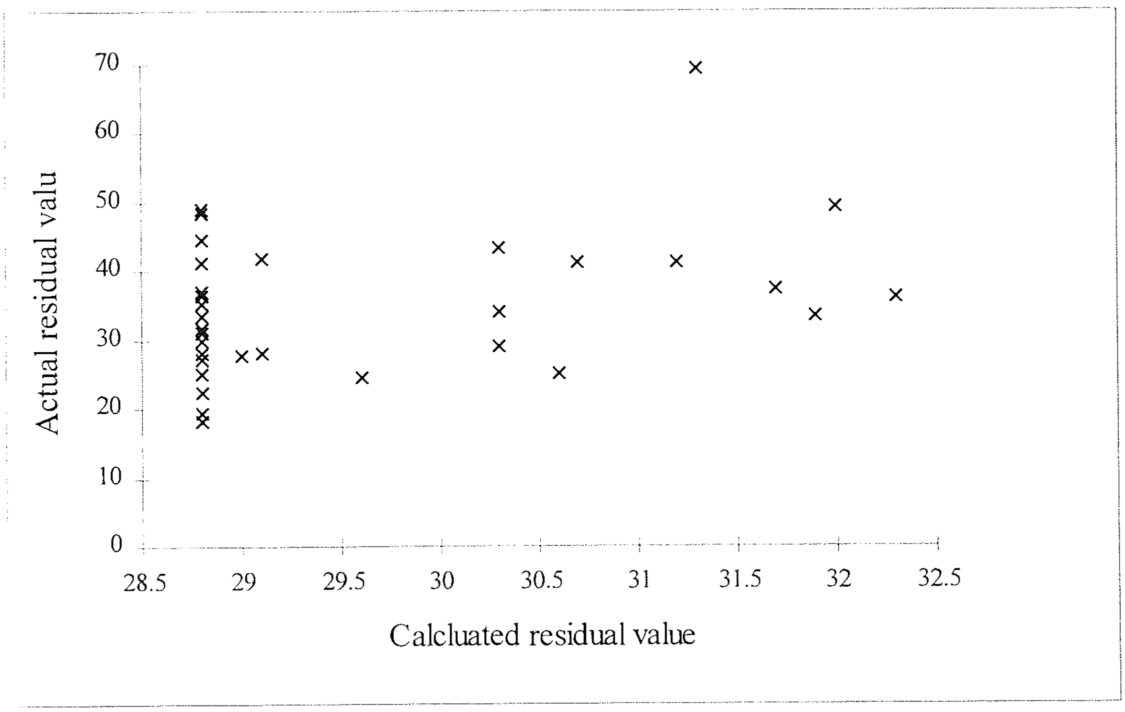

Figure 6.10 Scatter plot of the calculated and predicted values for the residue.

6.3.1.2 Breakdown into multiples of DWF

Having successfully obtained relationships, if somewhat weak, between the four main groups of sub-sample mass and the catchment characteristics, it was decided that stronger relationships might be found by splitting the tests down into separate sets based on the flow rate into the wastewater treatment plant at the time the sample was taken. For flows into the works greater than DWF, a multiple of DWF was calculated, with the assumption that storm flow occurred at 6 DWF. Each breakdown and the results from the analysis will be reported in turn.

1) (1-2) × DWF

Twenty one tests had flows between 1 and 2 DWF. The correlation coefficients for this sub-sample are provided in Appendix E.4. A summary of the correlation coefficients with values greater than ±0.7071 and at least 95% significance is provided in table 6.8.

Analysis of this group produced a greater spread of statistical results than resulted from the main grouping analysis (section 6.3.1.1), and may be due to the smaller set of test results from which they were calculated.

	% floaters	% residue	% heavy	Equivalent population	Sewer	No. of pump. stns	Total area	Area of farmland
% residue	0.8789							
% light	0.8149	0.8043						
% heavy	0.7390							
DWF				0.9965				
System type			0.7313					
No. p. stns				0.9576				
Total area				0.9947		0.9466		
Imp. area				0.9597		0.8820	0.9428	
Area farm.	0.7672							
Comm. area					0.7070			
Resid. area								-0.9171

Table 6.8 Summary of the correlation coefficients with values greater than ±0.7071 and 95% significance.

It is interesting that the strongest correlation coefficient values occur between variables associated with the equivalent population and the total area. Total area, equivalent population and DWF were all expected to have fairly strong associations with the other catchment data, unfortunately they do not relate to any of the four sub-sample analysis groups: floaters, residue, light and heavy.

Multiple regression of the four groups against the catchment characteristics was then carried out on this sample set. This produced equations that provided a poorer model than for the complete set of test sites. It is of interest to note that the errors appeared in the same pattern as for all the sites (see table 6.7): the floater and light sub-sample masses had large errors and the heavy and residue sub-samples had much lower errors.

2) (2-5.9) × DWF

Eleven of the tests were sampled when the flow into the treatment works was between 2 and 5.9 DWF. The correlation coefficients for all the variable pairs in this set are tabulated in Appendix E.5. A summary of the correlation coefficients with values greater than ±0.7071 and more than 95% significance is provided in table 6.9 below.

	% residue	% heavy	Equiv. pop.	DWF	System	No. of pump. stns	Total area
DWF			0.9337				
Total area			0.9417		-0.7138	0.8331	
Area comm.	-0.7332		0.8718	0.7836	-0.7436	0.8384	0.8974
Area farmland		-0.8543					
Area resid.					-0.7506	0.7617	

Table 6.9 Summary of the correlation coefficients with values greater than ±0.7071 and 95% significance.

The strongest relationships occur between the equivalent population, the total area and DWF. This is a similar trend to the all tests and (1-2) DWF analyses. It should be remembered that with a smaller set of results the accuracy of the analysis may be reduced.

Multiple regression of the four fractions against the catchment characteristics produced a weaker model than for (1-2) × DWF.

3) (1-5.9) × DWF

Thirty two tests had flows between 1 and 5.9 DWF. The table of correlation coefficients for this set is included in Appendix E.6. A summary of the correlation coefficients with values greater than ±0.7071 is provided in table 6.10 below.

	% floaters	Equiv. pop.	DWF	Sewer system	No. of pump. stns
% light	0.7921				
DWF		0.9960			
No. p. stns		0.9384	0.9308		
Total area		0.9948	0.9890		0.9321
Area comm.				0.7174	

Table 6.10 Correlation coefficients greater than ±0.7071 and with 95% significance for sites with (1-5.9) DWF at time of sampling.

Table 6.10 is interesting when compared to table 6.6, which summarises the 95% significant correlation coefficients for all the tests. In table 6.6, the only correlation coefficient greater than 0.7071 at 95% significance was between the floating and light groups of sub-sample mass. In this set of tests, which excludes the tests carried out on storm sewage, the only relationship between the groups is on the same pair of groups:

floating and light. However, in addition to this there are several relationships between the catchment characteristics, although none relate to the sub-sample groups. The tendency for the highest degree of association between DWF, total area and the equivalent population is continued in this sub set of results.

When the pairs of catchment characteristics in table 6.10 are compared to those in table 6.1, which summarises the 95% significant correlation coefficients for all the test sites, some interesting points arise. The only pairs of catchment characteristics that appear in both tables are DWF with total area and number of pumping stations with total area. In both cases the correlation coefficients for these pairs had high values. There were several variable pairs in both the catchment site analysis and the flow analysis (table 6.10) that had high correlation coefficients. The fact that there were not more significant (95%) correlating pairs common to both sets was not as expected because the majority of the test sites in the study have been included in this set of results. This shows that for the tests carried out, there is very little continuity in the results.

Multiple regression of the four groups against the catchment characteristics was then carried out on this set of tests. The relationships for the groups were almost identical to those for all flows (equations 6.1 to 6.4). This is not surprising because there was only one case of storm flow to be removed from the data set prior to analysis. It does show that the inclusion of a single storm water settling velocity distribution did not greatly affect the resultant linear relationship.

4) Storm flow

This set only contained one set of data and so no correlation coefficients could be calculated and no multiple regression could be carried out. Therefore, on the basis of the available data no conclusions on the relationship between the effect of the catchment characteristics and the settling velocity grading of storm sewage could be drawn. Since this was not one of the original project objectives it is not of particular concern. For storm sewage the variation in the settling velocities of are even greater than that of DWF sewage due to its highly changeable nature (see chapter 2).

6.3.1.3 Peak and trough mass values and the velocities at which they occurred

The peak and trough values of the sinker sub-sample masses (see figures 6.9a and b) and the settling velocities at which they occurred were noted and included in the analysis. Correlation coefficients were calculated between these peak and trough mass values and the velocities at which they occurred, both with each other and with the catchment characteristics. This was carried out first for tests where samples had been taken at DWF into the treatment works and then for all tests. Full tables of these correlation coefficients can be seen in Appendix F.

Multiple regression equations were calculated for the peak and trough mass values and for the settling velocities at which they occurred with all the catchment variables to determine the linear relationship at 95% significance.

1) DWF

There were 12 cases found in the analysis with DWF. Only one correlation coefficient was calculated greater than ±0.7071, as can be seen from table 6.11 below. The t-test value proved this pair to be 99% significant.

	Trough in mass as % of total mass
Peak in mass as % of total mass	-0.7825

Table 6.11 Correlation coefficient greater than ±0.7071 for velocities at which peak and trough mass occurred at DWF.

The relationship between the peak and trough mass values appears to be a logical one. As the percentage of the particles that settle at the peak of the sub-sample mass increases, the trough in the percentage mass at a slower fall velocity decreases. The most likely explanation would appear to be that when the peak in the mass has a large value, a large proportion of the particles have already settled out and so at the following settling velocities, there is a smaller percentage of the total mass left to be removed. This would mean that the mass of suspended solids measured at the trough in the bar chart would have a lower value than if the peak mass of SS was a low value. This can be observed by visual comparison of the bar charts in Appendix D. Not all of the tests exhibit this trend, but it should be borne in mind that the coefficient of determination in this case is 0.612, i.e. 38.8% of the results cannot be explained by the linear relationship between these two variables.

Multiple regression of the peak and trough mass and settling velocity values with the catchment parameters produced the following relationships.

At 95% significance:

$$\text{peak} = 14.70 - (2.469 \times \text{trough}) + (4.97 \times \text{system}) \qquad \text{eqn 6.11}$$

$$\text{trough} = 7.00 - (0.224 \times \text{peak}) \qquad \text{eqn 6.12}$$

$$\text{peakvel} = 2.23 + (0.078 \times \text{ind}) \qquad \text{eqn 6.13}$$

At 90% significance:

$$\text{trouvel} = 0.523 + (0.073 \times \text{system}) \qquad \text{eqn 6.14}$$

where:

peak = peak mass value of the sinking fraction (g)
trough = trough mass value of the sinking fraction (g)
peakvel = velocity at which peak mass occurred (mm/sec)
trouvel = velocity at which trough mass occurred (mm/sec)
system = system type i.e. combined or separate
ind = area of industry as a percentage of the total catchment area

Because of the inter-relationship of the above equations, multiple regression equations for the peak and trough values and the peak velocity with the catchment characteristics were produced.

At 90% significance:

$$\text{peak} = (15 \times \text{system}) + (2\times10^{-5} \times \text{sewer}) + (0.699 \times \text{park}) - (0.917 \times \text{comm}) - (2.7\times10^{-4} \times \text{area}) - 16.52 \qquad \text{eqn 6.15}$$

$$\text{trough} = 3.17 - (1.96\times10^{-6} \times \text{sewer}) \qquad \text{eqn 6.16}$$

To prove the model equations, the predicted values of the peak, trough, peak velocity and trough velocity for each DWF settling velocity distribution has been calculated and compared with the real test results. Equation 6.15 has been used to calculate the peak value of the sub-sample mass. Equations 6.12, 6.13 and 6.14 have then been used to calculate the values of the trough value of sub-sample mass and the velocities at which the peak and trough mass occur. The results are shown in tables 6.12 and 6.13.

The model relationships for the peak and trough in the sub-sample mass of the sinking fraction at DWF, and the velocities at which they occurred have very large errors associated with them. For this reason it would be considered reasonable to conclude that using this model is not a feasible method of gaining accurate information on the settling velocity distribution of DWF sewage at the point that it enters the wastewater treatment works.

TEST REF.	CALCULATED PEAK MASS VALUE	CALCULATED TROUGH MASS VALUE	OBSERVED PEAK MASS VALUE	OBSERVED TROUGH MASS VALUE
1	19.9	2.5	23.49	1.17
2	17.8	3.0	20.76	1.65
4i	18.4	2.9	21.19	1.21
5	11.1	4.5	12.00	3.7
7	23.3	1.8	26.33	2.04
12	20.3	2.4	19.23	2.64
13	22.0	2.1	22.35	2.26
14	-12.3	9.8	20.35	1.46
18	13.9	3.9	13.98	5.33
19	13.7	3.9	13.98	4.57
21	13.4	4.0	11.64	4.62
24	-15.9	10.6	10.86	2.68
25	-1.6	7.3	14.72	2.56
26	19.8	2.6	19.83	0.87

Table 6.12 Comparison of the predicted and real values of the peaks and troughs in the sub-sample masses at DWF.

TEST REF.	CALCULATED PEAKVEL	CALCULATED TROUVEL	OBSERVED PEAKVEL	OBSERVED TROUVEL
1	91.36	0.67	2.71	0.68
2	79.73	0.67	2.71	0.68
4i	79.73	0.67	2.71	0.68
5	56.48	0.67	2.71	0.68
7	17.73	0.74	2.71	0.9
12	79.73	0.74	2.71	0.68
13	2.23	0.67	2.71	0.68
14	13.08	0.52	2.71	0.68
18	171.96	0.67	2.71	0.68
19	273.48	0.67	5.42	0.68
21	17.73	0.67	1.35	0.68
24	25.48	0.52	2.71	0.68
25	2.23	0.60	2.71	0.68
26	87.48	0.67	5.42	0.68

Table 6.13 Comparison of the predicted and real values of the velocities at which the peak and trough masses occurred at DWF.

2) All flows

When all 33 tests were analysed there were no correlation coefficients greater than -0.4907 for the peak and trough mass values and the velocities at which they occurred with any of the catchment characteristics. The linear association between the peak and trough values was reduced to -0.4165, which produces a coefficient of determination of 0.173, which is very low. It must therefore be assumed that the distribution of the masses within storm flows do have a different relationship to the DWF, and so distort the results.

The multiple regression analysis did produce some equations for the peak and trough percentage masses at 95% significance, but the equations for 'peakvel' and 'trouvel' were produced at lower significance levels.

At 95% significance:

$$\text{peak} = 25.68 - (2.282 \times \text{trough}) - (0.319 \times \text{park}) \qquad \text{eqn 6.17}$$

$$\text{trough} = 3.39 - (0.039 \times \text{farm}) - (0.084 \times \text{peak}) + (1.05 \times \text{pumped}) \qquad \text{eqn 6.18}$$

At 90% significance:

$$\text{peakvel} = 3.05 + (0.107 \times \text{imp}) \qquad \text{eqn 6.19}$$

At 80% significance:

$$\text{trouvel} = 0.714 - (0.004 \times \text{park}) - (6.00\times10^{-8} \times \text{sewer}) \qquad \text{eqn 6.20}$$

It is interesting when comparing equations 6.11 and 6.12 with 6.17 and 6.18, the pairs of peak and trough values at DWF and for all tests, that the values of peak and trough mass have less influence on each other when all the test results are used than when just DWF only tests are analysed. This agrees with the indications given by the values of the correlation coefficients, that the storm sewage appears to weaken the relationship between peak and trough mass values. Again the velocity at which the peak and trough values occur do not appear, from the analysis, to associate with anything.

Multiple regression of the peak and trough values with the catchment characteristics produced the following relationships.

At 95% significance:

$$\text{trough} = 1.93 - (0.041 \times \text{farm}) + (1.16 \times \text{pumped}) - (1.13\times10^{-6} \times \text{pop}) \quad \text{eqn 6.21}$$

At 90% significance:

$$\text{peak} = 16.21 + (0.362 \times \text{comm}) \quad \text{eqn 6.22}$$

When the model relationships were proved, equation 6.21 was used to calculate the trough values for all the tests. This was chosen over calculating the peak value from equation 6.22 because it had been developed at a higher level of significance. The results of the comparison study are shown in tables 6.14 and 6.15.

The results of the analysis for the peak and trough values of the sinker sub-sample appear to be more consistent when all the tests are considered than when DWF samples are considered alone. The same applies for the prediction of the settling velocities at which the peak masses occur. However, considering the small range in the real values of peak, trough, peakvel and trouvel, the errors do appear to be high and this can be illustrated by the extreme scatter in results when the calculated and predicted values of the peak in sub-sample mass and the velocities at which the peak in the sub-sample mass occurs are plotted for all tests (figures 6.11 and 6.12). This analysis may provide some indication of the likely values of the peak and trough values of the sub-sample mass and the velocities at which they occurred, but it would be unwise to use it as the basis for any design.

TEST REF.	CALCULATED PEAK	CALCULATED TROUGH	OBSERVED PEAK	OBSERVED TROUGH
1	21.38	1.60	23.49	1.17
1s	21.38	1.60	19.64	2.33
2	18.31	2.53	20.76	1.65
3	18.30	2.96	14.95	0
4	21.86	1.68	21.71	1.32
4i	21.86	1.68	21.19	1.21
4iii	21.86	1.68	21.89	2.45
5	18.76	3.03	12	3.7
7	17.35	2.95	26.33	2.04
8	16.96	2.98	19.31	2.79
9	17.43	3.62	30.22	1.65
10s	18.66	3.08	17.34	3.2
11	18.70	3.06	20.4	3.47
12	19.17	2.85	19.23	2.64
13	15.52	3.05	22.35	2.26
14	22.34	0.58	20.35	1.46
15	18.68	3.07	17.02	3.22
16	18.66	3.08	18.77	3.32
17	17.74	1.53	12.66	1.81
18	16.00	4.24	13.98	5.33
19	19.13	2.87	13.98	4.57
20	16.00	4.24	13.78	4.11
21	12.87	4.22	11.64	4.62
22	1.18	3.08	9.78	7.13
22s	1.18	3.08	22.93	3.87
23	16.01	4.24	18.78	4.83
24	21.09	1.90	10.86	2.68
25	25.07	0.27	14.72	2.56
26	19.06	1.67	19.83	0.87
28	17.74	1.65	6.82	1.8
29	10.41	2.31	14.99	2.82
30	17.98	2.26	9.19	1.57

Table 6.14 Comparison of the predicted and real values of the peaks and troughs in the sub-sample mass for all tests.

TEST REF.	CALCULATED PEAKVEL	CALCULATED TROUVEL	OBSERVED PEAKVEL	OBSERVED TROUVEL
1	3.09	0.63	2.71	0.68
1s	3.09	0.63	1.35	0.68
2	3.07	0.67	2.71	0.68
3	3.05	0.70	0.45	0
4	3.05	0.65	2.71	0.45
4i	3.05	0.65	2.71	0.68
4iii	3.05	0.65	2.71	0.68
5	3.05	0.71	2.71	0.68
7	3.05	0.68	2.71	0.9
8	3.05	0.69	2.71	0.68
9	3.05	0.71	2.71	0.68
10s	3.05	0.71	2.71	0.68
11	3.05	0.70	9.03	0.68
12	3.05	0.71	2.71	0.68
13	3.05	0.67	2.71	0.68
14	3.05	0.69	2.71	0.68
15	3.53	0.71	2.71	0.68
16	5.19	0.71	5.42	0.68
17	3.46	0.65	2.58	0.68
18	3.05	0.71	2.71	0.68
19	3.05	0.71	5.42	0.68
20	5.16	0.71	5.42	0.68
21	3.05	0.67	1.35	0.68
22	3.05	0.48	0.9	0.68
22s	3.05	0.48	1.35	0.9
23	3.05	0.71	1.35	0.68
24	3.05	0.71	2.71	0.68
25	3.26	0.71	2.71	0.68
26	3.05	0.68	5.42	0.68
28	3.05	0.66	2.71	0.68
29	3.34	0.58	2.71	0.45
30	3.05	0.68	2.71	0.9

Table 6.15 Comparison of the predicted and real values of the velocities at which the peak and trough masses occurred for all tests.

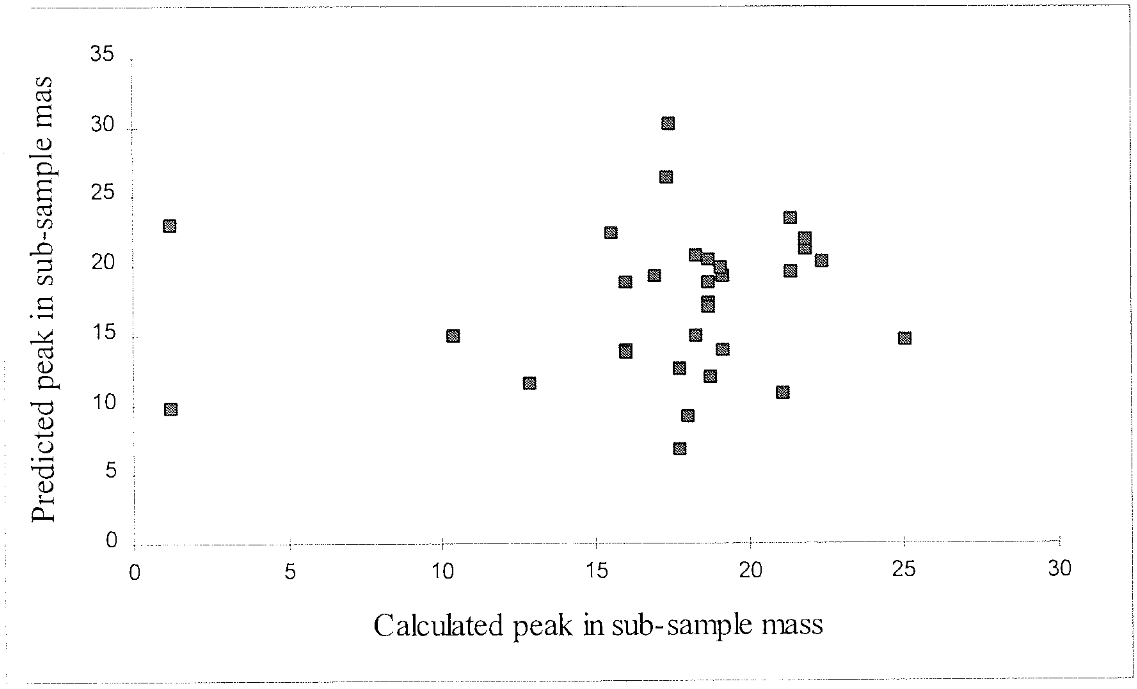

Figure 6.11 Scatter plot of the calculated values against the predicted values for the peak in sub-sample mass for all tests.

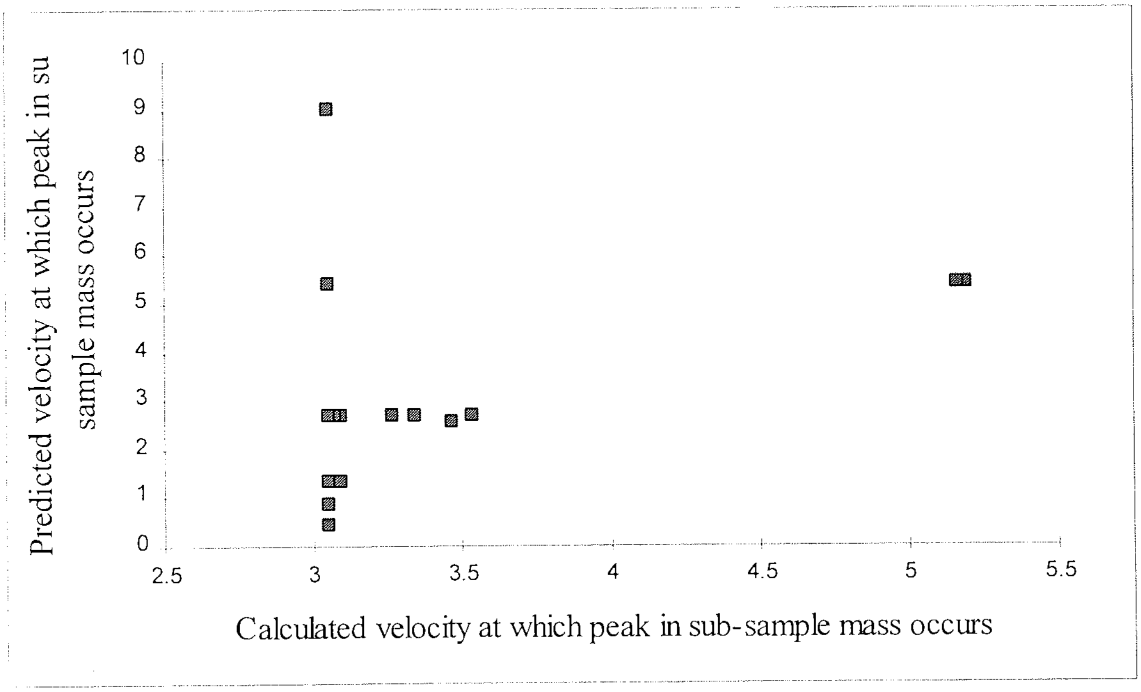

Figure 6.12 Scatter plot of the calculated values against the predicted values for the velocity at which the peak in sub-sample mass occurs for all tests.

6.3.2 Curve fitting

The general shape of the settling velocity grading curve can be modelled by the equation:

$$y = 1 - \frac{a}{\left(a + x^{b}\right)} \qquad \text{eqn 6.23}$$

where:

y represents the percentage fraction of the total mass of suspended solids with settling velocities less than a particular value;

x represents the settling velocity; and

a and b are empirical constants.

This is a modification of the Brooks and Corey equation (Brooks and Corey, 1964) used by Binley (1986) to describe observed soil moisture characteristics. The Brooks and Corey equation was chosen because it has a similar shape to the settling velocity grading curve when rotated through 90°, in that it is asymptotic to limiting y-values (0% and 100%) instead of x-values (see figure 6.13).

Consideration was given to the use of other equations, such as a quadratic equation, to describe the settling velocity grading curve. However, no suitable polynomial was obtained in that none of them were asymptotic to the limiting y-values and in many cases a good curve fit was only obtained when the polynomial was able to exceed 100% before returning to fit any remaining points. This line of investigation was not pursued.

Another way of expressing y, the percentage fraction, is shown below:

$$\mathrm{PF} = \left(\frac{\mathrm{P} - \mathrm{P_r}}{\mathrm{P_m} - \mathrm{P_r}}\right) \qquad \text{eqn 6.24}$$

where:

PF = percentage fraction

P = actual percentage value

P_r = residual percentage

P_m = maximum percentage

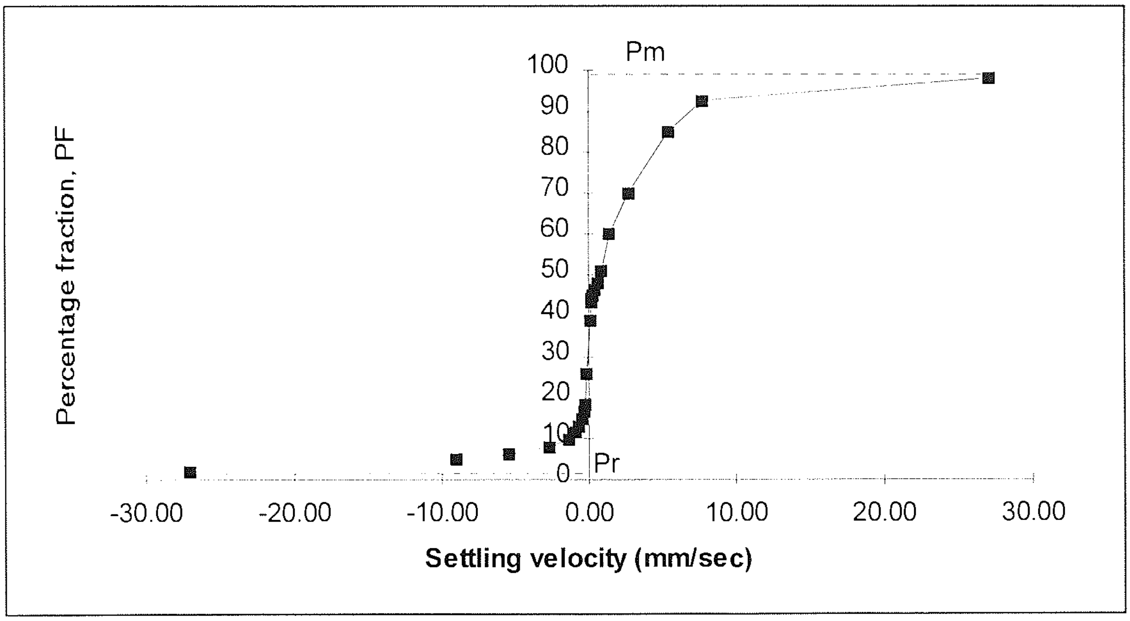

Figure 6.13 Typical settling velocity grading curve.

Revising equation 6.23 in terms of settling velocity grading parameters and substituting for equation 6.24:

$$PF = \left(\frac{P - P_r}{P_m - P_r} \right) = 1 - \frac{a}{\left(a + u_s^{\ b}\right)} \qquad \text{eqn 6.25}$$

If $P_m = 100$

and $P_r = 0$

$\Rightarrow$ PF = 1 if the percentage fraction being measured represents all the particles.

therefore:

$$P = \left[1 - \left(\frac{a}{a + u_s^{\ b}} \right) \right] \left(P_m - P_r\right) + P_r \qquad \text{eqn 6.26}$$

The Gauss-Newton method of least squares was used to fit equation 6.26 to each settling velocity data set as described by Dixon (1974). As a result the values of constants a and b were derived for each set of data and the values obtained are tabulated in table 6.16. During the curve fitting procedure there were great differences in the sensitivity of the curve fit to the values of a and b. A large change in the value of a had a small effect on the value of the sum of the squares, whilst a relatively small change in the value of b had a great effect on the value of the sum of the squares.

Test ref.	a	b
1	130800	11
1s	7870000	15.01
2	74000	10.17
3	5.00E+46	103.02
4	16230	9.089
4iii	103000	10.409
5	3.46E+08	18.79
6	5554560	14.19
8	27131350	16.04
9	5.57E+08	18.36
10s	1088830	12.89
11	4418	7.49
12	402614	12.25
14	219630	11.64
15	39860	9.54
16	96391	10.57
17	218950	12.3
18	3.27E+08	18.26
19	418250	11.86
20	814560	12.78
21	8.12E+10	24
22	1.10E+23	51
22c	50129600	16.7
23	4.51E+12	27.6
24	1560000	14
25	3.91E+10	23.3
26	6186	8.14
28	4.9E+08	20.06
29	41407	9.98
30	192278	12.4

Table 6.16 Values of a and b derived from the curve fitting analysis.

The correlation between the constants a and b and the catchment characteristics were calculated for all the tests, the tabulated results are given in Appendix G.1. The only correlation coefficient greater than ± 0.4 was between a and b. The correlation coefficient, r = 0.8878, indicates a fairly strong linear relationship between a and b and accounts for 78.8% of the results obtained. All the remaining correlation coefficients had values less than 0.4, which meant that less than 16% of results for each catchment characteristic had a linear relationship with the constants a or b. When multiple regression was used to determine relationships between a and b and the catchment characteristics, no variables were entered into the calculations due to their low levels of significance. At 95% significance the only relationship was between a and b, as expected from the poor correlation coefficients and levels of significance.

When the values of the constants a and b were studied, it appeared that two of the pairs of constants were very much outside the rest of the set of results. It was considered that these two sets of results should be removed and the remaining values recalculated to determine if a relationship was present. The correlation between a and b was in fact reduced to 0.5298 by this action, with the coefficient of determination reduced to 0.28. This is an extremely low level (28%) at which results can be considered to be governed by a linear relationship. The remaining correlations were all very weak. When the correlation coefficients of the full set and the reduced set were compared, the coefficients differed both in their values, with some increasing, some decreasing and in their being either positive or negative. These values were therefore discounted as no relationship was found. The values of the correlation coefficients between the constants a and b and the catchment characteristics for the full set and the reduced set of sites are included in Appendix G.2.

Out of interest multiple regression calculations were carried out on this reduced set. The significance limits were gradually reduced from 95% down to 80% for the multiple regression between a and b and the catchment characteristics in order to determine a relationship between one or other of the constants and the variables.

The relationship that exists between a and b remained the same at all significance levels:

$$b = 12.45 + \left(1.43 \times 10^{-10}\right)a \qquad \text{eqn 6.27}$$

No other variables were introduced into the equation at the reduced significance. This was not surprising due to the greater strength of the relationship between a and b when considering the correlation coefficients.

At 90% significance, when a and b were removed as independent variables from the calculations:

> No linear relationship existed between the constant a and the catchment characteristics.

$$b = 19.12 - (3.55 \times pump) \qquad \text{eqn 6.28}$$

where:

$pump$ = pumped or gravity fed sewer system: pumped system = 1
gravity fed system = 2

At 80% significance, if a and b are removed as independent variables from the calculations:

$$a = (9.49 \times 10^{9}) - (17.55 \times 10^{9}) pump + (10.00 \times 10^{9}) system \qquad \text{eqn 6.29}$$

where:

$pump$ = pumped or gravity fed sewer system: pumped system = 1
gravity fed system = 2

$system$ = system type: separate = 1
partially separate = 2
combined = 3

and, as before:

$$b = 19.12 - (3.55 \times pump) \qquad \text{eqn 6.30}$$

To test out these relationships, the values of a and b were calculated and then used in equation 6.46 to determine the percentage fraction of suspended solids with a settling velocity less than a particular value. The resulting grading curves were then plotted onto the actual curves to show how well the model fitted the real results. This was first carried out using b as the constant that related to the catchment characteristics because this relationship (equation 6.28) was developed at 90% significance. A typical result of this is shown in figure 6.14 below.

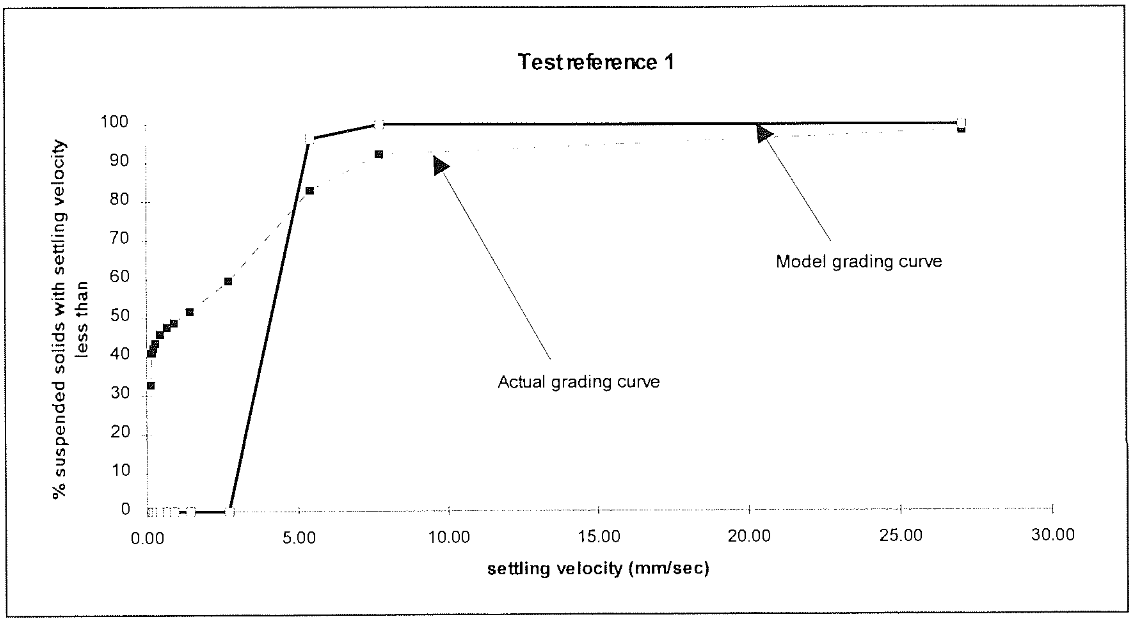

Figure 6.14 Settling velocity grading curve for test reference 1 showing the model curve fit.

As can be seen the curve fit is very poor. There is virtually no fit at all except in the general shape of the curve in the region of high settling velocity. This might be explained by the fact that the catchment variable in the calculation of b could only be one of two values, i.e. the system was either pumped or gravity fed. There was not enough flexibility in this value to create a wider range of curves. The set could have been broken down for separate analysis of the curves for catchments that were either pumped or gravity fed, however, the significance levels were already very low and with a smaller set of results the accuracy was likely to be reduced even further based on the experience of previous analysis.

When the process was repeated using a as the constant that was related to the catchment characteristics, the results were even worse. This was not unexpected because of the lower significance levels of the relationship combined with the inflexibility in the catchment characteristics incorporated into the equation as the independent variables. This time the system was either pumped or gravity fed, and combined or separate.

A similar multiple regression analysis was undertaken using the fist principal component identified in section 6.2.2. The first principal component was chosen because it describes almost 70% of the variation in the catchment data and relates to the catchment size. The analysis did not produce any relationship between a and b and the principal component down to a significance level of 50%. The second and third principal components produced relationships similar to the straightforward regression analysis in equations 6.27 to 6.30. There appears therefore to be no relationship between the settling velocity grading and the catchment size.

It has to be concluded that this method of curve fitting has not successfully produced a reliable method of relating catchment characteristics to the form of a settling velocity grading curve using the limited amount of data available.

6.3.3 Analysis of slope gradient

Having failed to find a relationship between the catchment characteristics and the constants of the settling velocity grading curve, it was decided that looking at the gradient of the curve in the region of positive settling velocity might reveal some information. There are similarities between sewage grading curves and the particle size distribution curves used in soil mechanics and sediment transport. When considering particle size distributions the Uniformity Coefficient (U) is used to determine the ratio of the diameters of 60% and 10% of particles. This is a measure of the gradient and hence is an indication of the uniformity of the particle size distribution plotted on a logarithmic scale. When this principle was transferred to the sewage grading curves, it was decided from inspection that the settling velocities at 40% and 90% of total mass should be used because they represented the bounds of a region with a fairly constant gradient that was present on most of the curves. An example of this can be seen in figure 6.15.

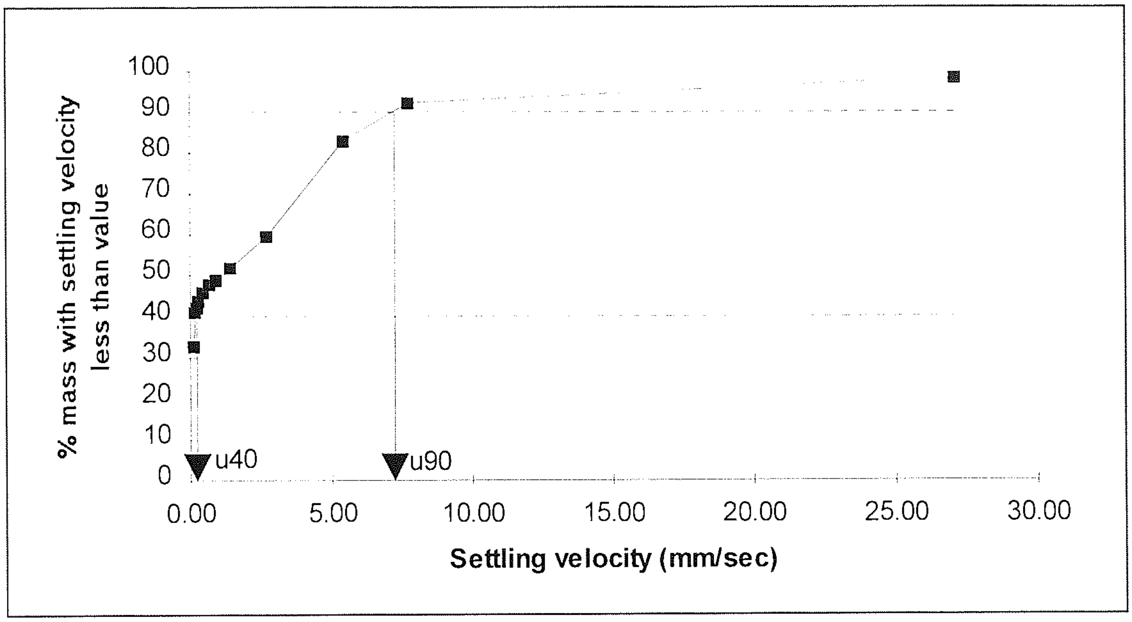

Figure 6.15 Settling velocity grading curve for test reference 1 to show limits taken for the uniformity coefficient for settling velocity grading, C_v.

Having determined the velocities u_{40} and u_{90} by interpolation, the uniformity coefficient for settling velocity grading, C_v, was calculated for each curve as:

$$C_v = \frac{u_{90}}{u_{40}} \qquad \text{eqn 6.31}$$

Using SPSS the correlation coefficients were calculated for the velocities u_{40} and u_{90} and the uniformity coefficient for settling velocity grading, C_v, together with the catchment characteristics. The full table of coefficients is provided in Appendix H, but all the coefficients between the catchment characteristics and u_{40}, u_{90} and the velocity coefficient had very low values. Even the linear relationships between the velocity coefficient and the 40% and 90% velocity values were not strong, as can be seen from table 6.17.

	Velocity coefficient, C_v	u_{40}
u_{40}	-0.6196	
u_{90}	-0.0215	0.5022

Table 6.17 Correlation coefficients between the uniformity coefficient for settling velocity grading and its determinants.

A multiple regression calculation between the uniformity coefficient for settling velocity grading and the catchment characteristics was executed, but as expected from the low correlation coefficient values no significant linear relationship was found.

It has to be concluded that for the values chosen, there appears to be no relationship between the gradient of the settling velocity grading curve and the catchment characteristics.

6.4 THE ENVELOPES FORMED BY THE SETTLING VELOCITY GRADING CURVES

The initial hypothesis at the start of the project was that there was a relationship between the settling velocity grading curve and the characteristics of the contributing catchment. In particular it was believed that there was a relationship between the size of the catchment and the settling velocity grading distribution, partly as a result of the length of time and the distance that the sewage travelled in the sewer system (Smisson, 1990 and Andoh, 1994). This hypothesis that the catchment characteristics influence the sewage settling velocity grading was not proven in this study, however there is an envelope within which all the grading curves fell, as illustrated in figure 6.16. The maximum, minimum and mean values of all the settling velocity grading data within this envelope is shown in figure 6.17.

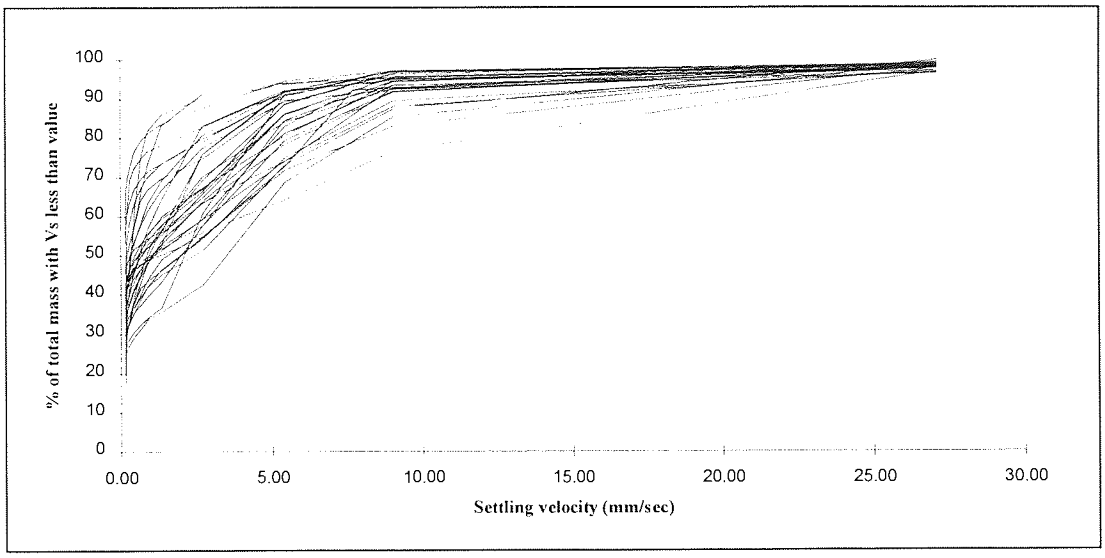

Figure 6.16 Envelope of all the settling velocity grading curves

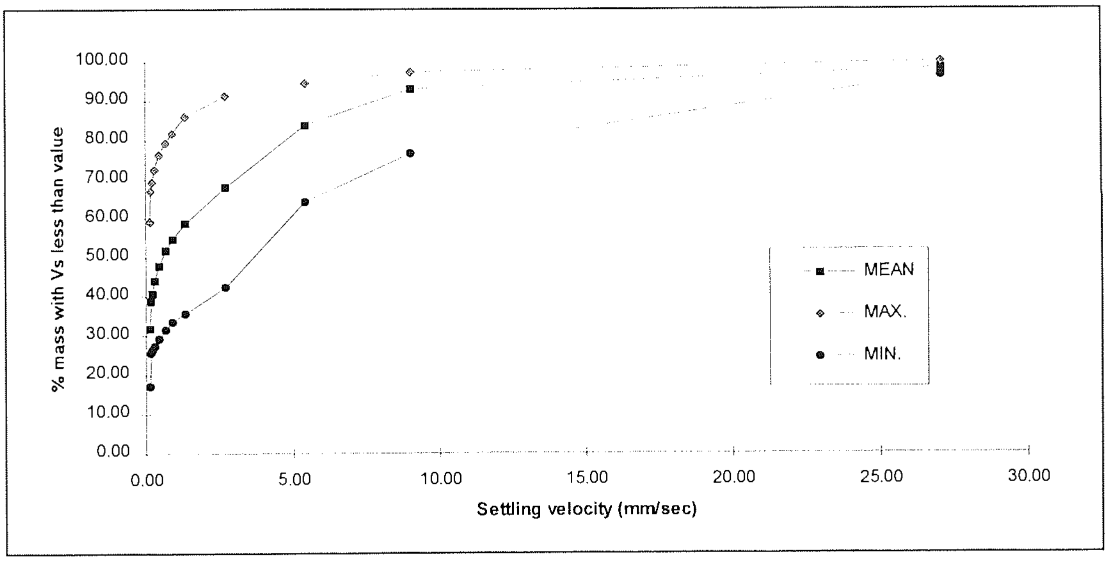

Figure 6.17 Maximum, minimum and mean settling velocity grading curves from all the settling velocity distribution data.

To confirm that there was a wide scatter in the settling velocity distributions, regardless of catchment area, the catchments were classified as large, medium and small on the basis of flow rate to the treatment works as indicated in table 6.18.

Flow rate (l/sec)	Catchment size	No. of sites
> 1000	large	2
10 - 1000	medium	22
0 - 10	small	5

Table 6.18 Catchment size defined in terms of DWF to the wastewater treatment works.

As can be clearly seen from table 6.18, most of the sites in this study fall within the medium sized category. There was a very marked difference between the medium and large categories, with no sites in the medium category having a flow rate above 500 l/sec.

To illustrate that the settling velocity gradings were not influenced by catchment area, the data has been separated by catchment size in figures 6.18, 6.19 and 6.20. It can be clearly seen that the settling velocity gradings are distributed evenly around the mean settling velocity grading. This supports the findings of the statistical and curve fitting analysis that there is no significant relationship between the settling velocity distribution and the area of the contributing catchment.

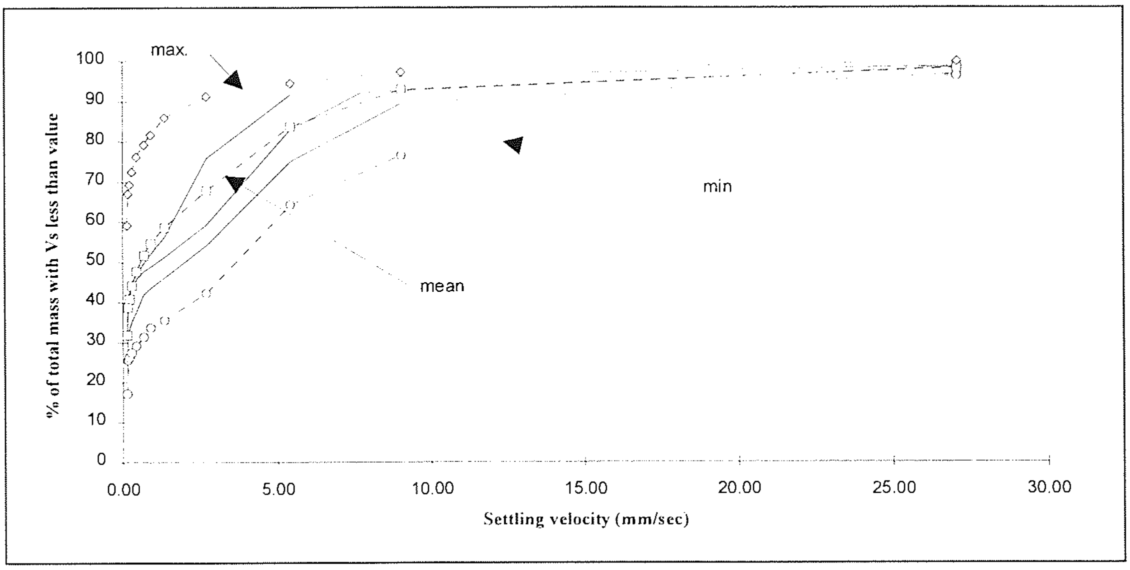

Figure 6.18 Settling velocity distributions for large catchments with the boundaries of the settling velocity grading envelope superimposed.

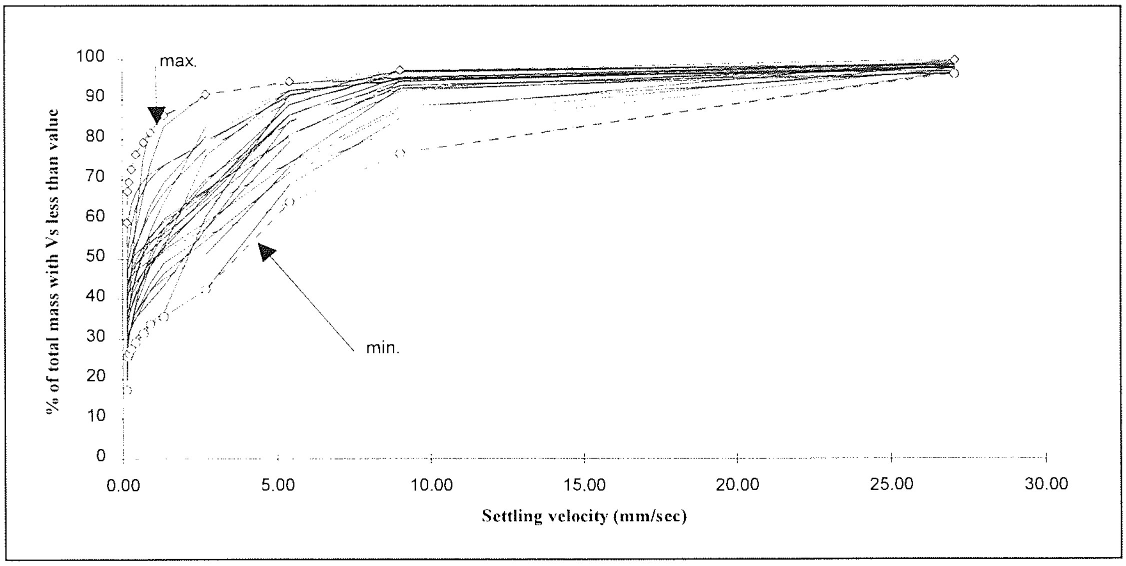

Figure 6.19 Settling velocity distributions for medium sized catchments with the boundaries of the settling velocity grading envelope superimposed.

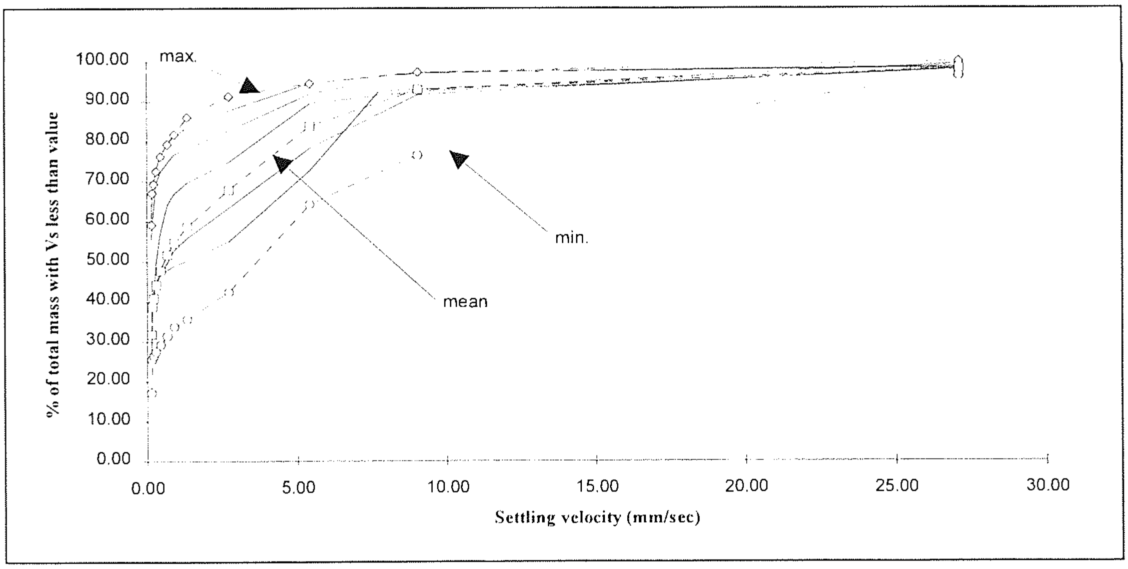

Figure 6.20 Settling velocity distributions for small catchments with the boundaries of the settling velocity grading envelope superimposed.

With all the settling velocity grading curves falling within well defined upper and lower bounds, it is possible to produce equations for these limits using the same curve equation (equation 6.23) as used in the analysis in section 6.3.2.

For the upper bound:

$$y = 1 - \frac{4.4 \times 10^{11}}{(4.4 \times 10^{11} + x^{27.25})} \qquad \text{eqn 6.32}$$

For the lower bound:

$$y = 1 - \frac{25800}{(25800 + x^{8.8})} \qquad \text{eqn 6.33}$$

The equation for the mean settling velocity grading curve:

$$y = 1 - \frac{575000}{(575000 + x^{12.7})} \qquad \text{eqn 6.34}$$

These equations can be used to determine the limits within which a settling velocity grading curve will fall when using the test method developed in this project.

6.5 ANALYSIS OF THE ORGANIC/INORGANIC ELEMENT OF THE SUSPENDED SOLIDS

As discussed in chapter 4, section 4.3, the proportion of organic to inorganic material in each of the sub-samples were determined by heating the filtered sub-samples to 500° ± 50°C to allow the organic element to be burnt off. The percentage of organic material within each sub-sample was determined and a mean value was then calculated for each site. Table 6.19 shows the summary of the percentage of organic material within each test sample along with the values of the main catchment characteristics for the appropriate site.

The very low percentage of organic material in test reference 28 is unusual, but it was noted during the experiment that the sample was very "sandy" with very fast sinking particles and no visible floaters. All the sub-samples and the crude sample filtered very fast. The notes indicate that there was a very low organics content in the sample which would explain the low value shown in table 6.19. This low organics value may be in part due to some loose granular bed material being captured in the sample bucket, or that there was a high degree of infiltration in a sandy catchment.

Test reference	Mean organics (as % of total mass)	Equivalent population	DWF (l/s)	Sewer length (m)	Total area (ha)
1s	77.7	1315325	5208	1198066	34754
2	66.9	380000	1296	400000	9700
3	83.4	118300	485	89536	3270
4	84.4	150000	428	1000000	5000
4iii	74.5	150000	428	1000000	5000
5	58.8	52165	355	37830	1295
6	78.5	90000	270	5300	5500
8	79.7	96000	210	9584	2485
9	59.5	14250	151	32980	450
10s	81.9	12000	99	2340	379
11	86.2	29000	80.3	157000	810
12	97.2	23000	80	60580	750
14	74.6	14200	66.1	1235	872
15	70.3	21300	53.4	24066	1400
16	69.8	12500	51	3750	500
17	82.6	15000	47.5	33450	630
18	80.5	8000	34	27600	400
19	63.5	12595	33	14309	400
20	79.3	9000	32	3940	249
21	86.9	28255	28	18693	300
22	70.7	9414	28	22800	230
22c	81.5	9414	28	22800	230
23	77.2	12700	18.9		
24	74.8		14	7720	265
25	85.1	1850	5.8	5100	500
26	80.5	1810	4.36	7330	91
28	29.3	685	1.06	1520	35
29	86.1	685	1.06	8920	220
30	82.6	250	0.46	1390	20

Table 6.19 Average values of the organics element of the suspended solids for each site along with the main catchment characteristics.

The Pearson correlation coefficient for each of the catchment characteristics paired with the mean organics was calculated, their values are shown in table 6.20. As can be seen from the table, all the correlation coefficients have very low values and therefore it can be concluded that there is no detectable linear relationship between the percentage of organic/inorganic material in the suspended solids and the characteristics of the contributing catchment.

Equivalent population	DWF	Sewer length	Total area
0.054	0.042	0.088	0.060

Table 6.20 Correlation coefficients of each of the main catchment characteristics with the mean organics values.

6.6 SUMMARY

To understand the full meaning of both the catchment data and the settling velocity grading data a complete analysis was carried out. The catchment data were analysed to determine if any relationships existed between the catchment characteristics. This was important for the subsequent analysis of the settling velocity grading data because if no relationships were found to be present between the catchment characteristics it might prove difficult to determine a relationship between them and the settling velocity grading data. The strongest linear relationships found were between variables paired with the total area of the catchment, as was anticipated. This trend was confirmed by a principal component analysis which produced three principal components which accounted for 88% of the total variation in the data. The first principal component explained 69.2% of the variation in the data and was associated with the size of the catchment. Plotting this first principal component against the other two clearly identified the largest sites as having the greatest variation in value.

Analysis of the settling velocity grading data was undertaken in several stages. There were no trends that could be observed by eye for the settling velocity grading curves from different sized catchments. As a result of this, more detailed analysis was carried out on a breakdown of the settling velocity distribution in terms of four groups of settling velocity range. The four groups were analysed with the wastewater treatment works catchment characteristics and some relationships were produced by the application of multiple regression analysis.

A standard curve was fitted to the test data by the method of least squares, and values for the curve constants were obtained. The constants were then analysed by multiple regression against each other and the catchment characteristics until a relationship was obtained from which a curve could be plotted in terms of the catchment characteristics. The predictive curves produced by this method were not accurate enough to be used for any design purposes.

Equations were produced for the upper and lower bounds of the envelope within which all the settling velocity grading curves fell. These equations can be used to define the boundaries within which a settling velocity grading curve will fall when using the test method developed during this project. An expression for the mean settling velocity grading curve was also produced.

Analysis of the organic element of the suspended solids revealed that there was no detectable linear relationship between the mean organics mass for a test sample and each of the characteristics for the contributing catchment.

The conclusions that can be drawn from the analysis that has been carried out on both the catchment data and the settling velocity grading data are first that there is a strong relationship between the size of a catchment and its other characteristics and second that there is not a relationship between the settling velocity grading of sewage and the characteristics of the contributing catchment, but the limits within which a settling velocity grading curve will fall can be clearly defined. These results will be discussed further in chapter 7, along with their implications.

CHAPTER 7

GENERAL DISCUSSION

7.1 INTRODUCTION

Having completed the column development and the analysis of the results, it is now pertinent to discuss the project within the wider framework of both the design of wastewater treatment works and the possible areas of future research. The aim of this project had been to develop a methodology that would enable sewage settling velocity grading curves to be determined from the characteristics of the contributing catchment. The resultant model could then have been used as a tool for evaluating the performance of separation devices. Three objectives were used to achieve this aim:

1) to develop a simple, economic method of determining the grading characteristics of sewage, which may then be used confidently by non specialists;

2) to examine the settling velocity characteristics of sewage samples from a number of different catchment areas and, from these data, to develop a model for predicting sewage grading curves;

3) to examine the potential for using sewage grading curves for designing and/or determining the performance of gravity, or gravity assisted, separation devices.

This chapter discusses how the project aims and objectives were met in terms of its design, limitations, and use to engineers and researchers in the future.

7.2 PROJECT DESIGN

7.2.1 Time constraints

This was quite an ambitious PhD project to approach within a three year time span, but the development of the test procedure was made simpler by the use of an existing piece of apparatus. The application of the prototype column was changed in this project from monitoring discharges from an individual storm overflow, to the determination of the settling velocity grading of any sewage. Although there was a wealth of information on the composition of sewage and its individual elements, there was very little literature available on measuring the settling velocity of all the suspended particles within a sewage simultaneously. One of the consequences of objective (3) was the decision to focus on crude sewage, which is easiest to sample and is the basis upon which separation devices at wastewater treatment works are designed at present. As a result the focus shifted to primary sedimentation tanks, which are close to the inlet to the works, and so the settling velocity measurement test was designed to measure the settling velocities of the particles in conditions that mimicked those that occur at the wastewater treatment plant. The decision to simulate primary settlement processes meant that the fluid and particle activities within the settlement column had to be studied and as a consequence the test method was modified to account for the problems encountered, and wherever possible allowance was made for the unavoidable errors that were incurred in the test. This development procedure had to be limited in order to have enough time to determine the settling velocity grading of samples from as many wastewater treatment works as practical in order to undertake a statistically significant analysis.

The settling velocity test method developed during the project reduced the total test time from the prototype test method, but with the preparation of filter papers, filtering, drying and weighing the sub-samples and sample collection times, only two tests per week could be performed. The original test programme allowed for all of the 33 sites selected to be sampled at least once at DWF, with some allowance for loss of time due to wet weather. However, after a promising start the weather turned very wet for a long period at the end of 1993 and the start of 1994. The programme was therefore modified and samples were taken regardless of the flow conditions to the wastewater treatment works.

At the end of the 12 month sampling programme 33 complete settling velocity gradings had been acquired. This was a smaller number than was originally anticipated, with only 15 samples having been taken at DWF.

7.2.2 The test method

All settling velocity measurement methods have disadvantages. Most have been devised to measure the settling velocity of the sewage or its separated constituents with a particular end use in mind, for example to determine the settling velocity of the inorganic fraction of sewer sediments (Chebbo, 1990), or to measure the settling velocity of activated sludge flocs (White, 1975a and 1975b). Alternative test methods were considered during development of the test and some of their features have been incorporated into the final recommended procedure, for instance, reducing the initial time used to separate the floating and sinking fractions and their subsequent separate measurement.

With all these features taken into consideration there are still several aspects of the test that are regarded as unsatisfactory. The major drawback is having to rotate the column in order to refill the sub-sample cell with clean water. This rotation causes disturbance of the settlement patterns that have developed. It was considered important that the settlement depth be maintained to allow the settlement mechanisms to develop fully at all stages of the test. With the design of the column, the only way of refilling the sub-sample cell without allowing the water column to drop is to rotate the column through 180 degrees until cell B, containing the sub-sample, is at the top of the column. For future projects, it might be possible to devise a method of detaching the end cell for refilling in such a way that there is minimum disturbance to the column contents. This would require considerable thought because air must be prevented from entering the column because its ingress and movement causes a large amount of turbulence.

The most important question that should be asked is whether the test method was suitable for the study in which it was used. The only answer is, that for the situation for which it was employed and developed, i.e. to measure the settling velocity distribution of sewage as it enters the wastewater treatment works for primary treatment, it was regarded the best method available at the time for the reasons given in section 3.4. This statement needs some additional support in that the original specification for the test method was that it should be cheap and easy to use by non technical personnel. This specification was achieved in that the apparatus was constructed from proprietary, off the shelf materials and was simple to construct. The test, with careful use, was easy to operate with repetitive, uncomplicated movements.

The size of the test apparatus was such that a 5 litre sample was required. This "large" sample meant that there was a sufficient mass of solids in each sub-sample to be detected down to the nearest milligramme on the balance, even for those collected from the floating fraction. The mass of suspended solids in the floating fraction was always a small proportion of the total mass of the sinking fraction. A further advantage was that there was a sufficient mass of solids to enable chemical analysis to be undertaken. A sister project is underway at present to investigate the chemical pollutants associated with solids within the settling velocity ranges of the grading curve.

The final test results were obtained within 2 days from the time of sampling, including transport back to the laboratory and overnight storage. This is quite adequate for sewage treatment works design purposes, where immediate results are usually unnecessary. However, if the performance of a treatment process under changing sewage inflow conditions or the effect of adding chemicals to facilitate the treatment process were to be monitored, then obviously a more immediate method of analysis would be required. Currently available methods to meet this requirement are jars tests, the turbidity meter or an Imhoff cone, all of which provide only limited information.

7.2.3 Test performance

Due to the time constraints of this project it was not possible to conduct an extensive programme to prove the reliability of the settling velocity distribution measurement method to produce repeatable results for the same site. However, research undertaken by Baker (1994), which was part supervised by the author, confirmed that the results of different grading tests using the same sewage sample do produce acceptably repeatable results (see section 4.2.4.2, figure 4.3). From Baker's study, the resultant grading curves were almost coincident. It should be remembered that these repeatability tests were carried out on the sewage when it had aged and on only one sample. Considering samples taken from the same site on different occasions, the settling velocity grading curves were of similar shape and position on the y-axis, indicating that the results were repeatable (figure 4.5). With further study, it is likely to be shown that for samples taken on different days, but at similar flow rates and antecedent weather conditions, the resultant settling velocity grading curves are likely to be almost coincident.

7.2.4 Testing storm sewage

Surprisingly, no evidence of a change in sewage composition, in terms of its settling velocity distribution, due to an increase in the flow in combined and partially separate sewers during wet weather conditions has been found. However, it is known that sewage is not simply diluted, but the composition of pollutants changes with time, as discussed in chapter 2. In order to gain a greater understanding of the relationship between the settling velocity grading curve and the variations in flow rate to the wastewater treatment works it would be of benefit to investigate perhaps 2 or 3 different sites in detail, particularly with regard to the change in settling velocity characteristics as a storm event progresses. The results may well be of use in understanding the variation in stormwater characteristics and hence in designing for storm flows to the treatment works.

7.3 RESULTS OF ANALYSIS

7.3.1 Results of the statistical analysis

The relationships between parameters representing the sewage settling velocity gradings and the catchment characteristics that were produced by the various statistical analyses were all very tentative. The catchment characteristics did not immediately exhibit the relationships between them that it was hypothesised would exist, even taking into account the problems encountered in the data collection procedure. A principal component analysis produced a variable that related the catchment data to the size of the catchment. The curve fitting analysis failed to produce a satisfactory relationship between the parameters of the curves that were fitted to the settling velocity distributions and the catchment characteristics. It can be concluded that there is no relationship between the settling velocity grading of a sewage and the characteristics of the contributing catchment.

The only analysis that produced results which may prove useful in the prediction of grading curves was the grouping of the sub-sample mass into four fractions. These fractions were used to produce relationships with the catchment characteristics by multiple regression analysis. The results of all the statistical analyses are discussed further in this section.

7.3.1.1 Catchment data analysis

It was anticipated that there would be a high level of linear association between the different catchment characteristics. In particular, it was anticipated that total catchment area, DWF and equivalent population would be the most probable characteristics to be related to other variables because they define, to a large extent, the design of wastewater treatment works. It was therefore quite a surprise that the level of linear association of these catchment characteristics with the others collected in this study was so low. The total area did indeed prove to have the highest levels of linear association with other catchment characteristics. DWF was highly associated with the total area and the sewer length, which was not unexpected. However, the equivalent population did not have a significant (at 95%) degree of association with any of the catchment characteristics. The principal component analysis confirmed this by producing one main factor that was generally associated with the scaling of size of the catchment.

There were some catchment characteristics, namely the area of farmland, whether the sewerage system was pumped or gravity fed and the type of sewer system, that had a very low correlation coefficient with all the other catchment characteristics. From this it is concluded that these factors were independent of the other catchment characteristics. This is interesting because they were the most common characteristics to appear in the relationships produced by multiple regression in all the analysis carried out. The area of farmland is a strange factor to be included, because often there is no farmland in a catchment. In the catchments where no farmland was present, the errors in predicting the proportion of suspended particles in each of the four sub-sample groups proved to be large (see section 6.3). The other two characteristics were also unexpected in that the sewer system was either pumped or gravity fed, or either combined, separate or partially separate. There was very little variation in the predictions of sub-sample groups for the different catchments when only these three factors were present. These three characteristics were highlighted in the second and third principal components.

All the correlation coefficients were positive, which meant that all the variables increased in value with each other. This result was expected because most of the factors had values that were related to the size of the catchment such as population, sewer length, total area, etc.

To demonstrate that the level of linear association between sites included in the testing programme were typical of a larger sample, an analysis of all the sites on which data was collected was undertaken. This analysis proved that the selected sites were a representative sample of the larger set.

7.3.1.2 Group analysis of sub-sample mass

The most promising relationships between the settling velocity distribution and the catchment characteristics were obtained by combining the sub-sample masses into four groups. The four groups were defined in terms of their settling velocity range: heavy sinkers, light sinkers, residue (neutrally buoyant or very slow settling particles) and floaters. The analysis, using correlation coefficients to determine the level of linear association between pairs of variables and by multiple regression for the linear relationship between all the variables at different significance levels, was first applied to all the settling velocity gradings produced in the test programme. The analysis was then repeated on smaller sub-sets which were determined by the flow to the treatment works at the time of sampling.

The relationships produced from the multiple regression analysis (equations 6.3 to 6.6) were proven against the real test results. The errors associated with the floating fraction are the greatest and those associated with the heavy fraction are the least. This is not too surprising because if the percentage of total mass in each group is considered, the floaters have the least mass, followed by the light sinking fraction, the residue and then the heavy sinking fraction. Although it could be considered that the error should be similar whatever the mass, the coarseness of the multiple regression relationships are such that it was difficult to estimate a small mass accurately. Additionally, the accuracy of the balance in weighing the mass of the sub-samples meant that there would be greater uncertainty in the values obtained for the smaller masses, such as the floaters, than the larger masses obtained in the residual fraction. The inclusion of a single large particle in any of these groups would affect the results significantly, which would lead to a greater relative variation in results for samples with a low overall mass. These weighing errors would produce greater errors in the predictive model for the lighter fractions.

If the floating fraction is considered negligible, the results of the settling velocity measurement test can be used as an indicator of the probable spread of the mass of suspended solids in an incoming sewage to a wastewater treatment works. The floating fraction could be considered to be the least important of the four groups for two reasons.

i) The mass of suspended solids in the floating fraction is small compared with the other groups (between 1.1% and 18.2% of the total sample mass) and so its prediction may be of least interest to designers and engineers.

ii) When designing for primary treatment, the aim is the removal of the inorganic and the large organic suspended solids. The fine floating particle fraction is usually removed by some sort of skimming device at the primary sedimentation stage. Large floating particles (gross solids) are removed by the screens in the inlet works: on the rare occasions that very large particles, such as tissue, were caught in a sample they were removed by hand because they distorted the result with their relatively large mass, so for this study they cannot be discussed further.

The equations produced by multiple regression for all the flows (equations 6.3 to 6.6) and for the (1-5.9) DWF grouping were almost identical. There was only one case of storm flow that was excluded from the (1-5.9) DWF set and so the similarity was understandable. The similarity between the equations possibly indicates that the inclusion of storm sewage data does not exert a great influence on the model, or to put it another way, the settling velocity distribution of storm sewage appeared to be similar to that of non-storm sewage. This is a weak conclusion to draw because it is based on the inclusion of only one storm sewage data set.

The large errors in the model predictions based on the (1-2) DWF data set can be explained by the small number of tests within the set (21 No.). This explanation is more likely than variation between sewages with flows between (1-2) DWF.

As a predictor for the distribution of mass within the four sub-sample groups, the equations for all the flows (equations 6.3 to 6.6) could be used with some confidence for the heavy and residual fraction of the sewage.

7.3.1.3 Peak and trough mass values

Most of the bar charts of sub-sample mass against settling velocity showed a peak and a trough in the sinkers section, as illustrated by figure 6.9a. The hypothesis that there was a relationship between the percentage of the total sample mass both at the peak and at the trough of the bar chart and the catchment characteristics was tested. From analysis the research showed that the level of association between the peak and trough values with the catchment characteristics was extremely low for both the DWF and the all flow conditions. The linear association between the peak and trough values was negative, showing that as the value of the peak increased, the trough decreased. The argument put forward for this in section 6.3.1.3 was that when the peak value is large, there is a large proportion of the total sample mass with a high settling velocity. This leaves a smaller quantity of sinking suspended solids to settle out at the lower settling velocities, and it is this which produces a smaller trough value.

The model equations produced by multiple regression to predict the peak and trough mass values incorporated a number of the catchment characteristics. Equations 6.12 to 6.15 were used to predict the DWF results and equations 6.17 and 6.19 to 6.21 to predict the 'all flows' results.

The results of the comparison between the model and real values of peak and trough mass values was most accurate when all the test results were used in the multiple regression calculations, see section 6.3.1.3(2). The error has too great a range upon which to base any design, but it does provide an indication of the distribution of masses in the sinkers range.

There was no linear association between the velocities at which the peak and trough in the sinker sub-sample mass occurred and any other variable. This lack of linear association was confirmed by the very high percentage errors in predicting the velocities using equations produced by multiple regression (section 6.3.1.3). The velocities should have been easier to predict because the range of their real test values was very small. Overall, very little was gained from this aspect of the analysis of the settling velocity distributions.

7.3.1.4 Curve fitting

The fitting of the curves to the real settling velocity grading distributions in order to determine the values of the constants a and b in equation 6.46 was quite successful, as can be seen by figure 7.1.

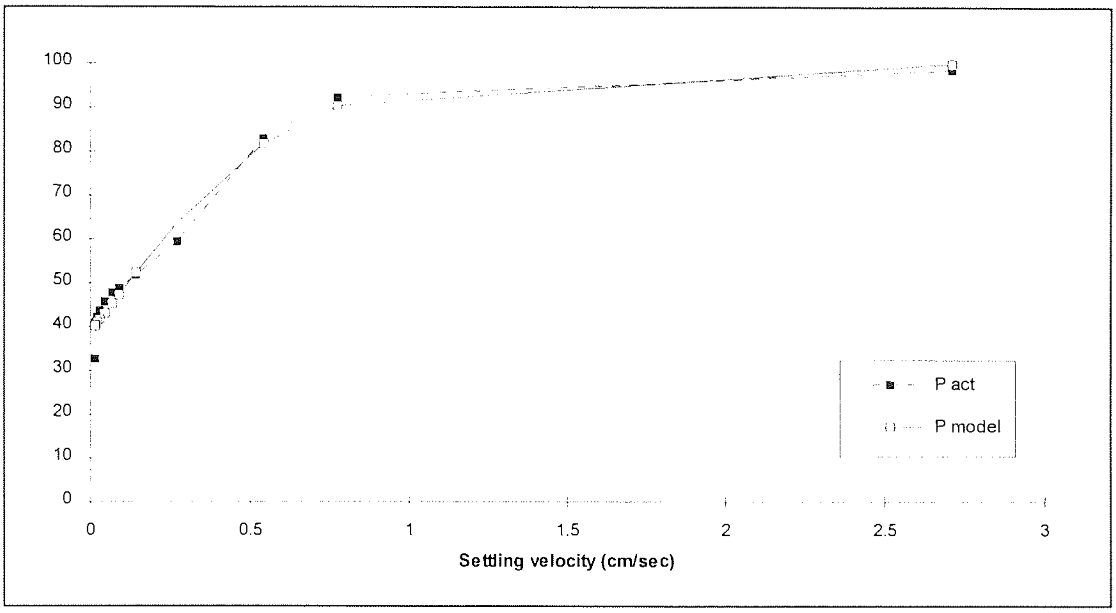

Figure 7.1 Curve fit for test reference 1.

When the model equations were produced (equations 6.23 to 6.26), and the values of the constants calculated (equations 6.27 and 6.28), the simulation of real events was not good, as can be seen from figure 6.14.

There were several possible reasons for the poor model that was generated.

i) Although a reasonably strong relationship existed between a and b (equation 6.27), the constants in the curve equation, at a significance level of 95%, no catchment variables were introduced during the regression analysis at significance levels above 80%. Although more variables may have been introduced by lowering the significance levels, it was not considered appropriate in this case because:

   a) the reliability of the model as a predictive tool was already low;

   b) the spread in the results was not broad enough to gain any distinction between the grading curves by lowering the significance of the model.

ii) When multiple regression analysis was used to determine the value of the constants in terms of the catchment characteristics, a relationship was not formed for the constant b until the 90% significance level was reached (equation 6.28). The value of b was related solely to whether the sewer system was pumped or gravity fed. This only allowed for two values of b to be calculated, giving only two possible settling velocity grading curves for any catchment, both of which revealed an unrealistic settling velocity distribution. Splitting the data into either pumped or gravity fed sewer systems and then undertaking analysis would not have produced any results because the catchment variables had low correlation coefficients that still would not have been introduced into the multiple regression calculations.

iii) Although the equation to calculate the constant a contained two catchment variables (equation 6.29), the resultant curve fit was even worse than when b was used to predict the settling velocity distribution. The equation to determine constant a, was produced at an 80% significance level and so would be expected involve some level of inaccuracy.

7.3.2 Factors affecting the analysis

There may be many reasons why the different methods of analysing the settling velocity distributions in terms of their relationship to the catchment characteristics did not produce more accurate prediction models. The obvious answer is that there is no relationship present. However, this section considers some of the factors that may have had some influence on the outcome of the analysis.

7.3.2.1 Analysis method

The methods of analysis chosen were thought at the time to be the most suitable for the data that had been collected for the catchments from the privatised water companies and the settling velocity measurement tests.

The breakdown of the sub-sample masses into four groups was decided upon after visual examination of the different methods of presenting the settling velocity distribution data.

This has provided the most accurate model for predicting information relating to the proportion of suspended solids in a sewage in terms of their settling velocity.

The choice of curve equation to which the settling velocity grading curve was fitted may not have been the most suitable. However, the curve chosen exhibited many of the same characteristics as a settling velocity distribution: it was S-shaped and asymptotic to the 0% and 100% values, and so there was a physical justification for its use. The curve equation has also been successfully used in predicting other similar relationships in the past, so must not be considered as wholly unsuitable.

It was suggested that a better model may have been produced by the use of a simple quadratic equation and preliminary analysis was undertaken to find a polynomial that might be used for analysis, but no suitable polynomial could be found. No polynomial provided a better fit to the data than equation 6.23 and none were asymptotic to the 0% and 100% values. The analysis was not continued further down this avenue.

7.3.2.2 Catchment data collection

The collection of data from the privatised water companies was a very time consuming and costly exercise and consequently the amount of data which could be collected was limited. The researcher (Withams) used her discretion in only collecting data on wastewater treatment works with the greatest likelihood of obtaining a full set of information suitable for all three sister projects (see section 5.2.2). As a result there were a restricted number of catchments available from which to select suitable study sites. In the end there was no choice in study site - the catchments with fullest sets of data were chosen for inclusion in the test programme.

If more wastewater treatment works catchments had been available, sites with problems, such as a high infiltration flow or questionable accuracy on some of the variables, could have been deleted from the test programme. This may well have improved the accuracy of the models produced.

The accuracy of the records held by the water companies was an unknown factor in this study. It was found that the most accurate records were provided by the drainage area studies. For future projects it is suggested that sites with drainage area studies are selected, since this would improve confidence in the final analysis.

7.3.2.3 Level of statistical association

It was very surprising that the correlations between the various catchment characteristics were not stronger. This indicates either that there was too much error in the data collected, or that there is no significant relationship, which is more likely. A principal component analysis found a strong variation in the data due to factors associated with the scaling of size. This highlighted the large catchments above the remainder (see section 6.2.2).

7.4 IMPLICATIONS

The major conclusion to be drawn from this project is that there is not a relationship between the settling velocity grading distribution and the characteristics of the contributing catchment. There is evidence that the distribution of mass in the fast and slow sinking fractions, the suspended solids fraction that cannot be removed by settlement and the floating fraction can be determined by knowing the characteristics of:

- the area of farmland in the catchment;
- the area of parkland in the catchment;
- number of pumping stations in the sewer network;
- the total area of the catchment;
- the area used by industry in the catchment.

This knowledge is unlikely to help designers in the selection of separation devices at the primary stage of wastewater treatment beyond an indication of the likely quantity of sludge to be produced by primary sedimentation. The ability to assist in the design of wastewater treatment works was the final objective of the project and although the outcome will not be of immediate benefit in influencing design procedures, it has shown that for the vast majority of cases, the present empirical methods of design are appropriate and at present cannot be added to significantly by considering the influence of catchment characteristics on suspended solids removal.

There is insufficient evidence from this study that the characteristics of the settling velocity grading curve are related in any way to the total area of the catchment as a clearly defined characteristic - which was the initial premise on which the research was based. The total area, when it appears in an equation, is there as one of many influencing factors, often at a low level of significance. The fact that in general the total area had a high positive level of linear association as one of a pair of characteristics, showed that the catchment variables increased in value as the area of the catchment rose, but not necessarily due to that one factor. This was most clearly indicated in the settling velocity grading envelopes in section 6.4, where no significant relationship between the total area of the catchment and the settling velocity distribution was observed. The grading curves were distributed evenly around the mean values regardless of flow to the works.

7.5 RECOMMENDATIONS FOR FUTURE RESEARCH

There are two main areas which may benefit from further research. First is the development of the settling velocity measurement technique. The second area is the use of settling velocity gradings in the study of the relationship between the settling velocity of sewage and the catchment characteristics.

7.5.1 Settling velocity measurement

From the discussions on column development in sections 3.3 and 3.4 and experience in the experimental techniques, the following areas of research are identified as being of potential benefit.

a) The initial phase of the settling velocity measurement method is to separate the floating, sinking and residual suspended solids within the sewage sample. By studying the floating element of the separated sewage a clearer relationship might be gained between the concentrations of the floating, sinking and residual fractions of sewage. In addition, more insight into the quantities of the suspended solids that truly float in primary treatment could be gained.

b) One of the areas of the test that tended to distort the results slightly was the movement of the neutrally buoyant residual suspended solids into the end cells when the sub-samples were collected. Quantification of this movement and subsequent adjustment of the results would enable the true mass of settled solids within a particular sub-sample to be determined more accurately.

c) This project was established to study a representative set of sewage samples collected from all over England and Wales. With the column construction as it is at present, the samples have to be returned to the laboratory for analysis. The development of a piece of apparatus that can be easily transported and erected on the sampling site would save time and would minimise disturbance to the sewage sample. Because only the mass of suspended solids is required, and not their chemical composition, the sub-samples could then be transferred to the laboratory for filtering and drying once the test was complete.

d) Although current knowledge indicates little change in the settling velocity distribution of a sample between 24 hr and 48 hr after sampling, investigation of the effect of the time between sampling and testing a sewage could indicate how the delay alters its physical composition. The first 24 hours after testing are thought to be particularly important. An element of this should be the temperature at which the sample is stored and tested. Research in this field might incorporate a study of the deterioration of the organic suspended solids and the micro-biological slimes attached to the inorganic materials.

e) Adaptation of the column design so that the end cells can be removed to allow them to be filled with clean water without rotating the column would eliminate the introduction of turbulence during the test. This should be accomplished with minimal disturbance to the column contents and the prevention of air entering the closed system. The removal mechanism must be fast in order not to interfere with the timing of the test.

f) The availability of a portable easy to use "instant" settling velocity measurement probe/meter would be of great benefit where rapid results for a grading curve are required, for example in assessing CSO operation or the performance of a solids removal process using chemical treatment. The main problem would be the ability to detect quickly the range of settling velocities and the mass within each range for a composite and varied material such as sewage. In addition the costs involved at present might well prove prohibitive to an individual organisation without the full backing of the wastewater industry: this might produce a product, the cost of which would make it inaccessible to potential users.

7.5.2 Settling velocity grading relationships

With the knowledge gained from the collection and analysis of both catchment and experimental data the following areas for future research have been identified as being of potential benefit to both research and the wastewater industry.

a) A desk top study is required to create an updated and accurate database of the catchment characteristics of a large number of wastewater treatment works. These treatment works could then be used both to identify relationships between the catchment characteristics and as sites for further experimental study. From the experience of this project this would be a very time consuming and potentially costly exercise without the full co-operation of the relevant water companies.

b) There was a large spread in the catchment types studied and hence the characteristics of the sites used in this project. It would be beneficial to further prove the relationships found in this research by studying the settling velocity grading curves of several catchments with one prime variable, such as total area or system type, the remainder being held as constant as possible. By having say 4 or 5 catchments in each group, a typical settling velocity grading for each site could be determined by multiple sampling and testing. This would show whether the tentative relationships developed in this study could be improved or not. This further research would not be costly, the apparatus and the test having already been developed.

c) The use of the settling velocity measurement method could be extended to monitor the performance of CSOs in terms of suspended solids removal. This study could include an investigation into the variation in the settling velocity grading of storm sewage as a storm event progresses and recedes. In particular the presence or absence of the first flush phenomena in terms of settling velocity grading could be identified as could the importance of the antecedent dry weather period. If several carefully selected CSOs in a catchment were chosen, the effect of catchment size and other variables could be included in the study.

CHAPTER 8

CONCLUSION

8.1 INTRODUCTION

Although there is a body of published literature on research into the settling velocity measurement of the individual constituents of sewage, both in the sewers and at various stages of treatment, prior to this project very little research had been carried out into measuring the settling velocity distribution of the whole sewage. Sewage is composed of both organic and inorganic suspended particles, colloids and dissolved pollutants that interact with one another to create a wide variety of different particle sizes, shapes and composition. The varied nature of these particles complicates the measurement of the settling velocity distribution of the suspended solids.

The aim of this research project has been to develop a methodology that would enable sewage settling velocity grading curves to be predicted from the characteristics of the contributing catchment, and hence be used as a tool for maximising the design performance of separation devices. The means to achieving this aim was via the three objectives defined in section 1.2, and the success of each is discussed in the following sections.

8.2 COLUMN DEVELOPMENT

One of the objectives of this project was to develop a settling velocity measurement technique to measure the grading characteristics of sewage, which could then be used confidently by non specialists. The test method was developed for use with a prototype settling velocity measurement column that was based on a device used by the Scottish

Development Department for their study of storm overflow performance. The test method developed and used in this project was suitable for both DWF and storm sewage and attempted to measure the settling velocity of both the sinking and floating fractions of the sewage.

In developing the test method, a transparent plastic column was constructed so that the particle and fluid activity could be observed throughout the test. Synthetic particles suspended in a salt water solution were introduced into the column. The salt water solution controlled the buoyancy of the suspended particles. The activities of the synthetic particles were observed and interpreted in terms of fluid flow in columns. Many of the particle and fluid activities noted with synthetic media were also present when the settling velocity distribution of sewage was measured in the column. The prototype test method was then changed to design out much of the disturbance to the column contents, whilst maintaining conditions as close as possible to those that occur at the primary sedimentation stage of a wastewater treatment works.

The revised testing method was a considerable improvement on the original procedure used in the James Bridge project (section 1.1). The floating and sinking fractions of a sewage could both be analysed, but the test could be shortened to determine the settling velocities just the sinking fraction if required. From other research (section 3.2.2) and experimental investigation, the dimensions of the column were confirmed appropriate for the measurement of the settling velocity of flocculating particles of sewage. The test was simplified so that with good instructions the column could be operated easily and accurately. It is considered that within the limited time available within this project the most appropriate and accurate method possible was developed (section 3.5).

The proportion of suspended solids in the floating fraction is always a small fraction of the total mass and is sometimes negligible. In the light of the experience gained from the testing programme the procedure has been developed further so that the settling velocity distribution of the floating fraction is not determined. This test method is recommended for use in all future studies. Full details of the revised test method are provided in Appendix A.

8.3 TO DETERMINE THE RELATIONSHIP BETWEEN THE SETTLING VELOCITY GRADING OF A SEWAGE AND THE CHARACTERISTICS OF THE CONTRIBUTING CATCHMENT

The test method developed during the first phase of the project was used to determine the settling velocity grading of 33 samples of sewage taken at the inlets to 29 wastewater treatment works.

Details of wastewater treatment works catchments, primary treatment processes and quality parameters had been collected for 77 sites in England and Wales. Not all of the data sets were complete, especially where the catchment details were concerned. Of the 77 sites, only 35 had complete sets of catchment data. The accuracy of the information could not be ascertained, but where data was extracted from drainage area studies, the information was not more than 2 years old.

The settling velocity distributions and the catchment data were analysed together to determine if there was a relationship between the settling velocity grading of a particular sewage and the characteristics of the contributing catchment. The main conclusions reached from the analysis are detailed below.

- There were very few linear associations between pairs of catchment characteristics. The variables that formed the most significant linear relationships with another were, in decreasing order: the total catchment area; the DWF; and the equivalent population. These factors rarely appeared in the multiple regression equations to predict the settling velocity distribution, which indicates that they were not associated due to a cause and effect relationship at a high level of significance.

- The percentage of the total area used for farmland, the type of sewer system and whether the sewer system was pumped or gravity fed did not have linear associations with any of the other catchment variables when tested in pairs. However, when the multiple regression calculations were carried out to model the relationships between the grading curve and the catchment, these variables were those most commonly found in the resulting equations. This would indicate that these three characteristics were independent, but had an influence on the sewage settling velocity grading.

- An indication of the proportion of suspended solids that settle out at high positive velocities, low positive velocities, negative velocities (floating particles) and those that cannot be removed by quiescent settlement within the test period can be achieved by use of a series of regression models. The accuracy of these models depend upon the incoming flow to the wastewater treatment works at the time of sampling, the most accurate models being produced for flows between 2 and 5.9 DWF.

  The errors in predicting the suspended solids in the floating and light sinking fractions is very high and should not be relied upon for design and evaluation purposes. The errors associated with the heavy sinking and residual fractions are around 30%, providing an indication of the magnitudes involved, but nothing more.

- Following a curve fitting exercise, statistical analysis was used in an attempt to relate the values of the constants within the equation employed to the catchment parameters. This analysis did not reveal any reliable relationships that would enable the settling velocity distribution to be predicted from the characteristics of the contributing catchment. Thus a model for predicting the grading curve was not established using this approach.

- The gradient of the central section of the settling velocity grading curve does not form any relationship with the characteristics of the contributing catchment.

This project has failed to conclusively determine a method of predicting sewage settling velocity grading curves from the characteristics of the contributing catchment.

8.4 POTENTIAL FOR USE IN DESIGN OR ASSESSMENT OF PRIMARY TREATMENT FACILITIES

This final objective has not been successfully achieved. At the point at which the project was completed there was little indication that the prediction techniques investigated could be used in the design of primary treatment separation devices without further refinement. The envelope of the settling velocity grading curves (figure 6.16) does indicate that there is a limited variation in settling velocity distribution between different catchments. There is no identifiable relationship between the catchment area and the settling velocity distribution that could be used for design purposes, but this confirms that the current empirical design approach that has evolved over time may not be possible to improve upon.

The settling velocity measurement test as recommended in this project can be used for measurement of the settling velocity grading characteristics of a sewage from a particular wastewater treatment works, but further research is required to prove repeatability and hence its use as a reliable comparative tool.

8.5 FINAL OUTCOME OF THIS STUDY

A procedure has been developed which measures the settling velocity distribution of particles within a complete sewage sample. The method produces repeatable results and is suitable for use with either DWF or storm sewage.

Information relating to the catchment characteristics of 35 No. wastewater treatment works was collected and 29 No. of these sites were used in an experimental programme to determine the settling velocity grading of sewage samples.

A series of analyses were applied to all the collected data in an attempt to relate the settling velocity distribution to the characteristics of the contributing catchment. The analysis proved that the settling velocity distribution of sewage does not have a significant relationship with the chosen catchment characteristics.

The settling velocity grading curves were found to be contained within a well defined envelope. The equations for the bounds of the envelope have been defined.

The regression equations produced cannot be used to assist in the design of separation devices. The present empirical approach to settling tank design cannot be improved upon at present.

This study has provided a basis for future research into the settling velocity measurement and should be of benefit to future workers within this field.

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GLOSSARY

BOD	biochemical oxygen demand: a measure of the biodegradable organics in sewage.
Catchment parameters	characteristics of a wastewater treatment works catchment that define it in terms of its physical attributes, i.e. total area, DWF, land usage, etc.
COD	chemical oxygen demand: a measure of the oxygen required for the chemical oxidation of all the organic matter in sewage.
DWF	dry weather flow, the flow to a wastewater treatment works during dry weather conditions that includes discharges from residential, commercial and industrial properties and an allowance for infiltration into the sewer system.
Elution	the act of washing out a substance(s) by the action of a solvent, as in chromatography.
Equivalent population	a number composed of the true population plus a value representing the industrial component of discharge calculated as a per capita flow.
Fixed suspended solids	the inorganic fraction of suspended solids.
Floaters	particles with a negative settling velocity.
Floating fraction	particles with a settling velocity greater than or equal to -0.15 mm/sec.

Gross solids any particles which measures more than 6 mm in any direction.

Macromolecule any very large molecule, such as a protein or a molecular polymer.

Residual fraction neutrally buoyant or very slow settling particles remaining in the central section of the column after settlement.

Residue neutrally buoyant or very slow settling particles.

Runoff that part of the rainfall which flows off the surface to reach a sewer or river.

Settling velocity the velocity at which any particle or floccule is falling (positive value) or rising (negative value) within a body of liquid.

Sinkers particles with a positive settling velocity.

Sinking fraction particles with a settling velocity greater than or equal to 0.15 mm/sec

Suspended solids the organic and inorganic solids that are flowing within the body of liquid in a sewer.

Terminal velocity the limiting settling velocity of a particle or floccule determined by its size, density and surface roughness and the viscosity of the liquid through which it is falling.

TOC total organic carbon

TON total organic nitrogen

Urban runoff that part of the rainfall which flows off the surfaces within an urbanised catchment to reach a sewer or river.

Volatile suspended solids the organic fraction of the suspended solids that is oxidised at 550°C ±50°C.

NOTATION

a	radius of a sphere
a	curve constant
area	total catchment area (hectares)
b	curve constant
C_V	uniformity coefficient for settling velocity grading curve
comm	area of commerce as a percentage of the total catchment area (%)
d	diameter of the rigid particle
d	diameter of the falling sphere
D	diameter of the column
F	gravitational force acting on a particle
F	"floaters": the sum of the particles collected in cell B in the settling velocity measurement of the sinking fraction
F_e	"floaters end": the contents of cell A at the end of the settling velocity measurement of the sinking fraction
F_S	"floaters at the start": the floating particles that have been collected in the end cell after the initial settlement phase of the test

floaters	percentage of floating particles, measured by weight, with a settling velocity greater than or equal to -0.23 mm/sec
farm	area of farmland as a percentage of the total catchment area (%)
heavy	percentage of sinking particles, measured by weight,, with a settling velocity greater than or equal to 0.68 mm/sec
imp	impermeable area expressed as a percentage of the total area (%)
ind	area of industry as a percentage of the total catchment area
K	proportionality factor for particle shapes used in Stokes equation
K_u	the velocity ratio
light	percentage of sinking particles, measured by weight, with a settling velocity between 0.18 mm/sec and 0.68 mm/sec
park	area of parkland as a percentage of the total catchment area (%)
pdwf	proportion of DWF reaching the treatment works when a sample was taken
peak	peak mass value of the sinking fraction (g)
peakvel	velocity at which peak mass occurred (mm/sec)
pop	equivalent population (number)
pump	pumped or gravity fed sewer system: 1 = pumped system 2 = gravity fed system

pumped pumped or gravity fed sewer system: 1 = pumped

2 = gravity fed

r distance from a sphere

R resistance or frictional force on a sphere falling freely through a stationary viscous liquid

R "residue": the residual fraction remaining in the central section of the column at the end of the test

residue percentage of suspended solids, measured by weight, with a settling velocity between -0.23 mm/sec and 0.18 mm/sec

S "sinkers": the sum of the particles collected in cell B in the settling velocity measurement of the sinking fraction

S_e "sinkers end": the contents of cell A at the end of the settling velocity measurement of the sinking fraction

S_s "sinkers at the start": the sinking particles that have been collected in the end cell after the initial settlement phase of the test

sewer length of the main sewers feeding the wastewater treatment works (m)

sinkers percentage of sinking particles, measured by weight, with a settling velocity greater than or equal to 0.18 mm/sec

system type of sewer system: 1 = separate

2 = partially separate

3 = combined

trough trough mass value of the sinking fraction (g)

trouvel	velocity at which trough mass occurred (mm/sec)
u	velocity of the sphere through the liquid
u_S	terminal velocity of a particle in a bounded liquid
$u_{S\infty}$	terminal velocity of a particle in an infinite liquid
λ	diameter ratio
μ	viscosity of the liquid
ρ	density of a fluid
ρ_p	density of a particle

APPENDIX A

METHODS OF ASSESSING THE SETTLING VELOCITY DISTRIBUTIONS OF SEWAGE/STORM SEWAGE

A.1

PROTOTYPE TEST METHOD

(PRE-1991)

APPARATUS FOR ASSESSING THE SETTLING VELOCITY DISTRIBUTIONS OF STORM SEWAGE

Method of Operation

1) With cell B at bottom and valve 1 shut fill the column with well mixed sewage sample (approx. 5 litres required).

2) Close valve 2, re-open and close. Repeat this until all air trapped behind the ball valve is released.

3) Repeat (2) for valve 3. Top up with sewage if necessary.

4) Repeat (2) for valve 4. Top up with sewage if necessary. There should be some liquid above the closed valve 4 when finished to ensure the column is full.

5) Open valves 2 and 3 and gently rotate column to ensure that the contents are well mixed (some deposition will have taken place during steps (1) to (4)). Take care to catch the liquid above valve 4 when commencing rotation.

6) Lock column in vertical position and quickly close valves 2 and 3.

7) Open valve 1 and drain cell B.

8) Rotate column through 180 degrees and drain cell A. In this position fill cell B with clean water, close valve 1 ensuring the air space behind the valve is filled (ie. fill to above valve then close - open - close the valve until all the air is released).

9) Rotate column through 180 degrees so that cell A is uppermost and fill with clean water as with cell B in (8).

10) Rotate column through 180 degrees so that cell B is uppermost. Lock in vertical position and leave overnight (or at least 12 hours). This will result in all the floaters collecting beneath valve 2 and all the sinkers by valve 3.

11) First thing in the morning rotate the column through 180 degrees to bring cell B to the bottom. Start stop clock. Open valves 2 and 3.

12) After a pre-selected time t_1 close valves 2 and 3. Open valve 1 and drain cell B.

13) min after time t_1, rotate column through 180 degrees, open valve 4 and drain cell A.

14) Refill cell B with clean water as in (8).

15) 2 mins after time t_1, reverse rotation. Start timer for next sample period and open valve 2.

16) Refill cell A (now at the top) with clean water close valve 4 and open valve 3.

17) After time period t_2 repeat steps (12) to (16) and continue for as long as required.

18) After final samples have been taken from cells A and B, do not refill with clean water, but drain the main column containing sewage (C) into a container so that the residual concentration, hence mass of SS can be determined.

19) A sample of raw sewage should be retained so that the initial concentration can be ascertained.

20) Filter the samples on previously washed, dried and weighed filter papers. Dry the samples and weigh the papers again to obtain the mass of suspended solids.

Principles

a) Steps (1) to (10) inclusive are preparation which result in:

i) Cells A and B full of clean water (ie. no solids present).
ii) Main column C is full of well mixed sewage.
iii) At start of step (11) all floaters are at top (adjacent to valve 2) and all sinkers at bottom (adjacent to valve 3).

If valves 2 and 3 are open, the solids accumulate in cells A and B and when the column is inverted, the lighter particles do not have time to get out before the time period is up - hence yield incorrect value for SS.

b) In steps (11) to (17) samples of sinkers (cell B at bottom) and floaters (cell A at top) are obtained, each of which relates to a distinct range of settling velocities.If column C is L cm long and first samples are obtained after t_1 secs, only particles with terminal velocities greater than $V_{o1} = L/t_1$ cm/sec are captured in cells A and B.

When the column is inverted to sample cell A, the direction of rise/fall of the particles is reversed. It has been found that inverting the column for a standard 1 min enables all activities to be completed. Having previously allowed 1 min for the emptying of cell B, on returning the column to its original vertical position (with B at the bottom), the particles will have returned to the positions they were in after time t_1.

In allowing a further period of dt the particles collected in the next sample have fallen for $t_2 = t_1 + dt$. Hence the time allowed between closing valves 2 and 3 and the next sample being taken is (dt + 2) mins.

All solids with $V_0 > L/t_1$ were collected in the first sample. Hence solids collected in the second sample have settling velocity greater than $V_{02} = L/t_2$ but less than V_{01}. Similarly for the next sample $V_{02} > V_0 > (V_{03} = L/t_3)$ and so on.

Time intervals used to date for storm sewage:
t_1 = 5 mins, t_2 = 10 mins, t_3 = 20 mins, t_4 = 30 mins, t_5 = 40 mins, t_6 = 60 mins, t_7 = 90 mins, t_8 = 120 mins, t_9 = 150 mins, t_{10} = 180 mins.

For foul sewage this was extended to t_{11} = 240 mins, t_{12} = 300 mins.
However each situation must be judged on its merits.

Analysis

1) Filter a known volume of raw sewage. Mass of SS enables the concentration to be found. Knowing the volume of sewage in column C and the concentration the *starting mass* can be determined.

2) Each filtered sample yields the mass of solids with that specific settling/terminal velocity range.

3) From the residual sewage in column C after the experiment the mass remaining can be determined either by filtering all the volume collected, or by filtering a known volume.

4) The sum of the mass of all the samples, plus the residual mass should give the original value - or a close approximation.

5) Knowing all the above data the graphs of % samples with a settling velocity less than a known value, and mass differences etc. can be plotted.

A.2

METHOD USED THROUGHOUT THE RESEARCH PROJECT TO ASSESS THE SETTLING VELOCITY DISTRIBUTION OF SEWAGE/STORM SEWAGE

(JUNE 1993)

MODIFIED METHOD FOR ASSESSING THE SETTLING VELOCITY DISTRIBUTION OF SEWAGE/STORM SEWAGE

Method

1. With cell A at the bottom and valve 4 shut fill the column with well mixed sewage sample (approx. 5 litres required).

2. A sample of at least 1 litre of raw sewage should be retained so that the initial concentration can be ascertained.

3. Close valve 3, re-open and close. Repeat this until all air trapped behind the ball valve is released.

4. Repeat (3) for valve 2. Top up with sewage if necessary.

5. Repeat (3) for valve 1. Top up with sewage if necessary. There should be some liquid above the closed valve 1 when finished to ensure the column is full.

6. Gently rotate column through about 90° and back again in order to catch the liquid left above valve 1. Make sure that there is a container under valve 1 to catch the sewage!
   Open valves 2 and 3.

7. Lock column in vertical position and leave undisturbed for 3 hours. Ensure that cell A is at the bottom, valves 2 and 3 are open and valves 1 and 4 are closed.
   This will result in floaters collecting in cell B and sinkers collecting in cell A.

8. After 3 hours close valves 2 and 3. Open valve 4, drain cell A and retain the contents. These are the sinkers.

9. Rotate column through 180°, drain cell B and retain the contents. These are the floaters.

10. Rotate column through 180° so that cell B is at the top. In this position fill cell B with clean water, close valve 1 ensuring the air space behind the valve is filled (ie. fill to above valve then close - open - close the valve until all the air is released).

11. Rotate column through 180° so that cell A is uppermost. Lock the column in the upright position. Open valve 4.

12. With the lid firmly sealed shake the retained sinkers up thoroughly to break up any flocs that have formed. Pour the contents of the bucket into cell A, purge valve 4 of air by opening and closing the valve. Close valve 4, open valve 3 and immediately start the stop clock. Immediately open valve 2.

13. After a pre-selected time t_1 close valve 2. Open valve 1 and drain cell B.

14. 30 secs after time t_1, rotate column through 180°, refill cell B with clean water as in (9).

15. 1 min after time t_1, reverse rotation, so that cell B is again at the bottom. Start timer for next sample period and open valve 2.

16. After time period t_2 repeat steps (12) to (14) and continue for as long as required. [See 'Principles (d)'].

17. After final samples have been taken from cell B, close valve 3. Rotate the column through 180°, drain cell A and retain contents. Refill cell B with clean water as in (9).

18. Rotate the column through 180° so that cell A is uppermost, open valve 4.

19. With the lid firmly sealed shake the retained floaters up thoroughly to break up any flocs that have formed. Pour the contents of the bucket into cell A, purge valve 4 of air by opening and closing the valve. Close valve 4.

20. Rotate the column through 180° so that cell A is at the bottom. Open valve 3 immediately and start the stop clock. Immediately open valve 2.

21. After a pre-selected time t_1 close valve 2. Rotate the column through 180° and drain cell B.

22. 30 secs after time t_1, reverse the rotation and refill cell B with clean water as in (9).

23. 1 min after time t_1, with cell B again at the top, start timer for next sample period and open valve 2.

24. After time period t_2 repeat steps (20) to (22) and continue for as long as required. [See 'Principles (d)'].

25. After final samples have been taken from cell B, do not refill cell B with clean water, but drain cell A containing sewage into one container. Then drain the main column

separately so that the residual concentration and hence mass of SS for the sample can be determined.

26. Filter the samples on previously washed, dried and weighed filter papers. Dry the samples and weigh the papers again to obtain the mass of suspended solids.

Principles

(a) Steps (1) to (6) are preparation of the sewage to allow the sinkers and the floaters to separate.

Three hours settlement is allowed so that no particles remain in the column that have settling velocities greater than the longest sample time (150 minutes in this case). All these particles will have collected in end cells A and B.

(b) In steps (7) to (10) the sinkers and floaters are removed from the column. The residue is left in the column to simulate real conditions by maintaining the density and background liquor quality.

(c) In steps (12) to (16) and (17) to (24) samples of sinkers (cell A at top) and floaters (cell A at bottom) are obtained, each of which relates to a distinct range of settling velocities.

If column C is L cm long and first samples are obtained after t_1 secs, only particles with terminal velocities greater than $V_1 = (L+dl)/t_1$ cm/sec are captured in cell A, where dl is taken as half the end cell length.

When the column is inverted to refill the sample cell, the direction of rise/fall of the particles is reversed. It has been found that inverting the column for a standard 30 secs enables all activities to be completed. Having previously allowed 30 secs for emptying the sample cell, on returning the column to its original vertical position the particles will have risen and fallen over the same distance and so returned to the positions they were in after time t_1.

In allowing a further period of dt the particles collected in the next sample have fallen for $t_2 = t_1 + dt$ Hence the time allowed between closing valves 2 and 3 at the end of the previous sampling period and the next sample being taken is (dt + 1) mins.

All solids with $V_1 > (L+dl)/t_1$ were collected in the first sample. Hence solids collected in the second sample have settling velocity greater than $V_2 = (L+dl)/t_2$ but less than V_1. Similarly for the next sample
$V_1 > V_2 > V_3$, (where $V_3 = (L+dl)/t_3$) and so on.

(d) Time intervals used to date for storm and foul sewage:
Sinkers: t_1 = 1 min, t_2 = 3 mins, t_3 = 5 mins, t_4 = 10 mins, t_5 = 20 mins, t_6 = 30 mins, t_7 = 40 mins, t_8 = 60 mins, t_9 = 90 mins, t_{10} = 120 mins, t_{11} = 150 mins.

Floaters: t_1 = 1 min, t_2 = 3 mins, t_3 = 5 mins, t_4 = 10 mins, t_5 = 20 mins, t_6 = 30 mins, t_7 = 40 mins, t_8 = 60 mins, t_9 = 90 mins, t_{10} = 120 mins.

However each situation must be judged on its merits.

Analysis

1. Filter a known volume of raw sewage. Mass of SS enables the concentration to be found. Knowing the volume of sewage in column C and the concentration the *starting mass* can be determined.

2. Each filtered sample yields the mass of solids with that specific settling/terminal velocity range.

3. From the residual sewage in column C after the experiment and the retained residues from the end cell after both the sinkers and the floaters have been tested, the mass remaining can be determined by filtering.

4. The sum of the mass of all the samples, plus the residual mass should give the original value - or a close approximation.

5. Knowing all the above data the graphs of % samples with a settling velocity less than a known value, and mass differences etc. can be plotted.

A.3

TEST METHOD RECOMMENDED FOR USE IN ALL FUTURE SETTLING VELOCITY ANALYSES

(MARCH 1994)

MODIFIED METHOD FOR ASSESSING THE SETTLING VELOCITY DISTRIBUTION OF SEWAGE/STORM SEWAGE

Method

1. With cell A at the bottom and valve 4 shut fill the column with well mixed sewage sample (approx. 5 litres required).

2. A sample of at least 1 litre, preferably more, of raw sewage should be retained so that the initial concentration can be ascertained.

3. Close valve 3, re-open and close. Repeat this until all air trapped behind the ball valve is released (approx 4 times).

4. Repeat (3) for valve 2. Top up with sewage if necessary.

5. Repeat (3) for valve 1. Top up with sewage if necessary. There should be some liquid above the closed valve 1 when finished to ensure the column is full.

6. Gently rotate column through about 90° and back again in order to catch the liquid left above valve 1. Make sure that there is a container under valve 1 to catch the sewage!
Open valves 2 and 3.

7. Lock column in vertical position and leave undisturbed for 3 hours. Ensure that cell A is at the bottom, valves 2 and 3 are open and valves 1 and 4 are closed.
This will result in floaters collecting in cell B and sinkers collecting in cell A.

8. After 3 hours close valves 2 and 3. Open valve 4, drain cell A and retain the contents. These are the sinkers.

9. Rotate column through 180°, drain cell B and retain the contents. These are the floaters.

10. Rotate column through 180° so that cell B is at the top. In this position fill cell B with clean water, close valve 1 ensuring the air space behind the valve is filled (ie. fill to above valve then close - open - close the valve until all the air is released).

11. Rotate column through 180° degrees so that cell A is uppermost. Lock the column in the upright position. Open valve 4.

12. With the lid firmly sealed shake the retained sinkers up thoroughly to break up any flocs that have formed. Pour the contents of the bucket into cell A, purge valve 4 of air by opening and closing the valve. Close valve 4, open valve 3 and immediately start the stop clock. Immediately open valve 2.

13. After a pre-selected time t_1 close valve 2. Open valve 1 and drain cell B.

14. 30 secs after time t_1, rotate column through 180°, refill cell B with clean water as in (9).

15. 1 min after time t_1, reverse rotation, so that cell B is again at the bottom. Start timer for next sample period and open valve 2.

16. After time period dt, where dt = (t_2 - t_1) repeat steps (12) to (14) and continue for as long as required. [See 'Principles (d)'].

17. After final samples have been taken from cell B, close valve 3. Rotate the column through 180°, drain cell A and retain contents. These are the remaining sinkers.

18. Drain the main column separately so that the residual concentration and hence mass of SS for the sample can be determined.

19. Filter the samples, including the floaters, the remaining sinkers, the residue and the retained crude sample, on previously washed, dried and weighed filter papers. Dry the samples and weigh the papers again to obtain the mass of suspended solids.

Principles

(a) Steps (1) to (6) are preparation of the sewage to allow the sinkers and the floaters to separate.

Three hours settlement is allowed so that no particles remain in the column that have settling velocities greater than the longest sample time (150 minutes in this case). All these particles will have collected in end cells A and B.

(b) In steps (7) to (10) the sinkers and floaters are removed from the column. The residue is left in the column to simulate real conditions by maintaining the density and background liquor quality.

(c) In steps (12) to (16) and (17) to (24) samples of sinkers (cell A at top) and floaters (cell A at bottom) are obtained, each of which relates to a distinct range of settling velocities.

If column C is L cm long and first samples are obtained after t_1 secs, only particles with terminal velocities greater than $V_1 = (L+dl)/t_1$ cm/sec are captured in cell A, where dl is taken as half the end cell length.

When the column is inverted to refill the sample cell, the direction of rise/fall of the particles is reversed. It has been found that inverting the column for a standard 30 secs enables all activities to be completed. Having previously allowed 30 secs for emptying the sample cell, on returning the column to its original vertical position the particles will have risen and fallen over the same distance and so returned to the positions they were in after time t_1.

In allowing a further period of dt the particles collected in the next sample have fallen for $t_2 = t_1 + dt$ Hence the time allowed between closing valves 2 and 3 at the end of the previous sampling period and the next sample being taken is (dt + 1) mins.

All solids with $V_1 > (L+dl)/t_1$ were collected in the first sample. Hence solids collected in the second sample have settling velocity greater than $V_2 = (L+dl)/t_2$ but less than V_1. Similarly for the next sample:

$V_1 > V_2 > V_3$, (where $V_3 = (L+dl)/t_3$) and so on.

(d) Time intervals used to date for storm and foul sewage:
Sinkers: t_1 = 1 min, t_2 = 3 mins, t_3 = 5 mins, t_4 = 10 mins, t_5 = 20 mins, t_6 = 30 mins, t_7 = 40 mins, t_8 = 60 mins, t_9 = 90 mins, t_{10} = 120 mins, t_{11} = 150 mins.
However each situation must be judged on its merits.

Analysis

1. Filter a known volume of raw sewage. Mass of SS enables the concentration to be found. Knowing the volume of sewage in column C and the concentration the *starting mass* can be determined.

2. Each filtered sample yields the mass of solids with that specific settling/terminal velocity range.

3. From the residual sewage in column C after the experiment and the retained residues from the end cell after both the sinkers and the floaters have been tested, the mass remaining can be determined by filtering.

4. The sum of the mass of all the samples, plus the residual mass should give the original value - or a close approximation.

5. Knowing all the above data the graphs of % samples with a settling velocity less than a known value, and mass differences etc. can be plotted.

APPENDIX B

RESULTS OF THE COMPARISON STUDY TO DETERMINE THE PATTERN OF SUSPENDED SOLIDS TRANSFER TO AND FROM THE RESIDUE DURING SETTLING VELOCITY MEASUREMENT TESTING

TEST	TEST FRACTION	MASS AS A PERCENTAGE OF TOTAL SAMPLE MASS TEST REFERENCE							
		4i	7	13	17	18	21	24	26
Full test	floater	13.33	6.14	8.12	17.63	0.63	3.55	14.63	18.22
	floater at end	15.03	9.64	9.46	18.53	11.25	14.99	16.51	7.66
	residue	12.05	4.09	9.79	16.65	12.78	15.88	14.19	13.03
	sinker	52.48	74.46	60.09	41.03	72.05	59.97	47.87	56.70
	sinker at end	7.06	5.68	12.56	5.88	3.27	5.63	6.81	4.41
Comparison	floater at start	8.05	8.86	5.92	17.91	14.71	16.98	13.63	7.48
	residue at start	32.70	19.81	38.55	45.85	42.41	43.79	44.05	34.25
	sinker at start	59.25	71.32	55.53	36.23	42.88	39.23	42.32	58.27

Results of the comparison study carried out during the experimental programme.

APPENDIX C

CATCHMENT DATA SHEET

CATCHMENT INFORMATION

General Information **Site Ref No :-** ....

Site Name ....

Location .... Grid Ref ....

Authority ....

Region ....

Contact: Name .... Position ....

Address ....
.... Phone ....
....
.... Fax ....

Catchment Data

Gross Area (ha) .... Longitudinal Fall ....

Predominant Geology ....

Approx Age of Development in Catchment ....

Catchment Shape

Shape Index ....

Useage

Areal Factors (ha)

Impermeable .... Industry ....

Commerce .... Residential ....

Farmland .... Park / Recreation ....

Equivalent Population .... Domestic Population ....

Flowrates (l/sec)

DWF .... Diurnal Variation ....

Max .... Min ....

Main Sewer Details

Length (m) .... Fall / gradient ....

Sewer Shape .... Time of concentration ....

Type of System (ie Combined) ....

Pumped or Gravity System .... No Pump Stations ....

Treatment Processes

Screening .... Grit Removal ....

Primary Sed .... Biol Process ....

Secondary Sed .... Tertiary Treat ....

Approx Age of Works ....

Primary Sedimentation

Type of Tanks .... No of Tanks ....

Surface Loading (m^3/m^2. day) ....

Retention Time (hrs) .... Approx age of units ....

Size of Tanks (m^3) .... Depth of Tanks (m) ....

Quality Parameters - Primary Sedimentation Tanks

Parameter	Influent	Effluent
Suspended Solids	....	....
BOD	....	....
COD	....	....
TON	....	....
Chloride	....	....
pH	....	....
NH_4^-	....	....
NO_3^-	....	....
Total Phosphate	....	....
....	....	....
Heavy Metals		
Lead	....	....
Cadmium	....	....
Mercury	....	....
Zinc	....	....
Copper	....	....
Chromium	....	....
Nickel	....	....
....	....	....
Organic Chemicals		
Phenol	....	....
....	....	....
....	....	....
....	....	....

Quality Parameters - Works as a Whole

Parameter	Influent	Effluent
Suspended Solids	....	....
BOD	....	....
COD	....	....
TON	....	....
Chloride	....	....
pH	....	....
NH_4^-	....	....
NO_3^-	....	....
Total Phosphate	....	....
....	....	....
Heavy Metals		
Lead	....	....
Cadmium	....	....
Mercury	....	....
Zinc	....	....
Copper	....	....
Chromium	....	....
Nickel	....	....
....	....	....
Organic Chemicals		
Phenol	....	....
....	....	....
....	....	....
....	....	....
....	....	....
....	....	....
....	....	....
....	....	....
....	....	....
....	....	....
....	....	....

Miscellaneous

Availability of Site Plans	Y / N	Date	....
		Source	....
			....
Availability of Aerial Photos	Y / N	Date	....
		Source	....
			....
Drainage Area Study Undertaken	Y / N	Date	....
		Source	....
			....

Large Seasonal Population Fluctuations Y / N

Has Population Grown Significantly
Since Works Commissioned Y / N

Notes / Observations :-

Record

Compiled By .... Date ....

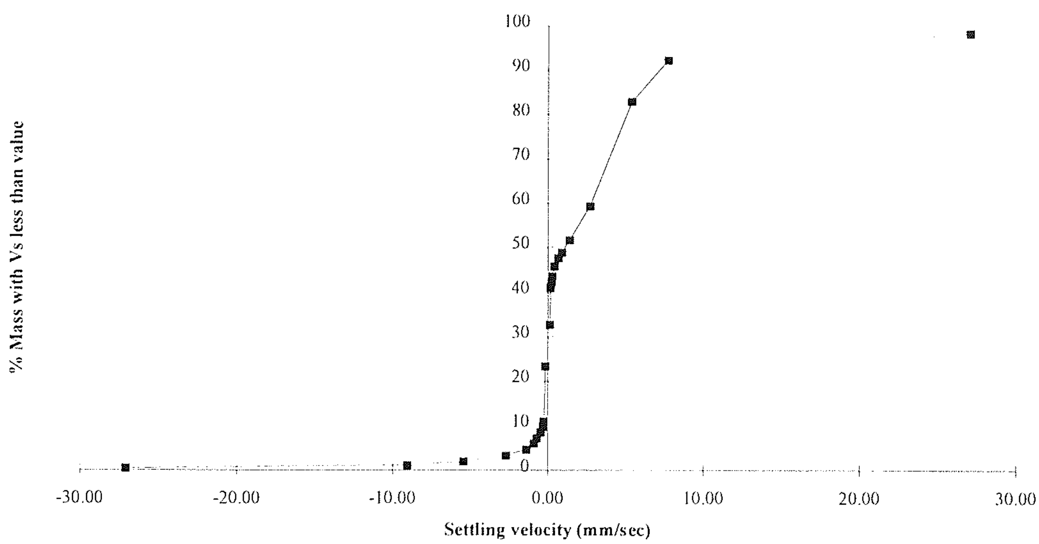
Sample Date 1. .... 2. ....

Grading Anal Date 1. .... 2. ....

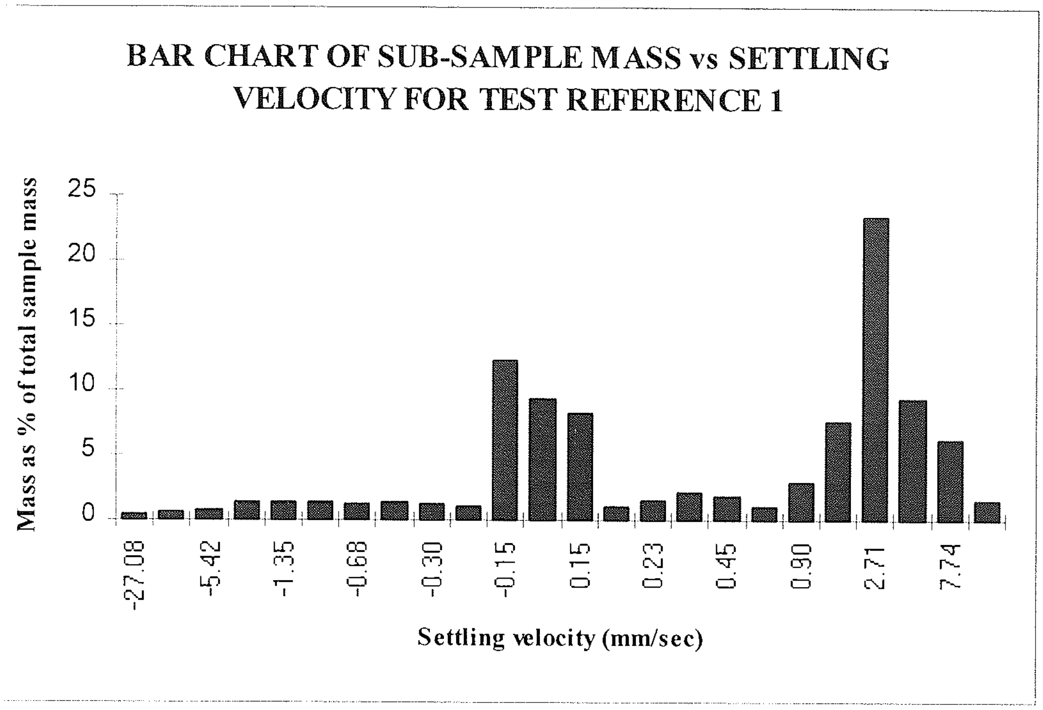
APPENDIX D

RESULTS OF SETTLING VELOCITY MEASUREMENT TESTS

Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)
-27.08	0.47	0.006	0.47
-9.03	1.17	0.009	0.70
-5.42	1.95	0.010	0.78
-2.71	3.36	0.018	1.41
-1.35	4.69	0.017	1.33
-0.90	6.02	0.017	1.33
-0.68	7.27	0.016	1.25
-0.45	8.60	0.017	1.33
-0.30	9.85	0.016	1.25
-0.23	10.95	0.014	1.10
-0.15	23.33	0.158	12.38
0.00		0.120	9.40
0.15	32.73	0.106	8.30
0.18	41.03	0.014	1.10
0.23	42.13	0.019	1.49
0.30	43.62	0.028	2.19
0.45	45.81	0.024	1.88
0.68	47.69	0.015	1.17
0.90	48.86	0.037	2.90
1.43	51.76	0.098	7.67
2.71	59.43	0.30	23.49
5.42	82.92	0.119	9.32
7.74	92.24	0.079	6.19
27.08	98.43	0.02	1.57

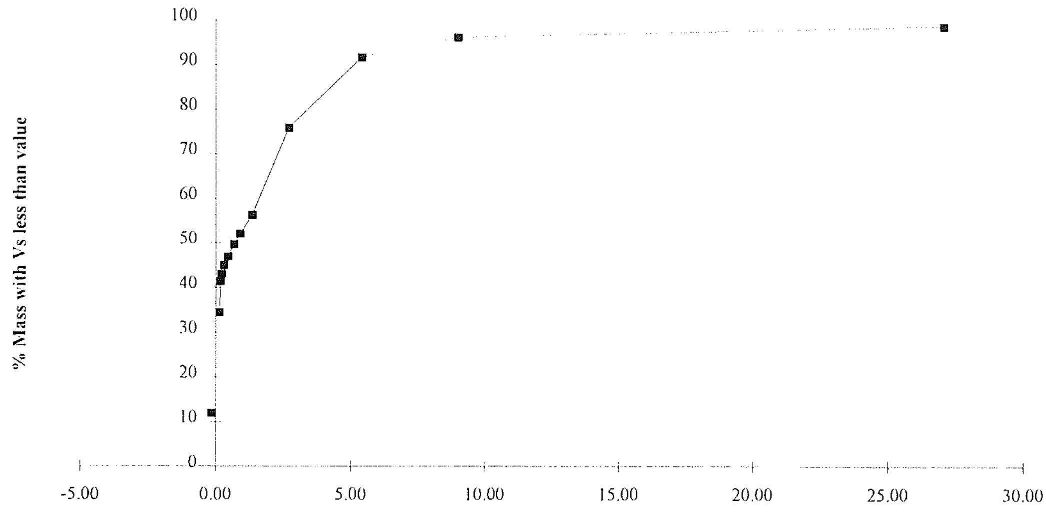


Results of the settling velocity measurement test and the grading curve for site reference 1, test 1.

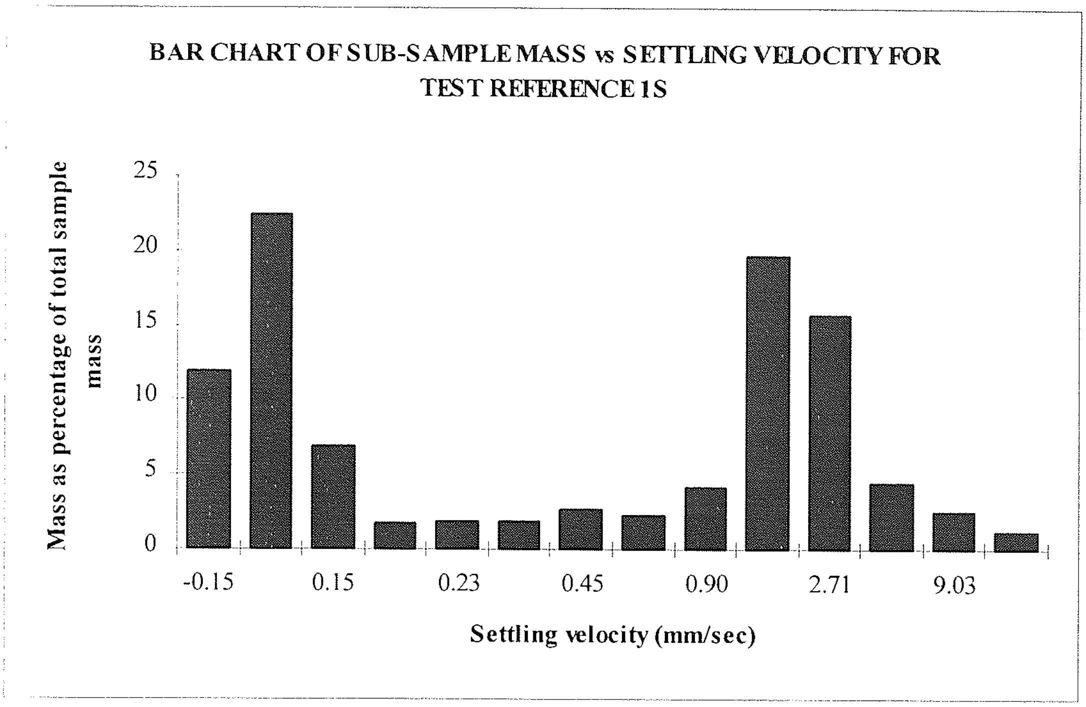


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 1
Mass as % of total sample mass
25
20
15
10
5
0
-27.08
-5.42
-1.35
-0.68
-0.30
-0.15
0.15
0.23
0.45
0.90
2.71
7.74
Settling velocity (mm/sec)

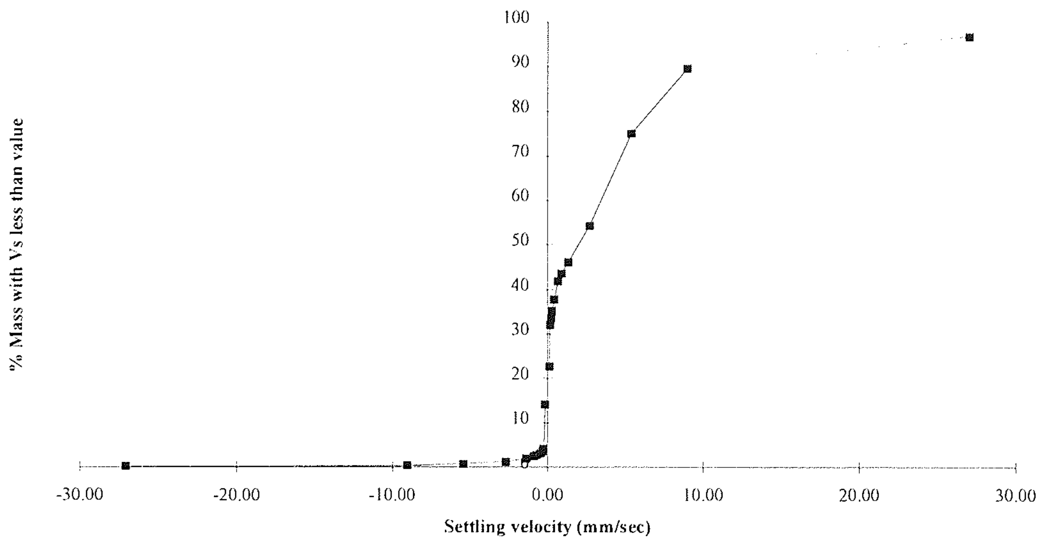
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	11.94	0.118	11.94	0.09	76.3	0.028
0.00		0.222	22.47	0.187	84.2	0.035
0.15	34.41	0.069	6.98	0.052	75.4	0.017
0.18	41.39	0.017	1.72	0.012	70.6	0.005
0.23	43.11	0.019	1.92	0.015	78.9	0.004
0.30	45.03	0.019	1.92	0.014	73.7	0.005
0.45	46.95	0.027	2.73	0.02	74.1	0.007
0.68	49.68	0.023	2.33	0.016	69.6	0.007
0.90	52.01	0.042	4.25	0.032	76.2	0.01
1.35	56.26	0.194	19.64	0.159	82.0	0.035
2.71	75.90	0.156	15.79	0.129	82.7	0.027
5.42	91.69	0.044	4.45	0.037	84.1	0.007
9.03	96.14	0.026	2.63	0.022	84.6	0.004
27.08	98.77	0.012	1.21	0.009	75.0	0.003



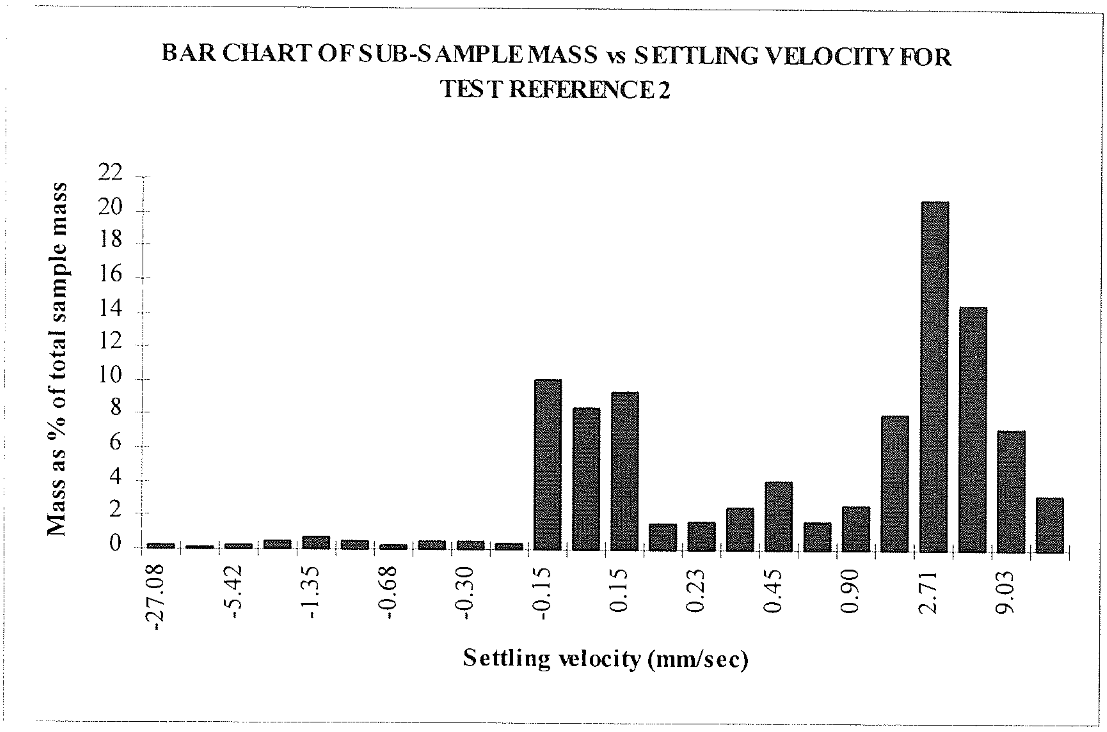
Results of the settling velocity measurement test and the grading curve for site reference 1, test 1S.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 1S
Mass as percentage of total sample mass
25
20
15
10
5
0
-0.15
0.15
0.23
0.45
0.90
2.71
9.03
Settling velocity (mm/sec)

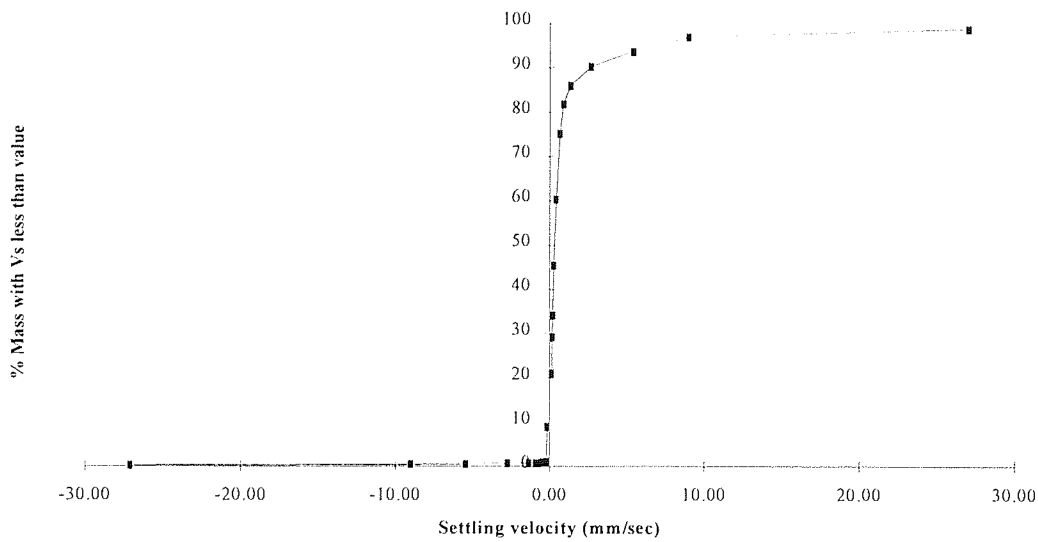
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.29	0.006	0.29	0.001	16.7	0.005
-9.03	0.44	0.003	0.15	0.002	66.7	0.001
-5.42	0.73	0.006	0.29	0.004	66.7	0.002
-2.71	1.26	0.011	0.53	0.007	63.6	0.004
-1.35	1.94	0.014	0.68	0.011	78.6	0.003
-0.87	2.47	0.011	0.53	0.008	72.7	0.003
-0.68	2.76	0.006	0.29	0.005	83.3	0.001
-0.45	3.24	0.010	0.48	0.007	70.0	0.003
-0.30	3.72	0.010	0.48	0.007	70.0	0.003
-0.23	4.11	0.008	0.39	0.006	75.0	0.002
-0.15	14.20	0.208	10.09	0.146	70.2	0.062
0.00		0.174	8.44	0.146	83.9	0.028
0.15	22.64	0.194	9.41	0.129	66.5	0.065
0.17	32.05	0.032	1.55	0.022	68.8	0.010
0.23	33.60	0.034	1.65	0.026	76.5	0.008
0.30	35.25	0.051	2.47	0.036	70.6	0.015
0.45	37.72	0.085	4.12	0.062	72.9	0.023
0.68	41.84	0.034	1.65	0.022	64.7	0.012
0.90	43.49	0.055	2.67	0.036	65.5	0.019
1.35	46.16	0.167	8.10	0.109	65.3	0.058
2.71	54.26	0.428	20.76	0.270	63.1	0.158
5.42	75.02	0.299	14.5	0.185	61.9	0.114
9.03	89.52	0.150	7.27	0.084	56.0	0.066
27.08	96.79	0.066	3.20	0.037	56.1	0.029



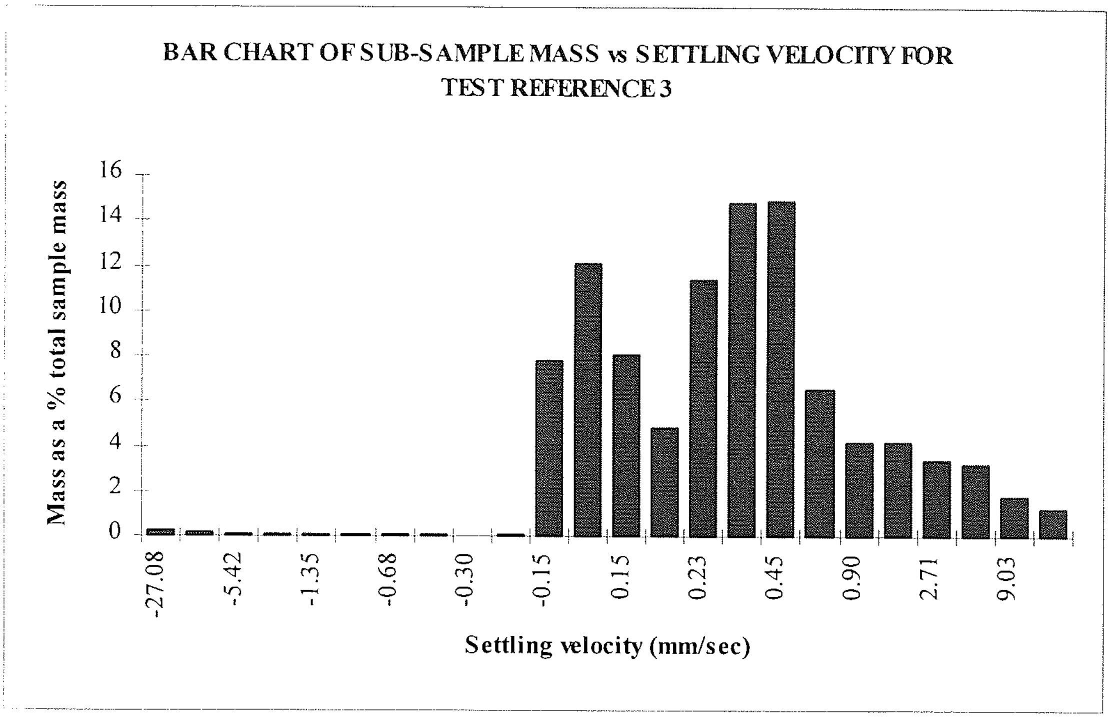
Results of the settling velocity measurement test and the grading curve for site reference 2, test 2.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 2
Mass as % of total sample mass
22
20
18
16
14
12
10
8
6
4
2
0
-27.08
-5.42
-1.35
-0.68
-0.30
-0.15
0.15
0.23
0.45
0.90
2.71
9.03
Settling velocity (mm/sec)

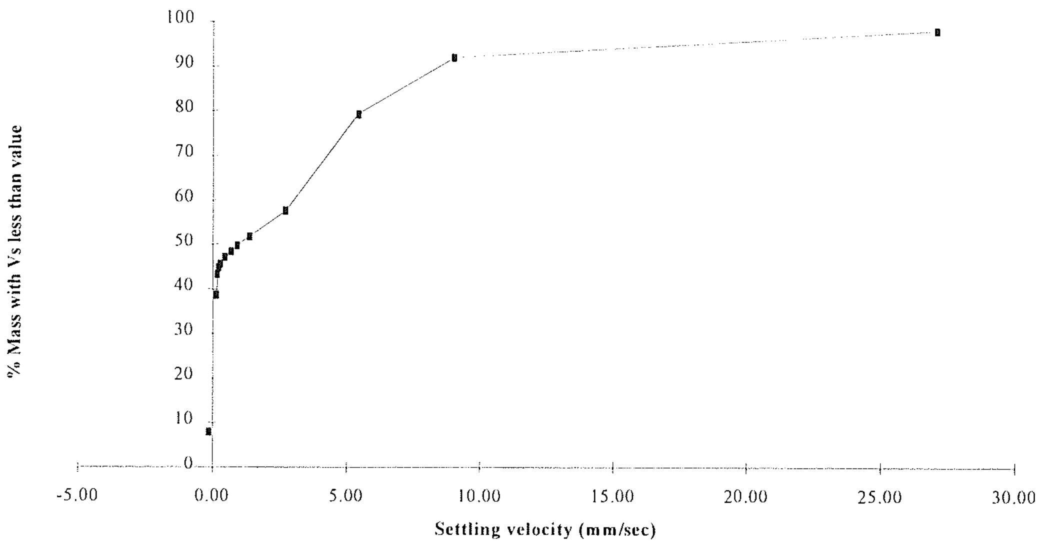
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.31	0.005	0.31	0.005	100.0	0.000
-9.03	0.49	0.003	0.18	0.003	100.0	0.000
-5.42	0.55	0.001	0.06	0.001	100.0	0.000
-2.71	0.67	0.002	0.12	0.001	50.0	0.001
-1.35	0.73	0.001	0.06	0.001	100.0	0.000
-0.90	0.85	0.002	0.12	0.002	100.0	0.000
-0.68	0.91	0.001	0.06	0.001	100.0	0.000
-0.45	1.03	0.002	0.12	0.002	100.0	0.000
-0.30	1.03	0.000	0.00	0.000	0.00	0.000
-0.23	1.15	0.002	0.12	0.002	100.0	0.000
-0.15	8.97	0.127	7.82	0.105	82.7	0.022
0.00		0.197	12.12	0.178	90.4	0.019
0.15	21.09	0.132	8.12	0.113	85.6	0.019
0.18	29.21	0.079	4.86	0.065	82.3	0.014
0.23	34.07	0.185	11.38	0.155	83.8	0.030
0.29	45.45	0.241	14.83	0.199	82.6	0.042
0.45	60.28	0.243	14.95	0.203	83.5	0.040
0.68	75.23	0.106	6.52	0.087	82.1	0.019
0.90	81.75	0.069	4.25	0.055	79.7	0.014
1.35	86.00	0.069	4.25	0.055	79.7	0.014
2.71	90.25	0.055	3.38	0.045	81.8	0.010
5.42	93.63	0.053	3.26	0.044	83.0	0.009
9.03	96.87	0.029	1.78	0.024	82.8	0.005
27.08	98.67	0.021	1.29	0.015	71.4	0.006



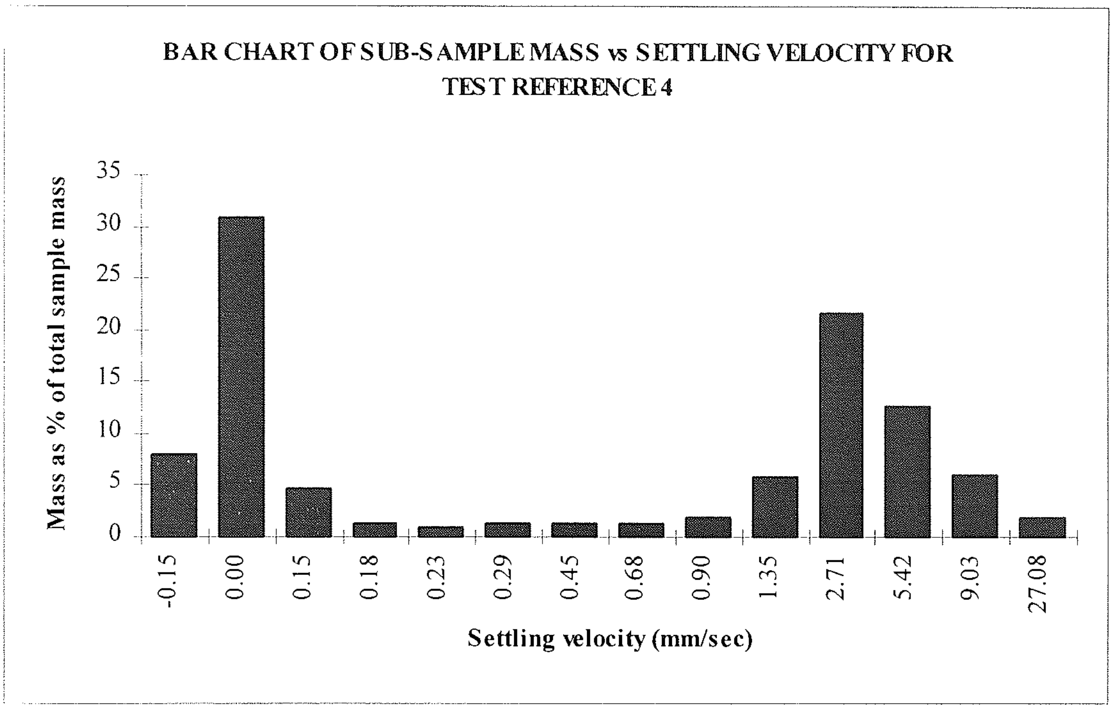
Results of the settling velocity measurement test and the grading curve for site reference 3, test 3.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 3
Mass as a % total sample mass
16
14
12
10
8
6
4
2
0
-27.08
-5.42
-1.35
-0.68
-0.30
-0.15
0.15
0.23
0.45
0.90
2.71
9.03
Settling velocity (mm/sec)

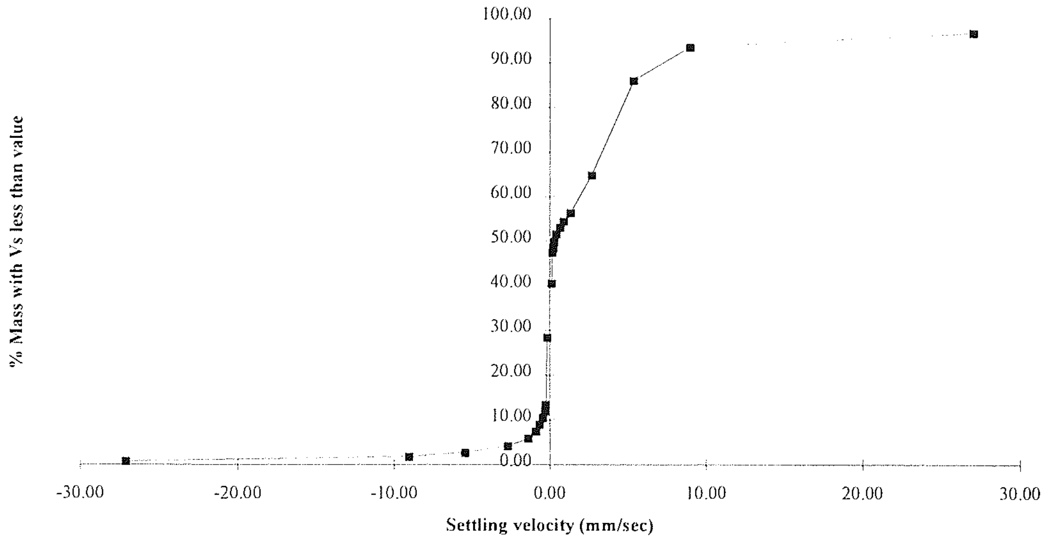
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	7.99	0.085	7.99	0.076	89.4	0.009
0.00		0.328	30.83	0.291	88.7	0.037
0.15	38.82	0.049	4.61	0.041	83.7	0.008
0.18	43.43	0.014	1.32	0.011	78.6	0.003
0.23	44.75	0.010	0.94	0.007	70.0	0.003
0.29	45.69	0.015	1.41	0.012	80.0	0.003
0.45	47.10	0.014	1.32	0.012	85.7	0.002
0.68	48.42	0.015	1.41	0.012	80.0	0.003
0.90	49.83	0.021	1.97	0.017	81.0	0.004
1.35	51.80	0.062	5.83	0.055	88.7	0.007
2.71	57.63	0.231	21.71	0.199	86.1	0.032
5.42	79.34	0.135	12.69	0.144	106.7	0.021
9.03	92.03	0.065	6.11	0.054	83.1	0.011
27.08	98.14	0.020	1.88	0.016	80.0	0.004



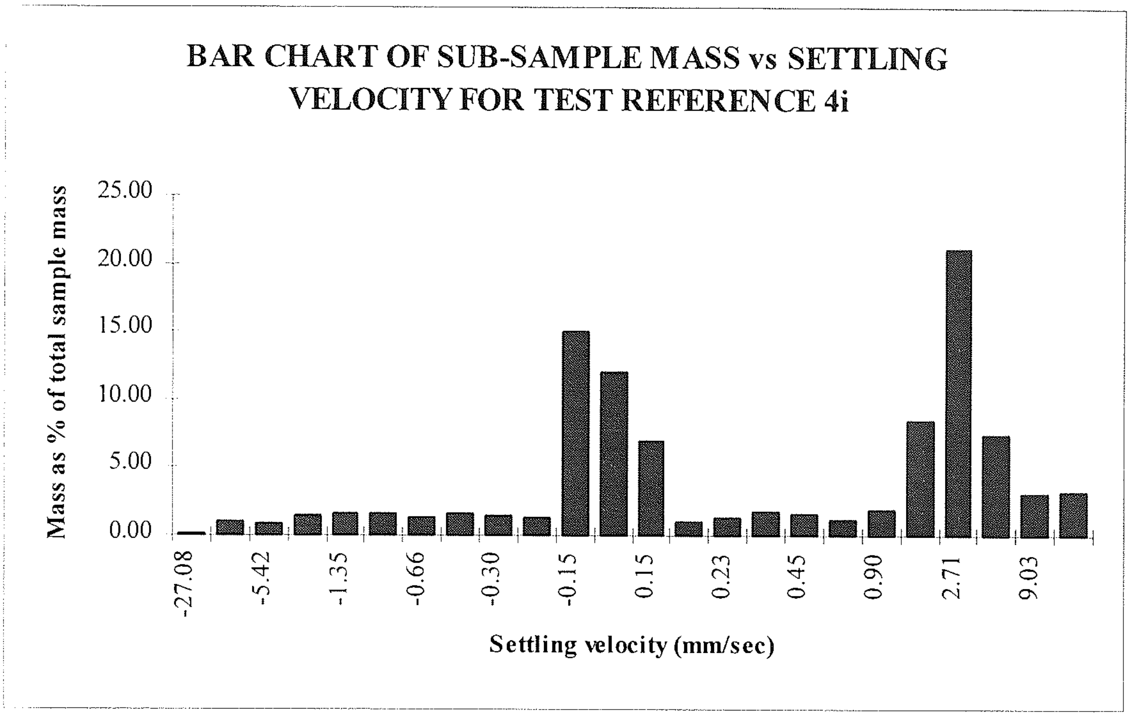
Results of the settling velocity measurement test and the grading curve for site reference 4, test 4.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 4
Mass as % of total sample mass
35
30
25
20
15
10
5
0
-0.15
0.00
0.15
0.18
0.23
0.29
0.45
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

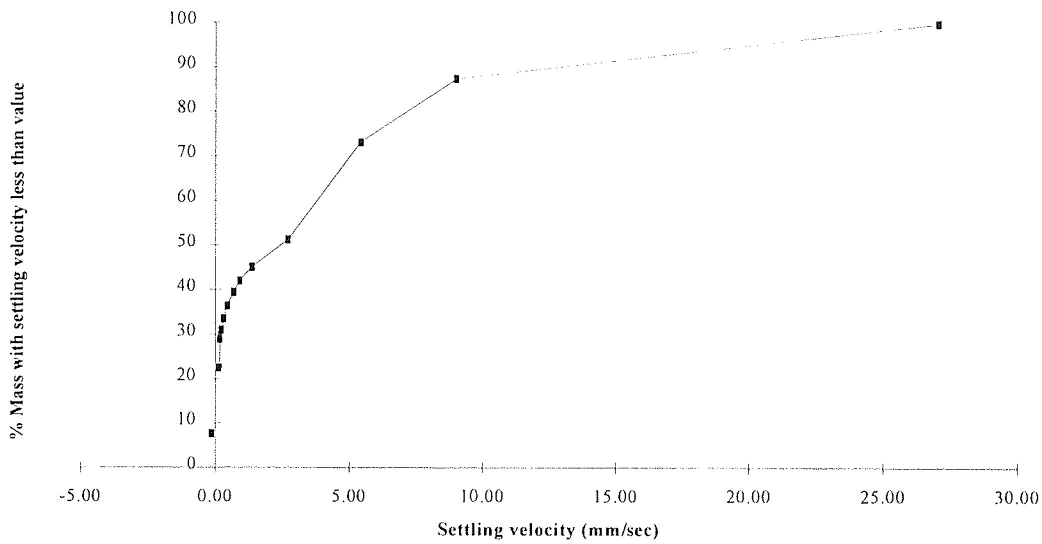
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.77	0.016	0.08	0.010	62.50	0.006
-9.03	1.88	0.023	1.11	0.017	73.91	0.006
-5.42	2.70	0.017	0.82	0.010	58.82	0.007
-2.71	4.15	0.030	1.45	0.022	73.33	0.008
-1.35	5.84	0.035	1.69	0.027	77.14	0.008
-0.90	7.48	0.034	1.64	0.025	73.53	0.009
-0.66	8.88	0.029	1.40	0.021	72.41	0.008
-0.45	10.52	0.034	1.64	0.030	88.24	0.004
-0.30	12.02	0.031	1.50	0.025	80.65	0.006
-0.23	13.33	0.027	1.31	0.022	81.48	0.005
-0.15	28.38	0.331	15.05	0.263	79.46	0.048
0.00		0.249	12.05	0.212	85.14	0.037
0.15	40.43	0.146	7.06	0.124	84.93	0.022
0.18	47.49	0.020	0.97	0.015	75.00	0.005
0.23	48.46	0.027	1.31	0.020	74.07	0.007
0.30	49.77	0.036	1.74	0.028	77.78	0.008
0.45	51.51	0.034	1.64	0.025	73.53	0.009
0.68	53.15	0.025	1.21	0.019	76.00	0.006
0.90	54.36	0.041	1.98	0.031	75.61	0.010
1.35	56.34	0.176	8.51	0.144	81.82	0.032
2.71	64.85	0.438	21.19	0.380	86.76	0.058
5.42	86.04	0.155	7.50	0.133	85.81	0.022
9.03	93.54	0.065	3.14	0.056	86.15	0.009
27.08	96.68	0.068	3.29	0.060	88.24	0.008



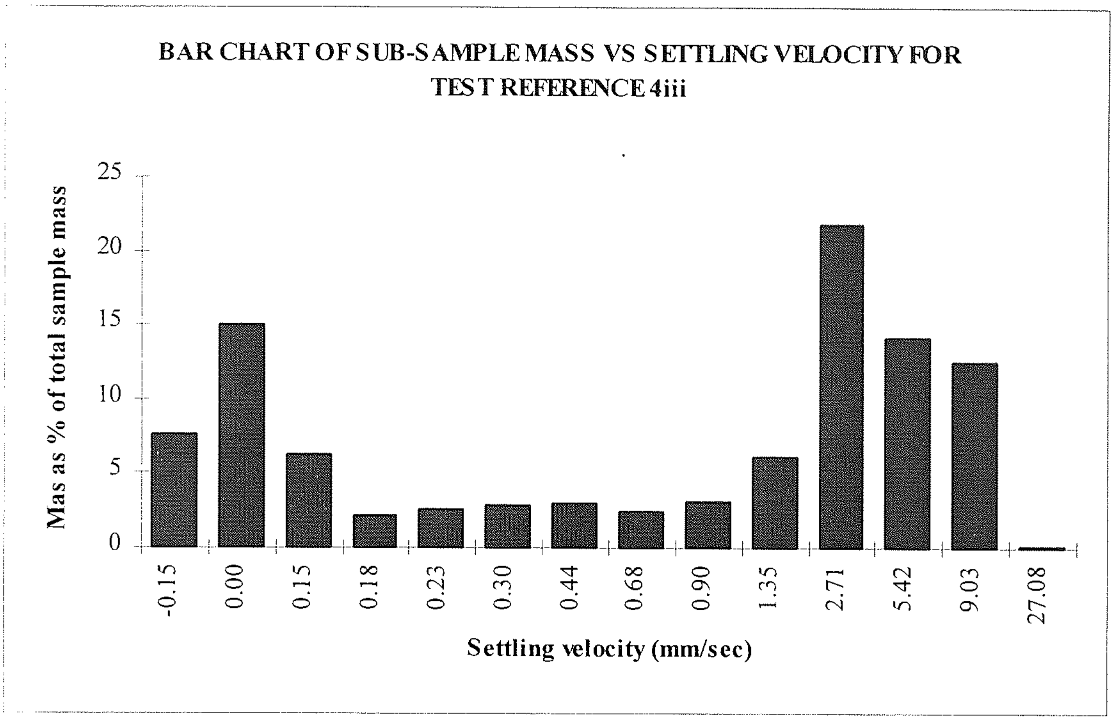
Results of the settling velocity measurement test and the grading curve for site reference 4, test 4i.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 4i
Mass as % of total sample mass
25.00
20.00
15.00
10.00
5.00
0.00
-27.08
-5.42
-1.35
-0.66
-0.30
-0.15
0.15
0.23
0.45
0.90
2.71
9.03
Settling velocity (mm/sec)

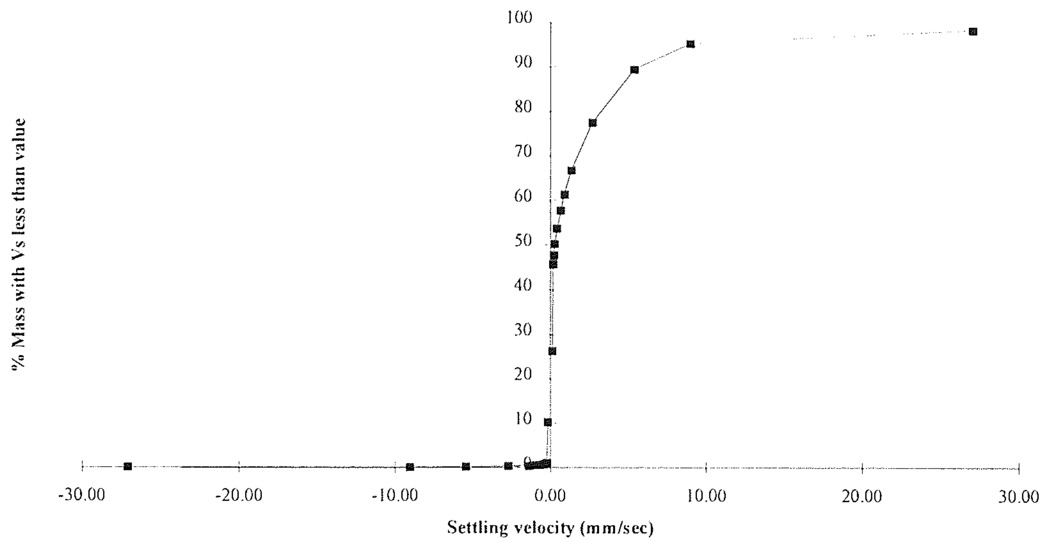
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	7.63	0.106	7.63	0.090	84.9	0.016
0.00		0.208	14.97	0.177	85.1	0.031
0.15	22.60	0.087	6.26	0.073	83.9	0.014
0.18	28.86	0.030	2.16	0.024	80.0	0.006
0.23	31.02	0.036	2.59	0.029	80.6	0.007
0.30	33.61	0.040	2.88	0.032	80.0	0.008
0.44	36.49	0.042	3.02	0.033	78.6	0.009
0.68	39.51	0.034	2.45	0.026	76.5	0.008
0.90	41.96	0.043	3.10	0.034	79.1	0.009
1.35	45.06	0.086	6.19	0.067	77.9	0.019
2.71	51.25	0.304	21.89	0.237	78.0	0.067
5.42	73.14	0.198	14.25	0.154	77.8	0.044
9.03	87.39	0.174	12.53	0.141	81.0	0.033
27.08	99.92	0.001	0.07	0.000	0.0	0.001



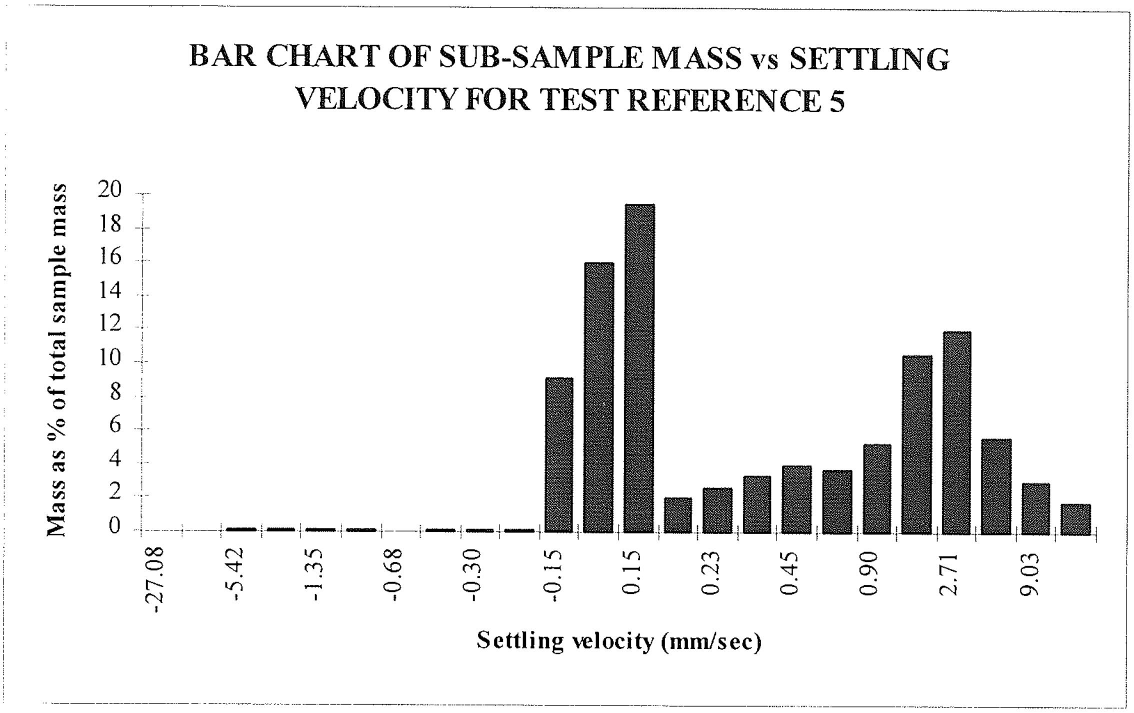
Results of the settling velocity measurement test and the grading curve for site reference 4, test 4iii.


BAR CHART OF SUB-SAMPLE MASS VS SETTLING VELOCITY FOR TEST REFERENCE 4iii
Mas as % of total sample mass
0
5
10
15
20
25
-0.15
0.00
0.15
0.18
0.23
0.30
0.44
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

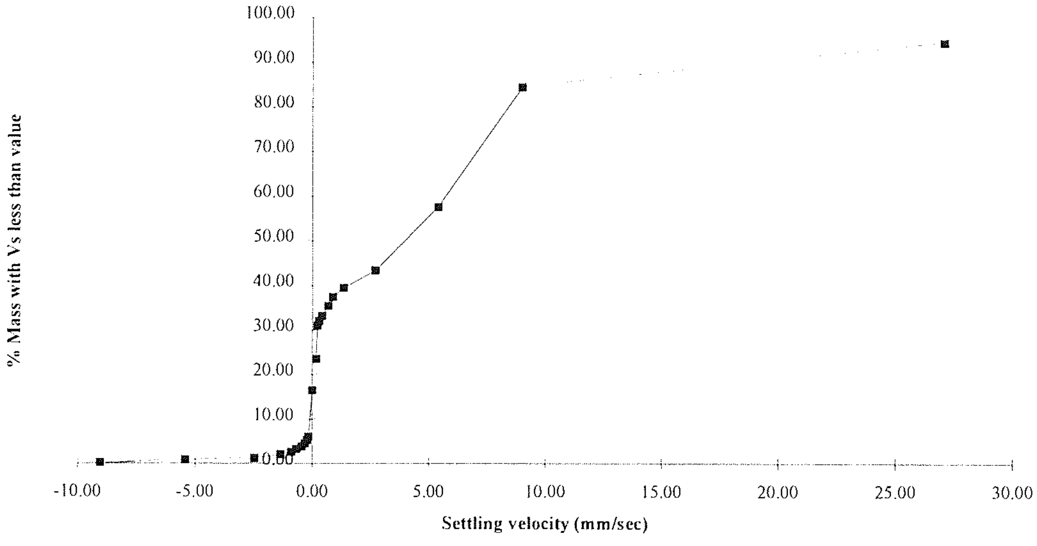
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.06	0.001	0.06	0.001	100.0	0
-9.03	0.12	0.001	0.06	0.001	100.0	0
-5.42	0.25	0.002	0.13	0.001	50.0	0.001
-2.71	0.38	0.002	0.13	0	0.0	0.002
-1.35	0.51	0.002	0.13	0.001	50.0	0.001
-0.90	0.64	0.002	0.13	0	0.0	0.002
-0.68	0.7	0.001	0.06	0	0.0	0.001
-0.45	0.83	0.002	0.13	0	0.0	0.002
-0.30	0.96	0.002	0.13	0	0.0	0.002
-0.22	1.09	0.002	0.13	0	0.0	0.002
-0.15	10.22	0.143	9.13	0.114	79.7	0.029
0.00		0.252	16.08	0.214	84.9	0.038
0.15	26.3	0.305	19.46	0.248	81.3	0.057
0.18	45.76	0.032	2.04	0.023	71.9	0.009
0.23	47.8	0.041	2.62	0.032	78.0	0.009
0.30	50.42	0.052	3.32	0.039	75.0	0.013
0.45	53.74	0.063	4.02	0.049	77.8	0.014
0.68	57.76	0.058	3.7	0.045	77.6	0.013
0.90	61.46	0.084	5.36	0.066	78.6	0.018
1.35	66.82	0.167	10.66	0.133	79.6	0.034
2.71	77.48	0.188	12	0.158	84.0	0.03
5.42	89.48	0.089	5.68	0.076	85.4	0.013
9.03	95.16	0.047	3	0.038	80.9	0.009
27.08	98.16	0.029	1.85	0.022	75.9	0.007



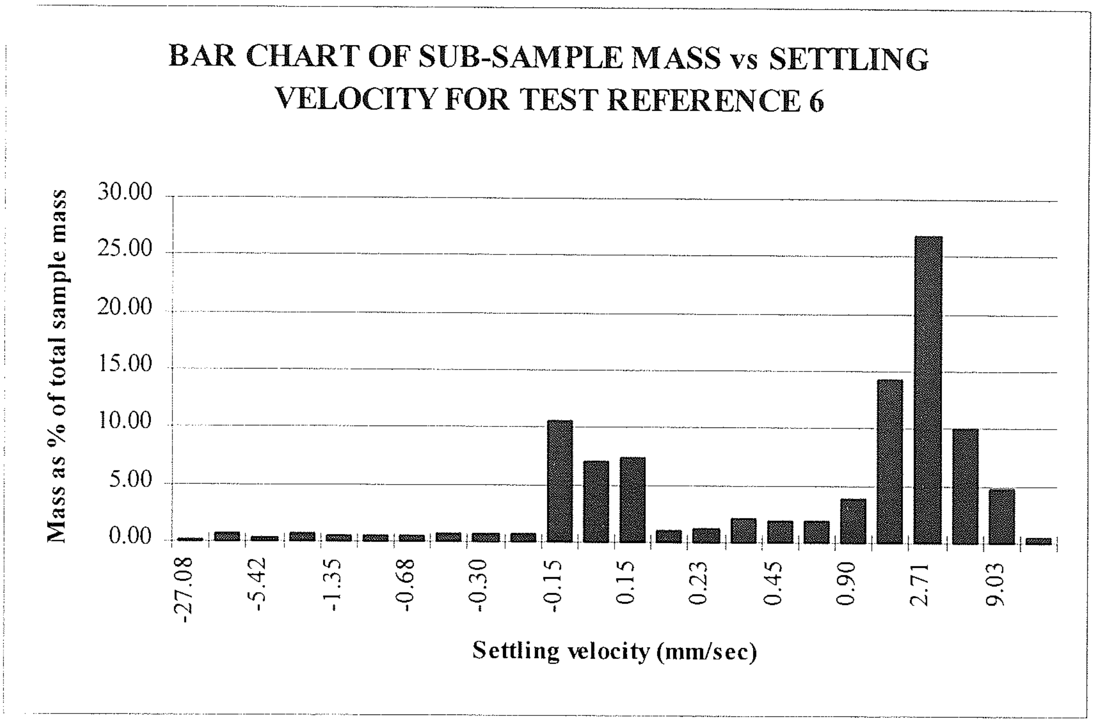
Results of the settling velocity measurement test and the grading curve for site reference 5, test 5.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 5
Mass as % of total sample mass
20
18
16
14
12
10
8
6
4
2
0
-27.08
-5.42
-1.35
-0.68
-0.30
-0.15
0.15
0.23
0.45
0.90
2.71
9.03
Settling velocity (mm/sec)

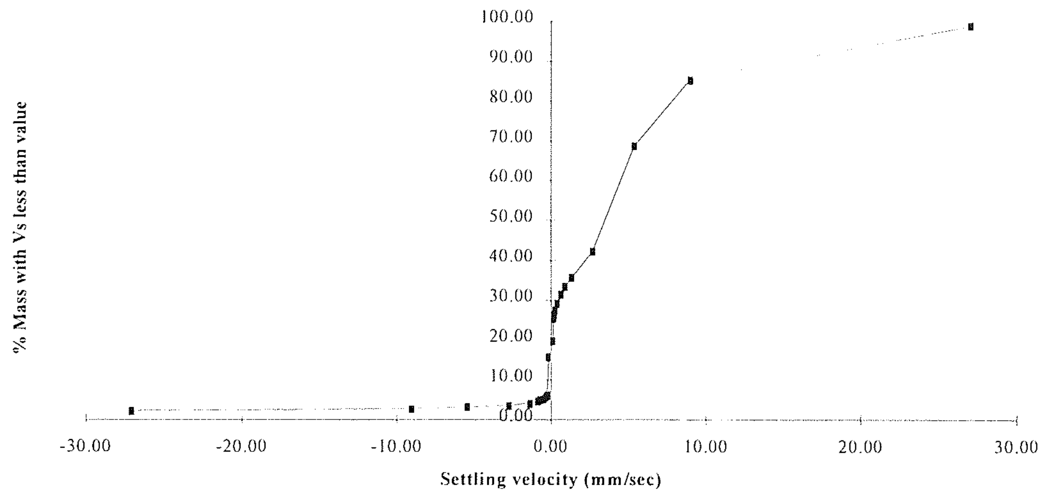
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.23	0.005	0.23	0.003	60.0	0.002
-9.03	0.92	0.011	0.69	0.009	81.8	0.002
-5.42	1.31	0.007	0.38	0.005	71.4	0.002
-2.46	2.08	0.013	0.77	0.010	76.9	0.003
-1.35	2.69	0.011	0.61	0.008	72.7	0.003
-0.90	3.31	0.011	0.61	0.008	72.7	0.003
-0.68	3.84	0.010	0.54	0.007	70.0	0.003
-0.45	4.53	0.010	0.69	0.009	90.0	0.001
-0.30	5.30	0.014	0.77	0.010	71.4	0.004
-0.23	6.00	0.012	0.69	0.009	75.0	0.003
-0.15	16.53	0.161	10.53	0.137	85.1	0.024
0.00		0.102	6.99	0.091	89.2	0.011
0.15	23.52	0.117	7.46	0.097	82.9	0.020
0.17	30.98	0.017	1.00	0.013	76.5	0.004
0.23	31.98	0.021	1.31	0.017	81.0	0.004
0.30	33.28	0.036	2.15	0.028	77.8	0.008
0.45	35.43	0.034	2.00	0.026	76.5	0.008
0.68	37.43	0.034	2.00	0.026	76.5	0.008
0.90	39.43	0.063	3.92	0.051	81.0	0.012
1.35	43.35	0.225	14.37	0.187	83.1	0.038
2.71	57.72	0.417	26.83	0.349	83.7	0.068
5.42	84.55	0.150	9.99	0.130	86.7	0.020
9.03	94.54	0.077	4.84	0.063	81.8	0.014
27.08	99.39	0.010	0.61	0.008	80.0	0.002



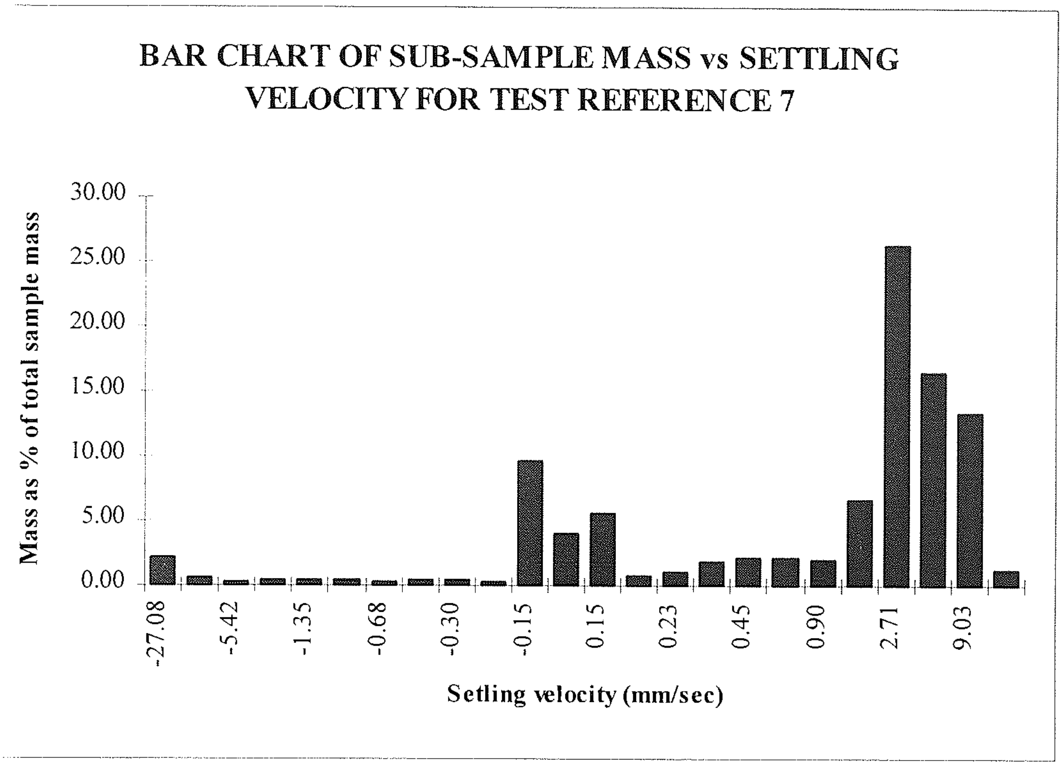
Results of the settling velocity measurement test and the grading curve for site reference 6, test 6.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 6
Mass as % of total sample mass
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-27.08
-5.42
-1.35
-0.68
-0.30
-0.15
0.15
0.23
0.45
0.90
2.71
9.03
Settling velocity (mm/sec)

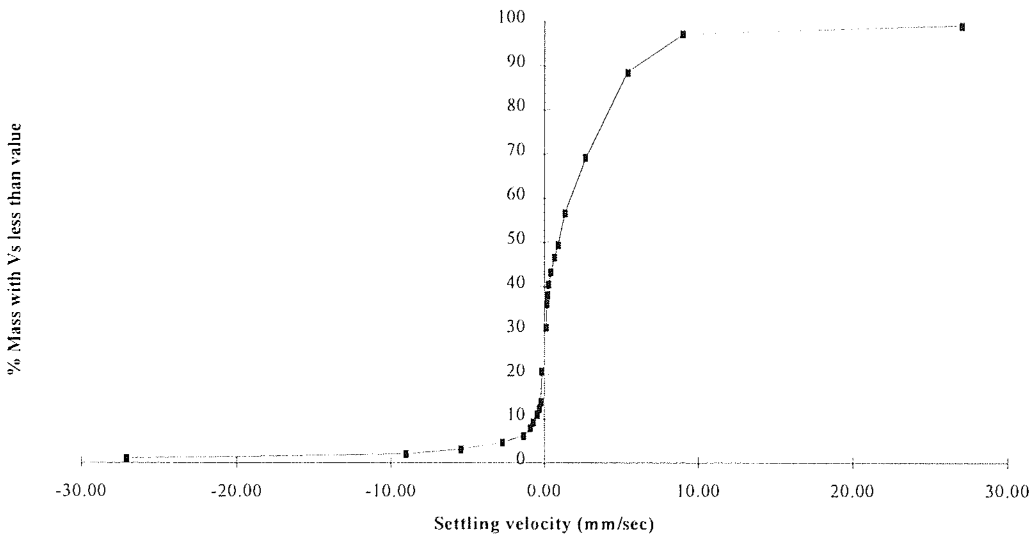
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	2.21	0.054	2.21	0.049	90.7	0.005
-9.03	2.81	0.015	0.61	0.012	80.0	0.003
-5.42	3.15	0.008	0.33	0.006	75.0	0.002
-2.71	3.64	0.012	0.49	0.008	66.7	0.004
-1.35	4.13	0.012	0.49	0.009	0.0	0.003
-0.87	4.62	0.012	0.49	0.011	91.7	0.001
-0.68	4.99	0.009	0.37	0.008	88.9	0.001
-0.45	5.40	0.010	0.41	0.009	90.0	0.001
-0.30	5.81	0.010	0.41	0.007	70.0	0.003
-0.23	6.14	0.008	0.33	0.007	0.0	0.001
-0.15	15.78	0.236	9.64	0.200	84.7	0.036
0.00		0.100	4.09	0.096	96.0	0.004
0.15	19.87	0.139	5.68	0.118	84.9	0.021
0.18	25.55	0.019	0.78	0.015	78.9	0.004
0.23	26.33	0.026	1.06	0.021	80.8	0.005
0.30	27.39	0.044	1.80	0.035	79.5	0.009
0.45	29.19	0.054	2.21	0.043	79.6	0.011
0.68	31.40	0.053	2.17	0.044	83.0	0.009
0.90	33.57	0.050	2.04	0.041	82.0	0.009
1.35	35.61	0.165	6.75	0.137	83.0	0.028
2.71	42.36	0.644	26.33	0.546	84.8	0.098
5.42	68.69	0.407	16.64	0.360	88.5	0.047
9.03	85.33	0.329	13.45	0.293	89.1	0.036
27.08	98.78	0.030	1.23	0.025	83.3	0.005



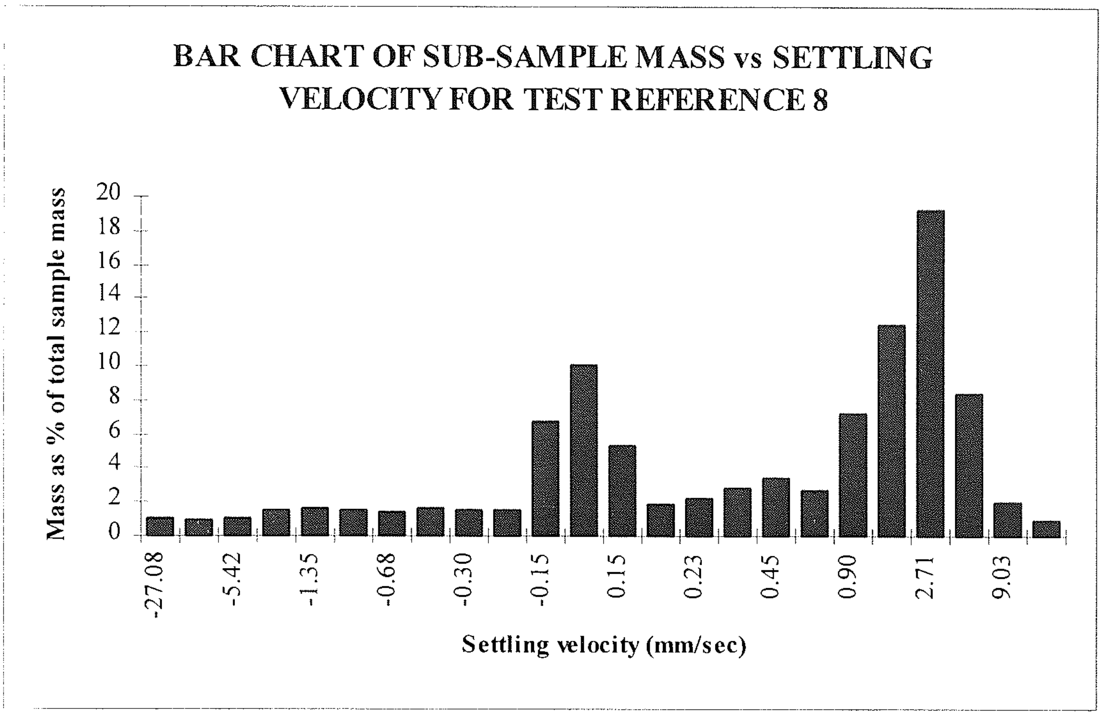
Results of the settling velocity measurement test and the grading curve for site reference 7, test 7.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 7
Mass as % of total sample mass
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-27.08
-5.42
-1.35
-0.68
-0.30
-0.15
0.15
0.23
0.45
0.90
2.71
9.03
Setling velocity (mm/sec)

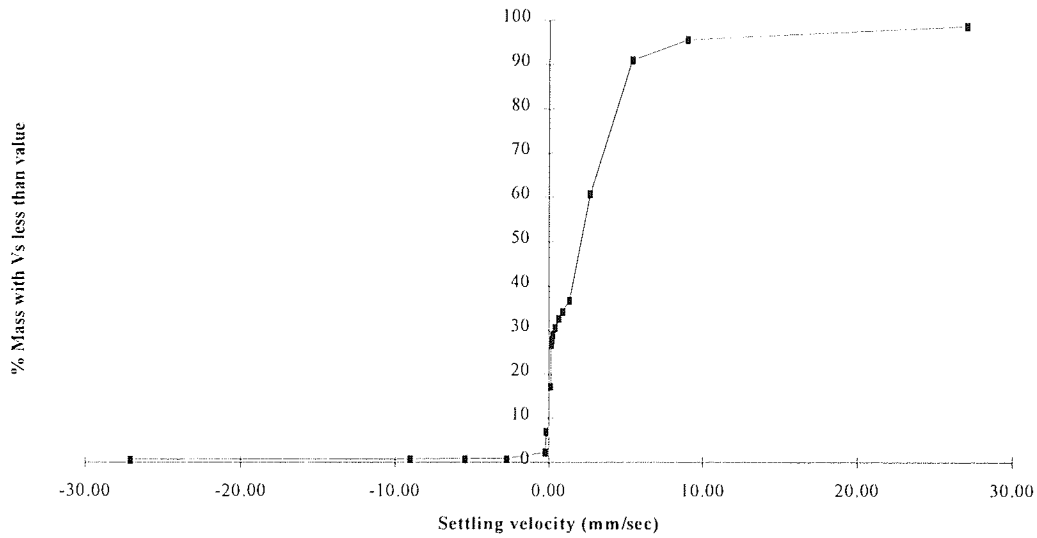
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	1.07	0.015	1.07	0.011	73.3	0.004
-9.03	2.00	0.013	0.93	0.009	69.2	0.004
-5.42	3.07	0.015	1.07	0.012	80.0	0.003
-2.71	4.64	0.022	1.57	0.017	77.3	0.005
-1.35	6.29	0.023	1.65	0.017	73.9	0.006
-0.90	7.86	0.022	1.57	0.016	72.7	0.006
-0.68	9.29	0.020	1.43	0.015	75.0	0.005
-0.45	10.94	0.023	1.65	0.018	78.3	0.005
-0.30	12.44	0.021	1.50	0.016	76.2	0.005
-0.23	13.94	0.021	1.50	0.017	81.0	0.004
-0.15	20.74	0.095	6.80	0.079	83.2	0.016
0.00		0.142	10.16	0.115	81.0	0.027
0.15	30.90	0.075	5.36	0.059	78.7	0.016
0.18	36.26	0.027	1.93	0.021	77.8	0.006
0.23	38.19	0.031	2.22	0.024	77.4	0.007
0.30	40.41	0.040	2.86	0.031	77.5	0.009
0.45	43.27	0.049	3.51	0.041	83.7	0.008
0.68	46.78	0.039	2.79	0.032	82.1	0.007
0.90	49.57	0.101	7.22	0.085	84.2	0.016
1.35	56.79	0.174	12.45	0.151	86.8	0.023
2.71	69.24	0.270	19.31	0.240	88.9	0.030
5.42	88.55	0.119	8.51	0.106	89.1	0.013
9.03	97.06	0.028	2.00	0.025	89.3	0.003
27.08	99.06	0.013	0.93	0.010	76.9	0.003



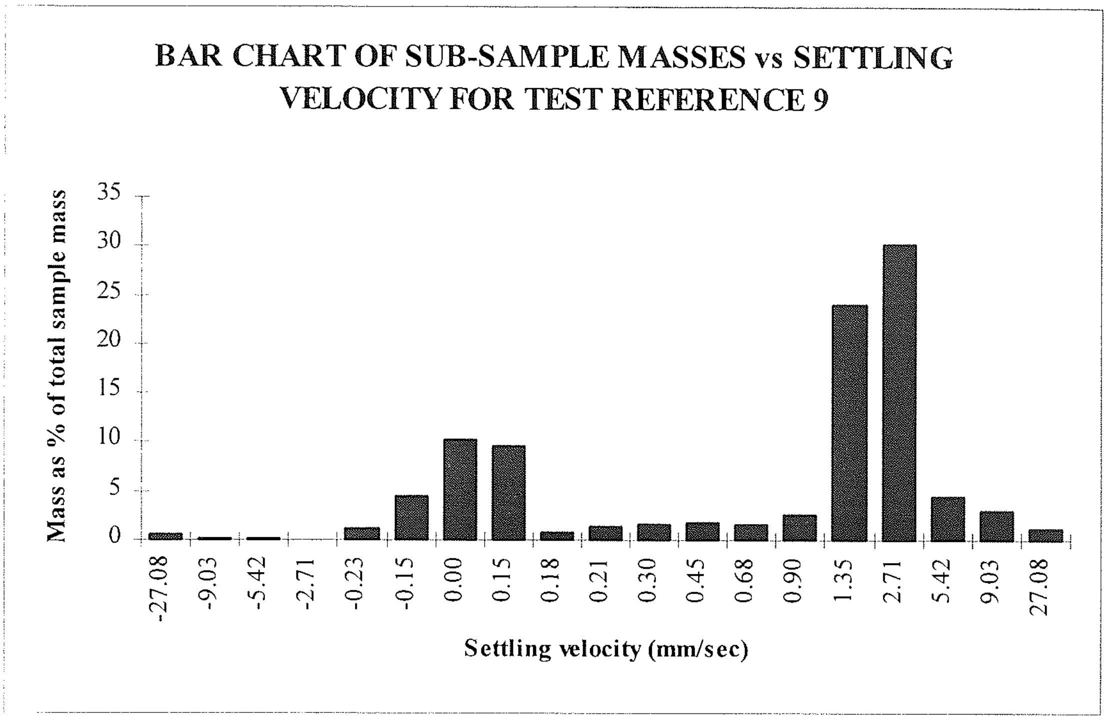
Results of the settling velocity measurement test and the grading curve for site reference 8, test 8.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 8
Mass as % of total sample mass
20
18
16
14
12
10
8
6
4
2
0
-27.08
-5.42
-1.35
-0.68
-0.30
-0.15
0.15
0.23
0.45
0.90
2.71
9.03
Settling velocity (mm/sec)

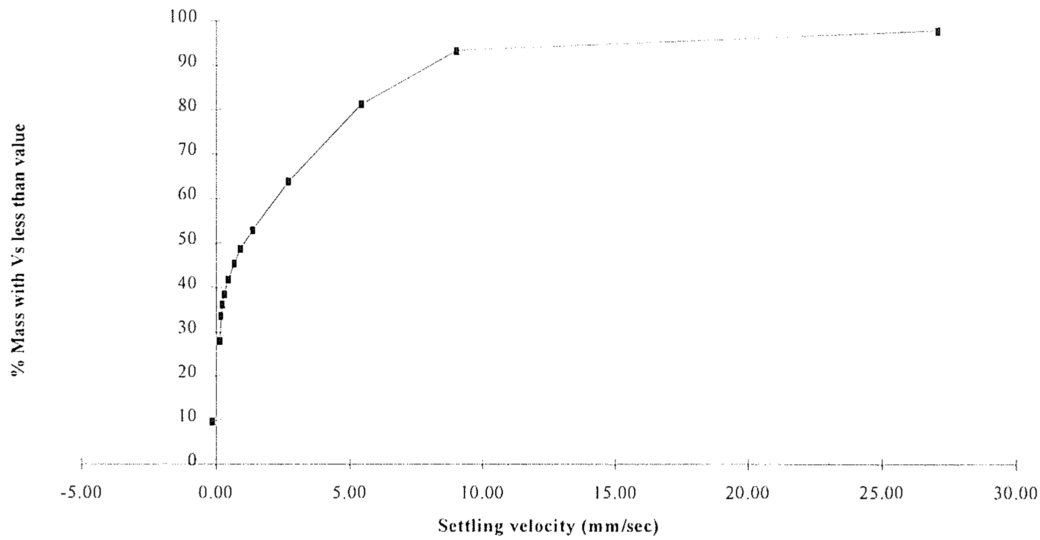
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.66	0.012	0.66	0.012	100.0	0.000
-9.03	0.77	0.002	0.11	0.002	100.0	0.000
-5.42	0.88	0.002	0.11	0.000	0.0	0.002
-2.71	0.88	0.000	0.00	0.000	0.0	0.000
-0.23	2.20	0.024	1.32	0.017	70.8	0.007
-0.15	6.82	0.084	4.62	0.054	64.3	0.030
0.00		0.187	10.27	0.150	80.2	0.037
0.15	17.09	0.176	9.67	0.108	61.4	0.068
0.18	26.76	0.015	0.82	0.010	66.7	0.005
0.21	27.58	0.025	1.37	0.013	52.0	0.012
0.30	28.95	0.030	1.65	0.016	53.3	0.014
0.45	30.60	0.034	1.87	0.018	52.9	0.016
0.68	32.47	0.030	1.65	0.017	56.7	0.013
0.90	34.12	0.047	2.58	0.027	57.4	0.020
1.35	36.70	0.439	24.12	0.255	58.1	0.184
2.71	60.82	0.550	30.22	0.328	59.6	0.222
5.42	91.04	0.084	4.62	0.056	66.7	0.028
9.03	95.66	0.055	3.02	0.037	67.3	0.018
27.08	98.68	0.024	1.32	0.015	62.5	0.009



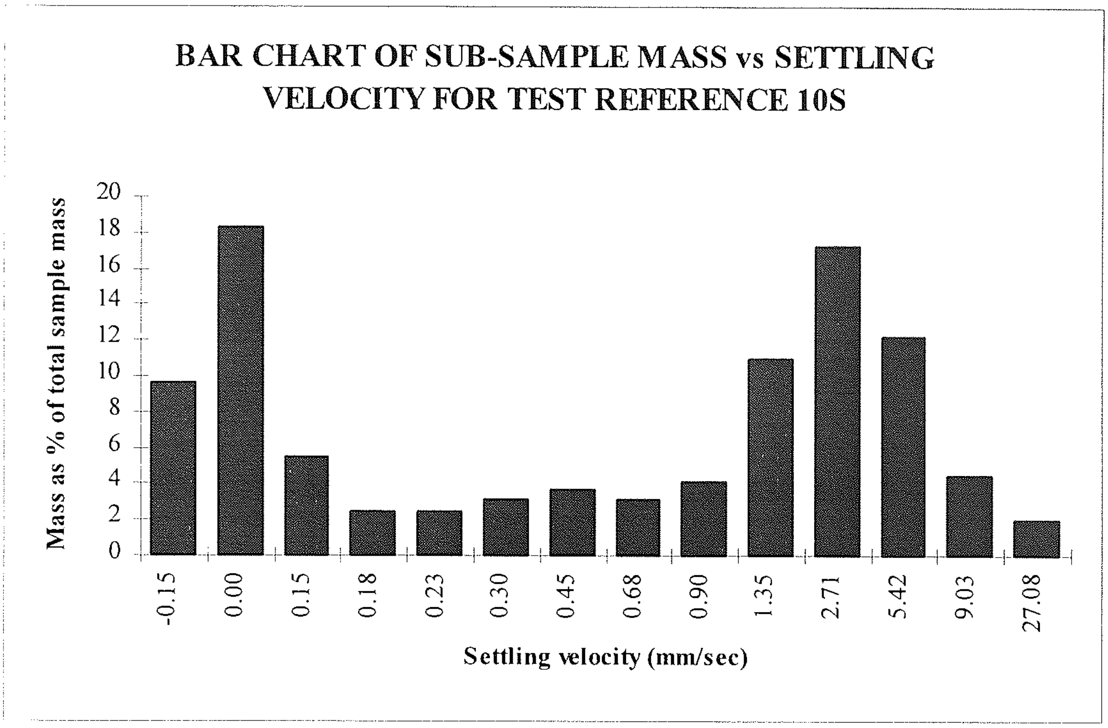
Results of the settling velocity measurement test and the grading curve for site reference 9, test 9.


BAR CHART OF SUB-SAMPLE MASSES vs SETTLING VELOCITY FOR TEST REFERENCE 9
Mass as % of total sample mass
35
30
25
20
15
10
5
0
-27.08
-9.03
-5.42
-2.71
-0.23
-0.15
0.00
0.15
0.18
0.21
0.30
0.45
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

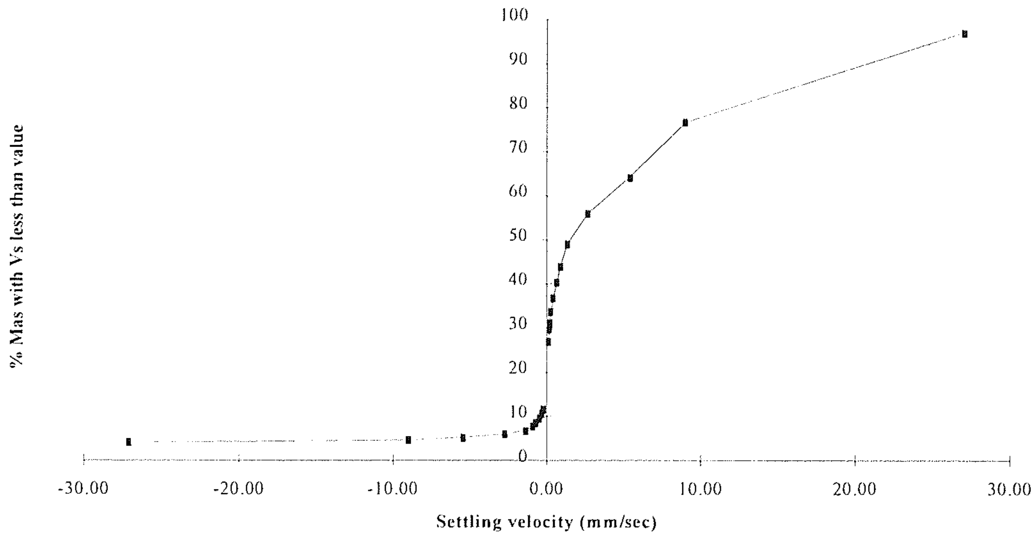
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	9.69	0.100	9.69	0.086	86.0	0.014
0.00		0.189	18.31	0.168	88.9	0.021
0.15	28.00	0.057	5.52	0.045	78.9	0.012
0.18	33.52	0.026	2.52	0.021	80.8	0.005
0.23	36.04	0.026	2.52	0.022	84.6	0.004
0.30	38.56	0.033	3.20	0.028	84.8	0.005
0.45	41.76	0.038	3.68	0.030	78.9	0.008
0.68	45.44	0.033	3.20	0.027	81.8	0.006
0.90	48.64	0.043	4.17	0.035	81.4	0.008
1.35	52.81	0.114	11.05	0.094	82.5	0.020
2.71	63.86	0.179	17.34	0.153	85.5	0.026
5.42	81.20	0.126	12.21	0.110	87.3	0.016
9.03	93.41	0.047	4.55	0.039	83.0	0.008
27.08	97.96	0.021	2.03	0.013	61.9	0.008



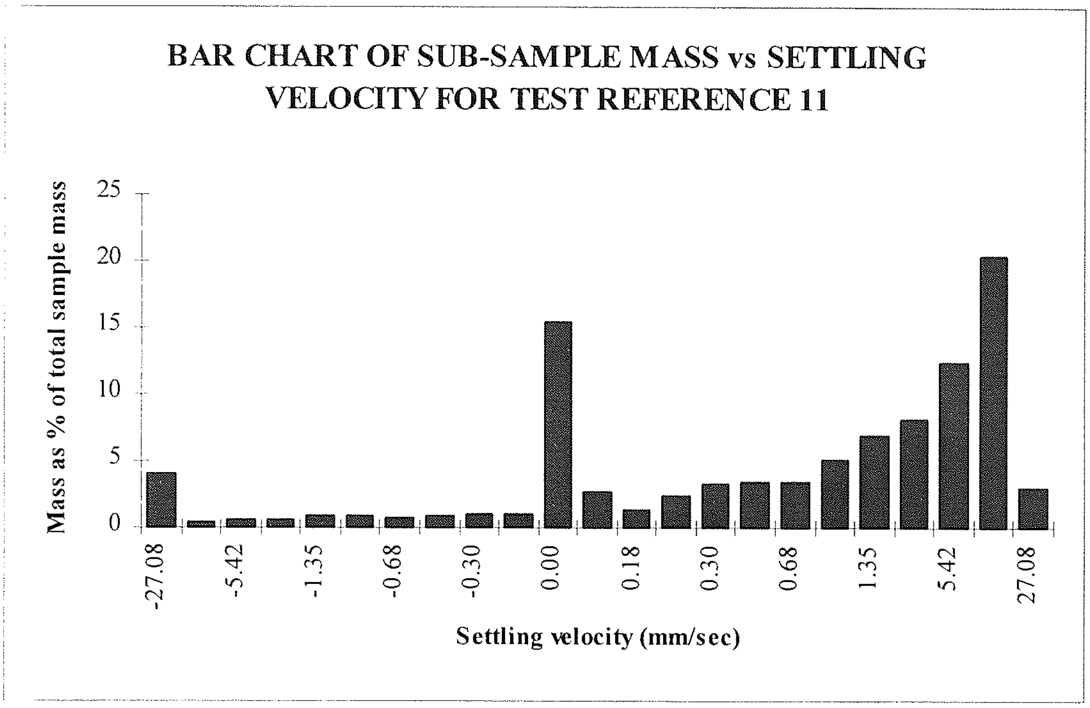
Results of the settling velocity measurement test and grading curve for site reference 10, test 10S.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 10S
Mass as % of total sample mass
20
18
16
14
12
10
8
6
4
2
0
-0.15
0.00
0.15
0.18
0.23
0.30
0.45
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

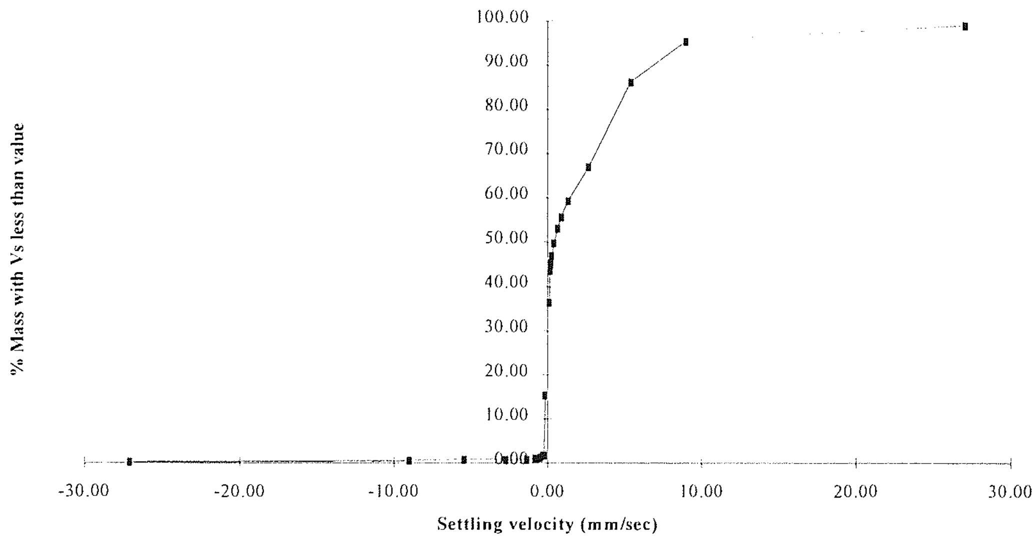
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	4.05	0.063	4.05	0.062	98.4	0.001
-9.03	4.56	0.008	0.51	0.008	100.0	0.000
-5.42	5.20	0.010	0.64	0.008	80.0	0.002
-2.71	5.84	0.010	0.64	0.008	80.0	0.002
-1.35	6.81	0.015	0.97	0.014	93.3	0.001
-0.90	7.78	0.015	0.97	0.013	86.7	0.002
-0.68	8.49	0.011	0.71	0.009	81.8	0.002
-0.45	9.39	0.014	0.90	0.012	85.7	0.002
-0.30	10.48	0.017	1.09	0.014	82.4	0.003
-0.23	11.51	0.016	1.03	0.015	93.8	0.001
0.00		0.241	15.51	0.220	91.3	0.021
0.15	27.02	0.042	2.70	0.034	81.0	0.008
0.18	29.72	0.022	1.42	0.019	86.4	0.003
0.23	31.14	0.037	2.38	0.030	81.1	0.007
0.30	33.52	0.051	3.28	0.041	80.4	0.010
0.45	36.80	0.055	3.54	0.044	80.0	0.011
0.68	40.34	0.054	3.47	0.047	87.0	0.007
0.90	43.81	0.081	5.21	0.068	84.0	0.013
1.35	49.02	0.108	6.95	0.089	82.4	0.019
2.71	55.97	0.128	8.24	0.112	87.5	0.016
5.42	64.21	0.192	12.36	0.168	87.5	0.024
9.03	76.57	0.317	20.40	0.283	89.3	0.034
27.08	96.97	0.047	3.02	0.039	83.0	0.008



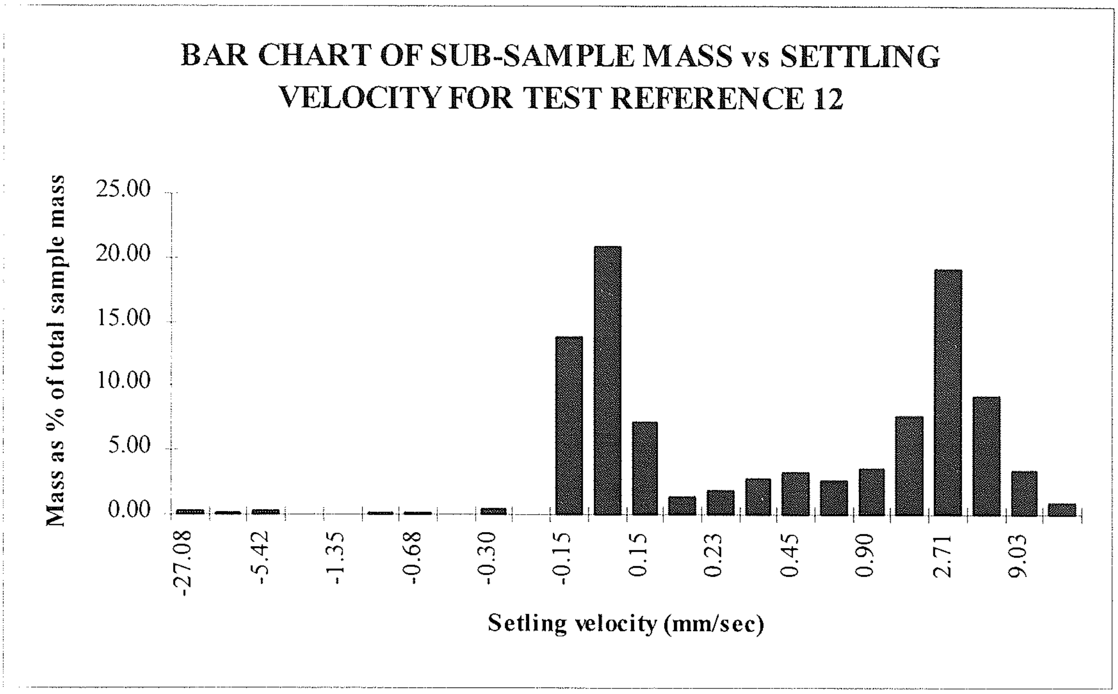
Results of the settling velocity measurement test and grading curve for site reference 11, test 11.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 11
Mass as % of total sample mass
25
20
15
10
5
0
-27.08
-5.42
-1.35
-0.68
-0.30
0.00
0.18
0.30
0.68
1.35
5.42
27.08
Settling velocity (mm/sec)

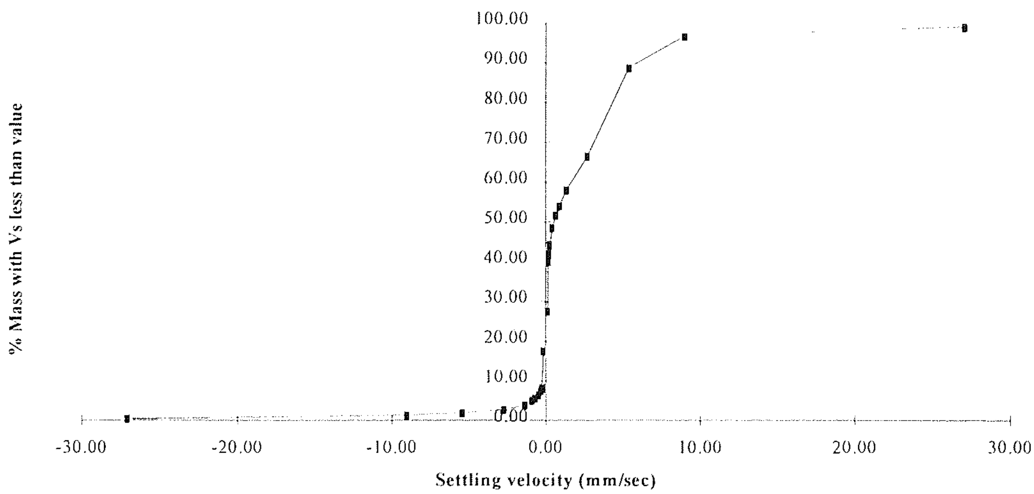
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.34	0.005	0.34	0.002	40.0	0.003
-9.03	0.54	0.003	0.20	0.000	0.0	0.003
-5.42	0.81	0.004	0.27	0.002	50.0	0.002
-2.71	0.88	0.001	0.07	0.001	100.0	0.000
-1.35	0.88	0.000	0.00	0.000	0.0	0.000
-0.82	1.02	0.002	0.14	0.001	50.0	0.001
-0.68	1.16	0.002	0.14	0.001	50.0	0.001
-0.45	1.23	0.001	0.07	0.000	0.0	0.001
-0.30	1.70	0.007	0.47	0.004	57.1	0.003
-0.23	1.70	0.000	0.00	0.000	0.0	0.000
-0.15	15.51	0.204	13.81	0.171	83.8	0.033
0.00		0.308	20.85	0.276	89.6	0.032
0.15	36.36	0.106	7.18	0.086	81.1	0.020
0.18	43.54	0.022	1.49	0.015	68.2	0.007
0.23	45.05	0.028	1.90	0.021	75.0	0.007
0.30	46.93	0.042	2.84	0.032	76.2	0.010
0.45	49.77	0.049	3.32	0.039	79.6	0.010
0.68	53.09	0.039	2.64	0.031	79.5	0.008
0.90	55.73	0.053	3.59	0.042	79.2	0.011
1.35	59.32	0.113	7.65	0.093	82.3	0.020
2.71	66.97	0.284	19.23	0.240	84.5	0.044
5.42	86.20	0.137	9.28	0.119	86.9	0.018
9.03	95.48	0.052	3.52	0.041	78.8	0.011
27.08	99.00	0.015	1.02	0.011	73.3	0.004



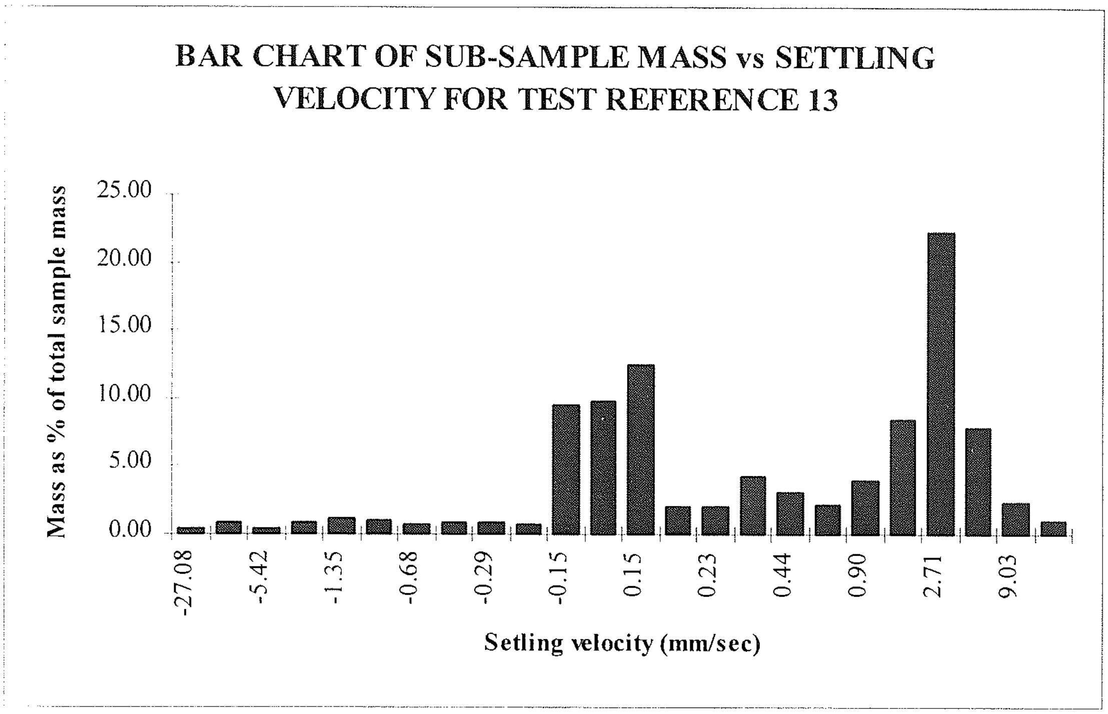
Results of the settling velocity measurement test and grading curve for site reference 12, test 12.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 12
Mass as % of total sample mass
25.00
20.00
15.00
10.00
5.00
0.00
-27.08
-5.42
-1.35
-0.68
-0.30
-0.15
0.15
0.23
0.45
0.90
2.71
9.03
Setling velocity (mm/sec)

Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.47	0.010	0.47	0.007	70.0	0.003
-9.03	1.32	0.018	0.85	0.013	72.2	0.005
-5.42	1.84	0.011	0.52	0.008	72.7	0.003
-2.71	2.69	0.018	0.85	0.013	72.2	0.005
-1.35	3.87	0.025	1.18	0.019	0.0	0.006
-0.90	4.91	0.022	1.04	0.017	77.3	0.005
-0.68	5.62	0.015	0.71	0.012	80.0	0.003
-0.45	6.47	0.018	0.85	0.013	72.2	0.005
-0.29	7.41	0.020	0.94	0.017	85.0	0.003
-0.23	8.12	0.015	0.71	0.011	0.0	0.004
-0.15	17.58	0.201	9.46	0.167	83.1	0.034
0.00		0.208	9.79	0.176	84.6	0.032
0.15	27.37	0.267	12.56	0.224	83.9	0.043
0.17	39.93	0.045	2.12	0.035	77.8	0.010
0.23	42.05	0.045	2.12	0.033	73.3	0.012
0.30	44.17	0.091	4.28	0.073	80.2	0.018
0.44	48.45	0.066	3.11	0.055	83.3	0.011
0.68	51.56	0.048	2.26	0.038	79.2	0.010
0.90	53.82	0.087	4.09	0.071	81.6	0.016
1.35	57.91	0.180	8.47	0.155	86.1	0.025
2.71	66.38	0.475	22.35	0.404	85.1	0.071
5.42	88.73	0.167	7.86	0.145	86.8	0.022
9.03	96.59	0.051	2.40	0.045	88.2	0.006
27.08	98.99	0.022	1.04	0.018	81.8	0.004

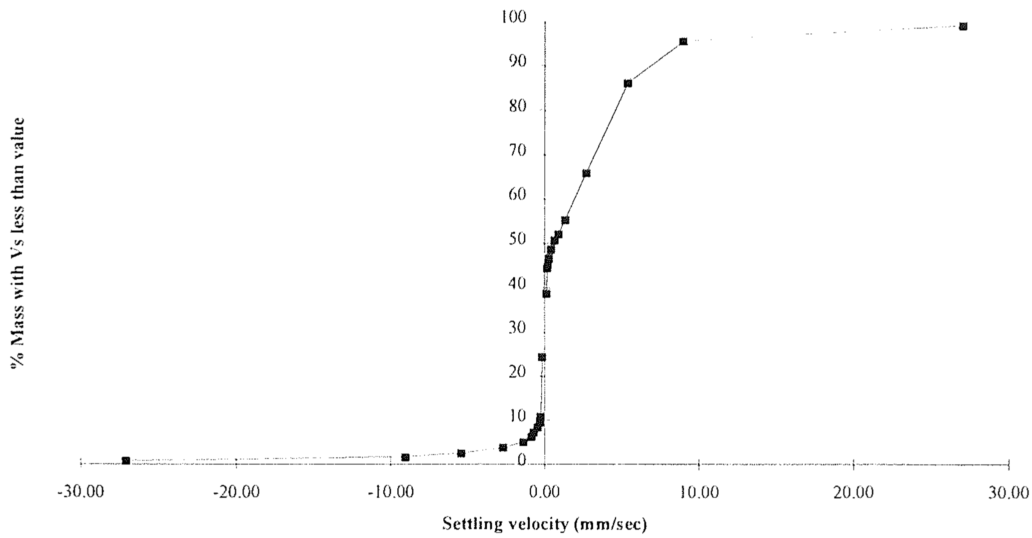


Results of the settling velocity measurement test and grading curve for site reference 13, test 13.

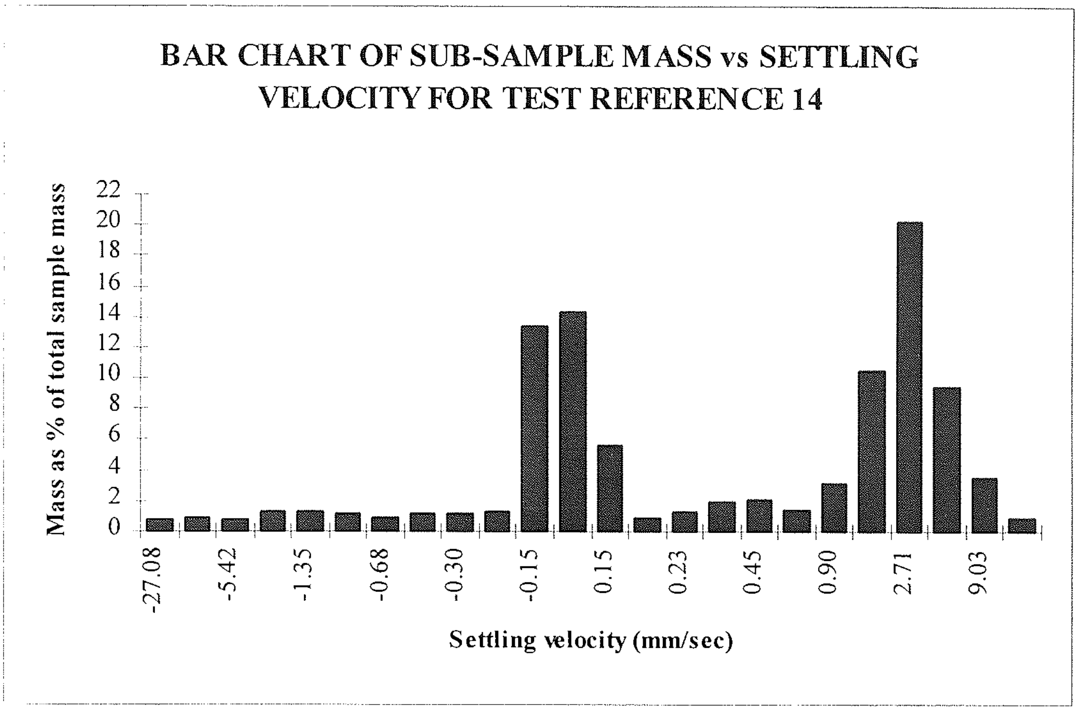


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 13
Mass as % of total sample mass
25.00
20.00
15.00
10.00
5.00
0.00
-27.08
-5.42
-1.35
-0.68
-0.29
-0.15
0.15
0.23
0.44
0.90
2.71
9.03
Setling velocity (mm/sec)

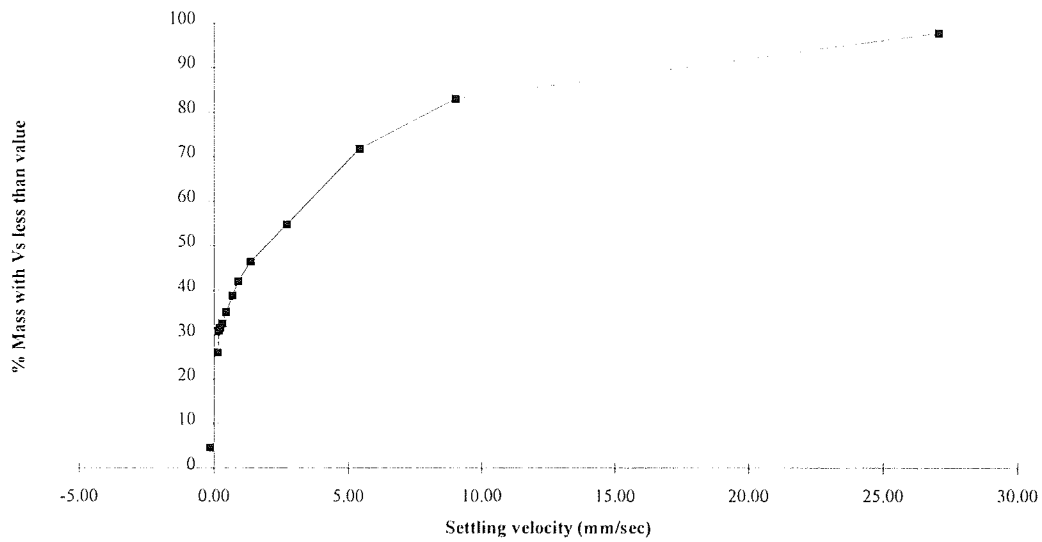
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.79	0.013	0.79	0.008	61.5	0.005
-9.03	1.70	0.015	0.91	0.010	66.7	0.005
-5.42	2.49	0.013	0.79	0.009	69.2	0.004
-2.71	3.77	0.021	1.28	0.015	71.4	0.006
-1.35	5.05	0.021	1.28	0.017	81.0	0.004
-0.85	6.27	0.020	1.22	0.015	75.0	0.005
-0.68	7.24	0.016	0.97	0.012	75.0	0.004
-0.45	8.39	0.019	1.15	0.013	68.4	0.006
-0.30	9.54	0.019	1.15	0.013	68.4	0.006
-0.23	10.88	0.022	1.34	0.017	77.3	0.005
-0.15	24.31	0.221	13.43	0.183	82.8	0.038
0.00		0.237	14.40	0.194	81.9	0.043
0.15	38.71	0.094	5.71	0.070	74.5	0.024
0.18	44.42	0.016	0.97	0.010	62.5	0.006
0.23	45.39	0.021	1.28	0.015	71.4	0.006
0.30	46.67	0.032	1.94	0.023	71.9	0.009
0.45	48.61	0.034	2.07	0.024	70.6	0.010
0.68	50.68	0.024	1.46	0.018	75.0	0.006
0.90	52.14	0.051	3.10	0.038	74.5	0.013
1.35	55.24	0.174	10.57	0.145	83.3	0.029
2.71	65.81	0.335	20.35	0.286	85.4	0.049
5.42	86.16	0.155	9.42	0.136	87.7	0.019
9.03	95.58	0.058	3.52	0.051	87.9	0.007
27.08	99.10	0.015	0.91	0.010	66.7	0.005



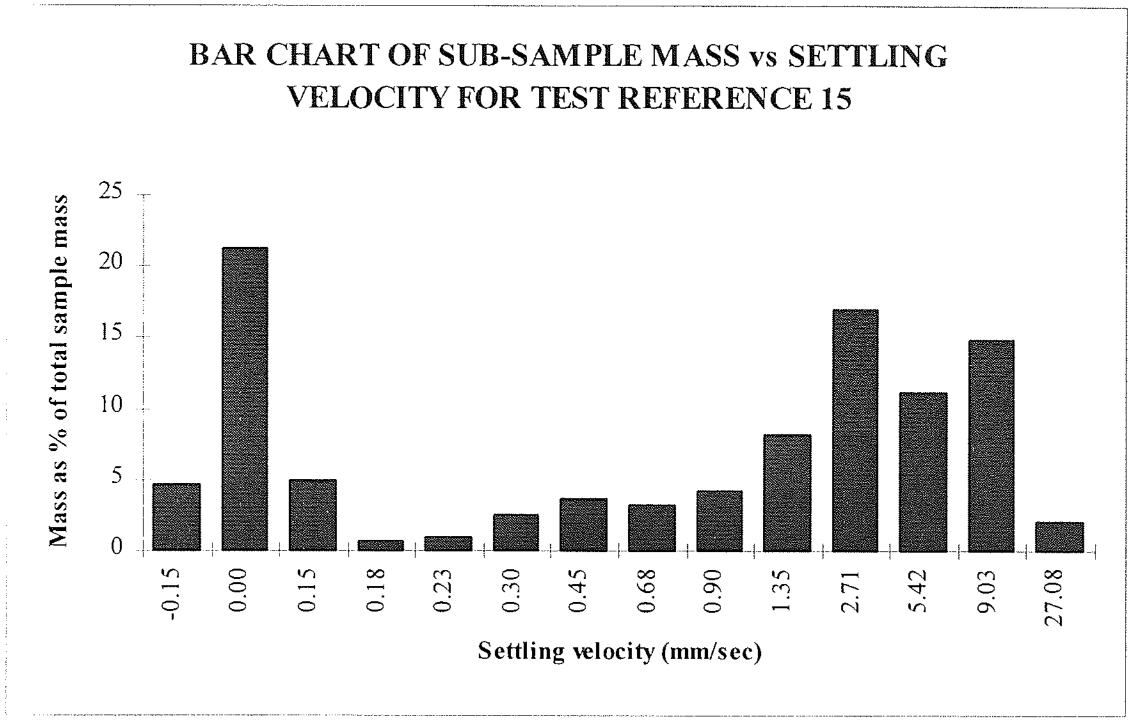
Results of the settling velocity measurement test and grading curve for site reference 14, test 14.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 14
Mass as % of total sample mass
22
20
18
16
14
12
10
8
6
4
2
0
-27.08
-5.42
-1.35
-0.68
-0.30
-0.15
0.15
0.23
0.45
0.90
2.71
9.03
Settling velocity (mm/sec)

Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	4.66	0.098	4.66	0.079	80.6	0.019
0.00		0.252	21.34	0.199	79.0	0.053
0.15	26.00	0.059	5.00	0.044	74.6	0.015
0.18	31.00	0.008	0.68	0.005	62.5	0.003
0.23	31.68	0.012	1.02	0.008	66.7	0.004
0.30	32.70	0.030	2.54	0.011	36.7	0.019
0.45	35.24	0.043	3.64	0.030	69.8	0.013
0.68	38.88	0.038	3.22	0.027	71.1	0.011
0.90	42.10	0.051	4.32	0.036	70.6	0.015
1.35	46.42	0.098	8.30	0.072	73.5	0.026
2.71	54.72	0.201	17.02	0.147	73.1	0.054
5.42	71.74	0.133	11.26	0.100	75.2	0.033
9.03	83.00	0.176	14.90	0.132	75.0	0.044
27.08	97.90	0.025	2.12	0.019	76.0	0.006

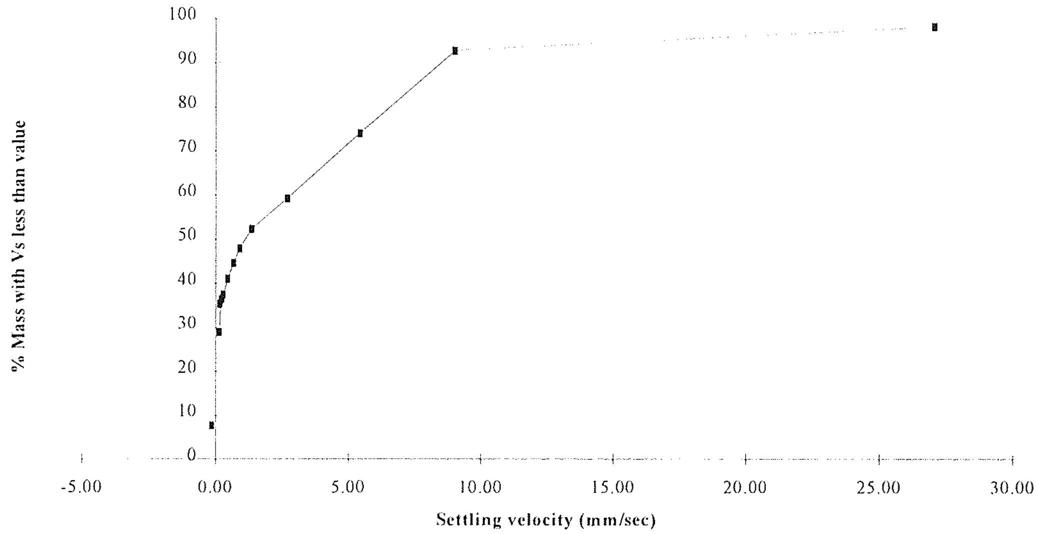


Results of the settling velocity measurement test and grading curve for site reference 15, test 15.

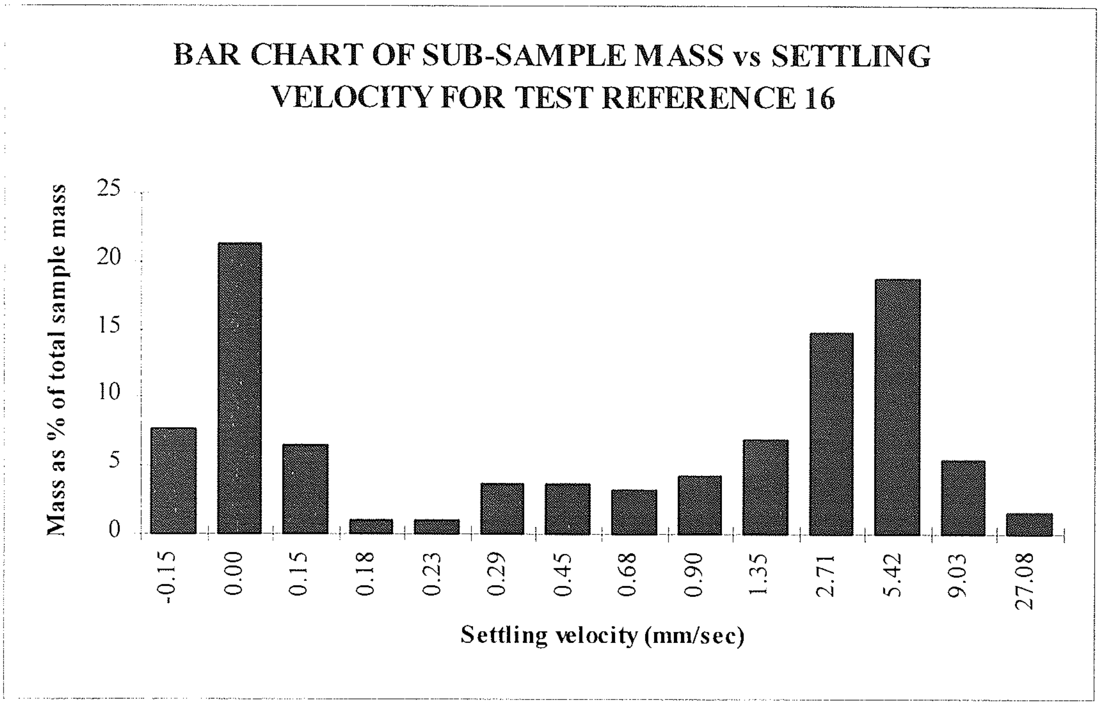


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 15
Mass as % of total sample mass
25
20
15
10
5
0
-0.15
0.00
0.15
0.18
0.23
0.30
0.45
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

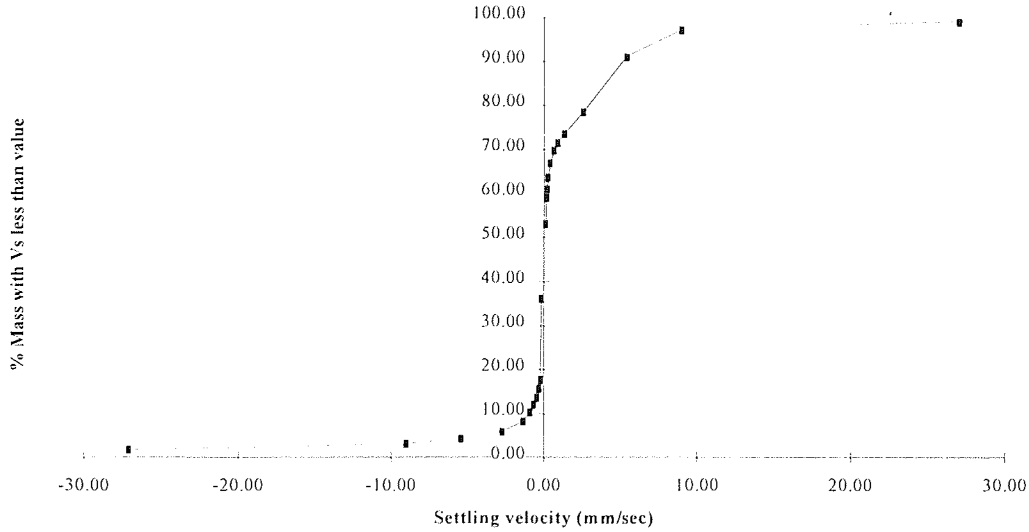
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	7.64	0.046	7.64	0.034	73.9	0.012
0.00		0.128	21.26	0.104	81.3	0.024
0.15	28.90	0.039	6.48	0.028	71.8	0.011
0.18	35.38	0.006	1.00	0.003	50.0	0.003
0.23	36.38	0.006	1.00	0.004	66.7	0.002
0.29	37.38	0.022	3.65	0.015	68.2	0.007
0.45	41.03	0.022	3.65	0.014	63.6	0.008
0.68	44.68	0.020	3.32	0.014	70.0	0.006
0.90	48.00	0.026	4.32	0.018	69.2	0.008
1.35	52.32	0.042	6.98	0.029	69.0	0.013
2.71	59.30	0.089	14.78	0.065	73.0	0.024
5.42	74.08	0.113	18.77	0.085	75.2	0.028
9.03	92.85	0.033	5.48	0.025	75.8	0.008
27.08	98.33	0.010	1.66	0.007	70.0	0.003



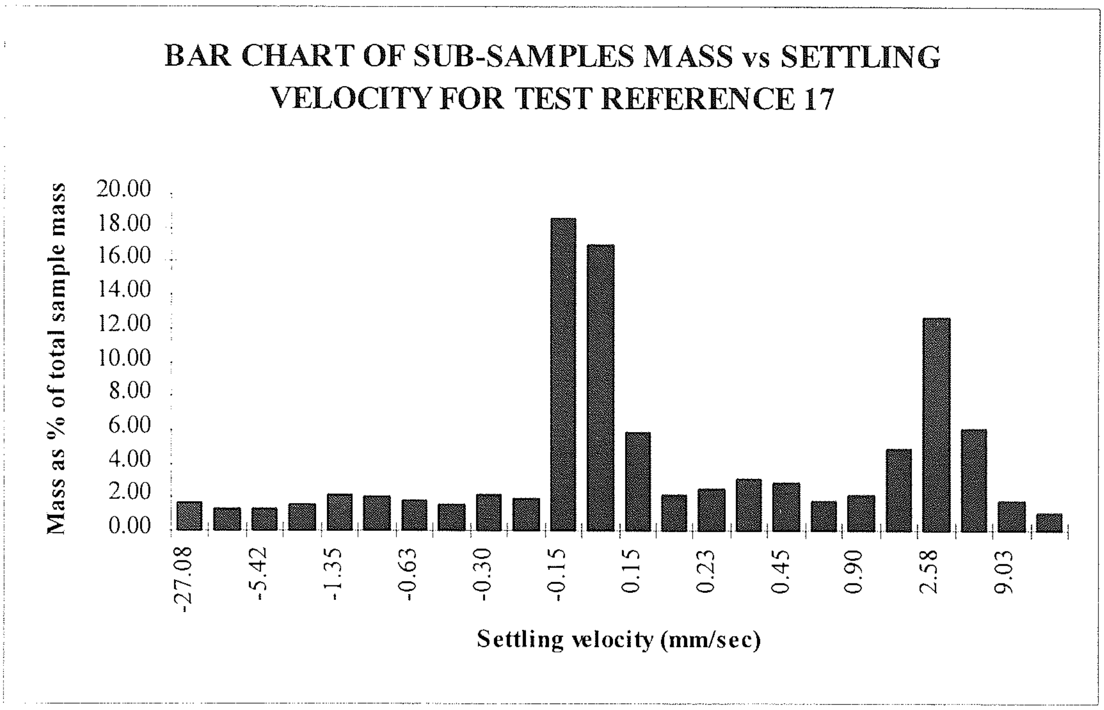
Results of the settling velocity measurement test and grading curve for site reference 16, test 16.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 16
Mass as % of total sample mass
25
20
15
10
5
0
-0.15
0.00
0.15
0.18
0.23
0.29
0.45
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

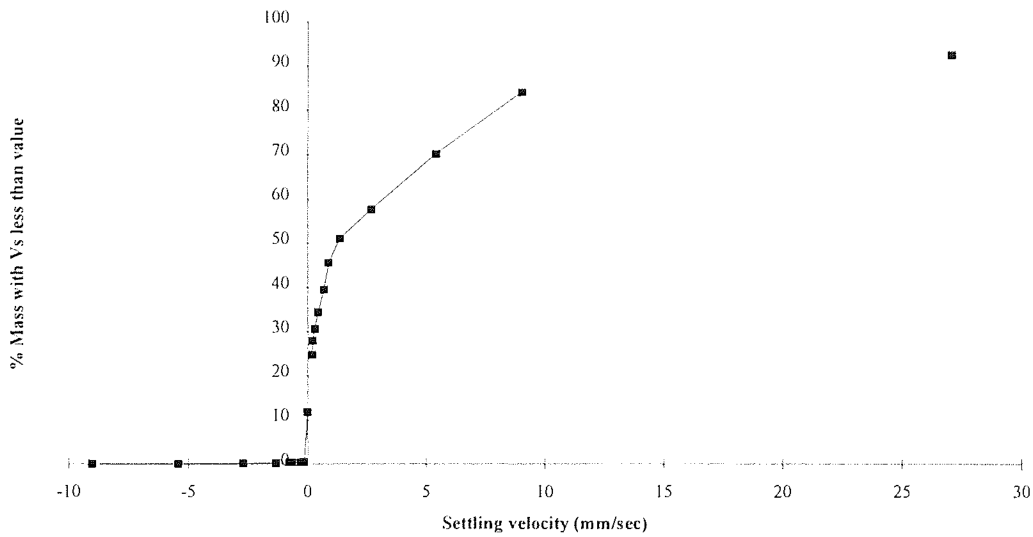
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	1.69	0.015	1.69	0.014	93.3	0.001
-9.03	3.05	0.012	1.36	0.010	83.3	0.002
-5.42	4.41	0.012	1.36	0.009	75.0	0.003
-2.71	5.99	0.014	1.58	0.011	78.6	0.003
-1.35	8.14	0.019	2.15	0.015	78.9	0.004
-0.90	10.17	0.018	2.03	0.013	72.2	0.005
-0.63	11.98	0.016	1.81	0.013	81.3	0.003
-0.45	13.56	0.014	1.58	0.011	78.6	0.003
-0.30	15.71	0.019	2.15	0.014	73.7	0.005
-0.23	17.63	0.017	1.92	0.011	64.7	0.006
-0.15	36.16	0.164	18.53	0.144	87.8	0.020
0.00		0.150	16.95	0.135	90.0	0.015
0.15	53.11	0.052	5.88	0.045	86.5	0.007
0.18	58.99	0.019	2.15	0.017	89.5	0.002
0.23	61.14	0.022	2.49	0.017	77.3	0.005
0.30	63.63	0.028	3.16	0.024	85.7	0.004
0.45	66.79	0.025	2.82	0.021	84.0	0.004
0.68	69.61	0.016	1.81	0.013	81.3	0.003
0.90	71.42	0.019	2.15	0.017	89.5	0.002
1.35	73.57	0.043	4.86	0.039	90.7	0.004
2.58	78.43	0.112	12.66	0.102	91.1	0.010
5.42	91.09	0.054	6.10	0.049	90.7	0.005
9.03	97.19	0.016	1.81	0.013	81.3	0.003
27.08	99.00	0.009	1.02	0.007	77.8	0.002



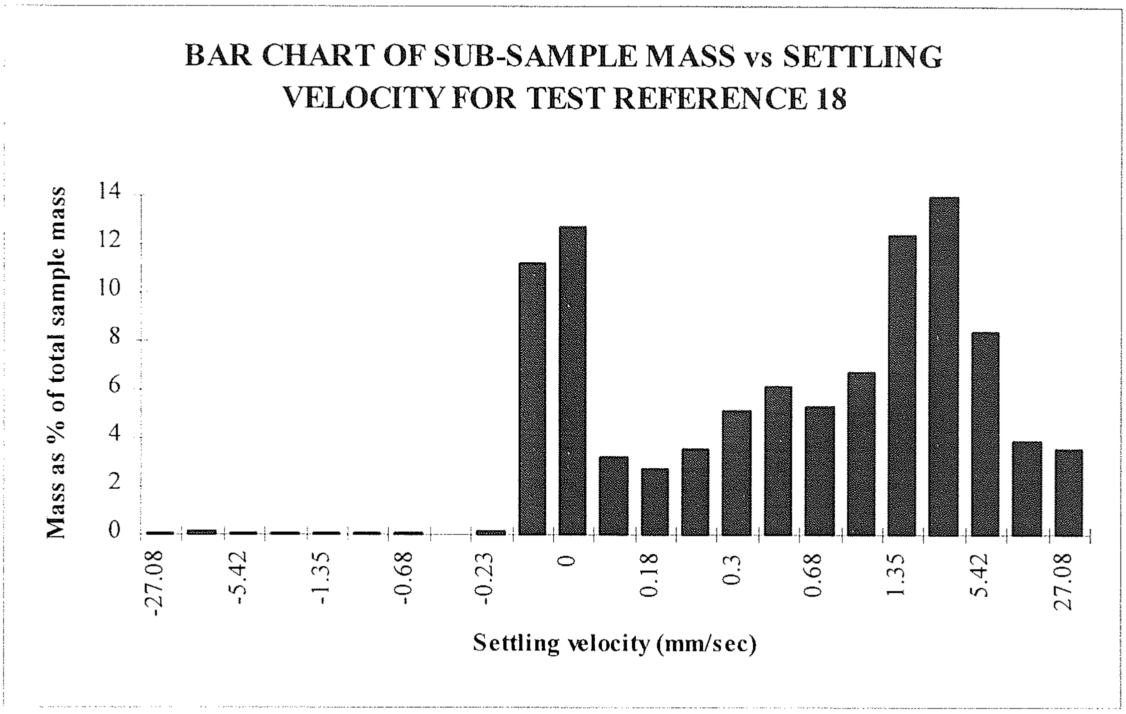
Results of the settling velocity measurement test and grading curve for site reference 17, test 17.


BAR CHART OF SUB-SAMPLES MASS vs SETTLING VELOCITY FOR TEST REFERENCE 17
Mass as % of total sample mass
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
-27.08
-5.42
-1.35
-0.63
-0.30
-0.15
0.15
0.23
0.45
0.90
2.58
9.03
Settling velocity (mm/sec)

Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.05	0.001	0.05	0.001	100.0	0
-9.03	0.19	0.003	0.14	0.003	100.0	0
-5.42	0.24	0.001	0.05	0	0.0	0.001
-2.71	0.34	0.002	0.1	0.001	50.0	0.001
-1.35	0.39	0.001	0.05	0.001	100.0	0
-0.77	0.44	0.001	0.05	0.001	100.0	0
-0.68	0.49	0.001	0.05	0.001	100.0	0
-0.3	0.49	0	0	0	0.0	0
-0.23	0.63	0.003	0.14	0.003	100.0	0
-0.15	11.88	0.234	11.25	0.196	83.8	0.038
0		0.266	12.78	0.232	87.2	0.034
0.15	24.66	0.068	3.27	0.06	88.2	0.008
0.18	27.93	0.058	2.79	0.049	84.5	0.009
0.23	30.72	0.075	3.6	0.062	82.7	0.013
0.3	34.32	0.107	5.14	0.09	84.1	0.017
0.45	39.46	0.129	6.2	0.111	86.0	0.018
0.68	45.66	0.111	5.33	0.095	85.6	0.016
0.9	50.99	0.14	6.73	0.117	83.6	0.023
1.35	57.72	0.259	12.45	0.222	85.7	0.037
2.71	70.17	0.291	13.98	0.254	87.3	0.037
5.42	84.15	0.175	8.41	0.157	89.7	0.018
9.03	92.56	0.081	3.89	0.07	86.4	0.011
27.08	96.45	0.074	3.56	0.064	86.5	0.01

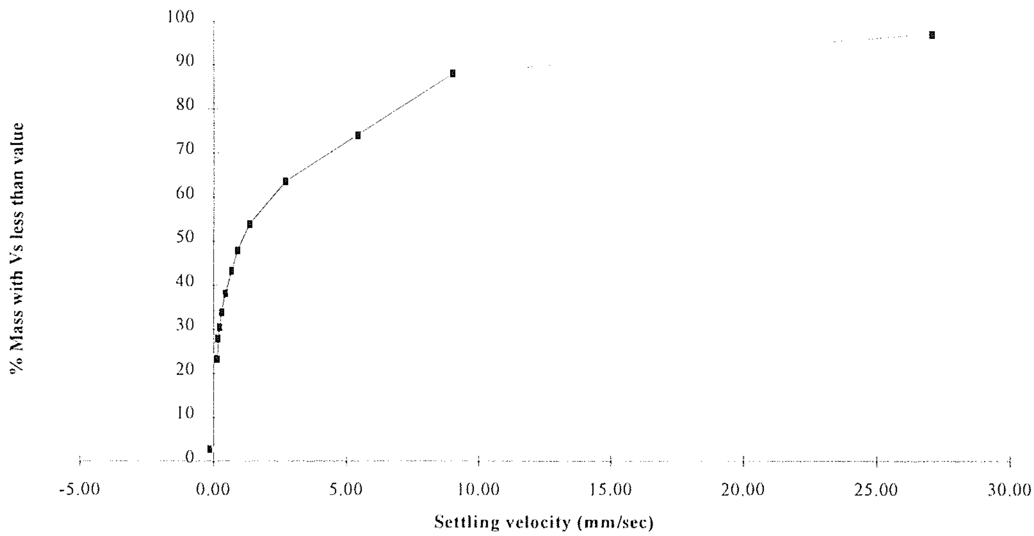


Results of the settling velocity measurement test and grading curve for site reference 18, test 18.

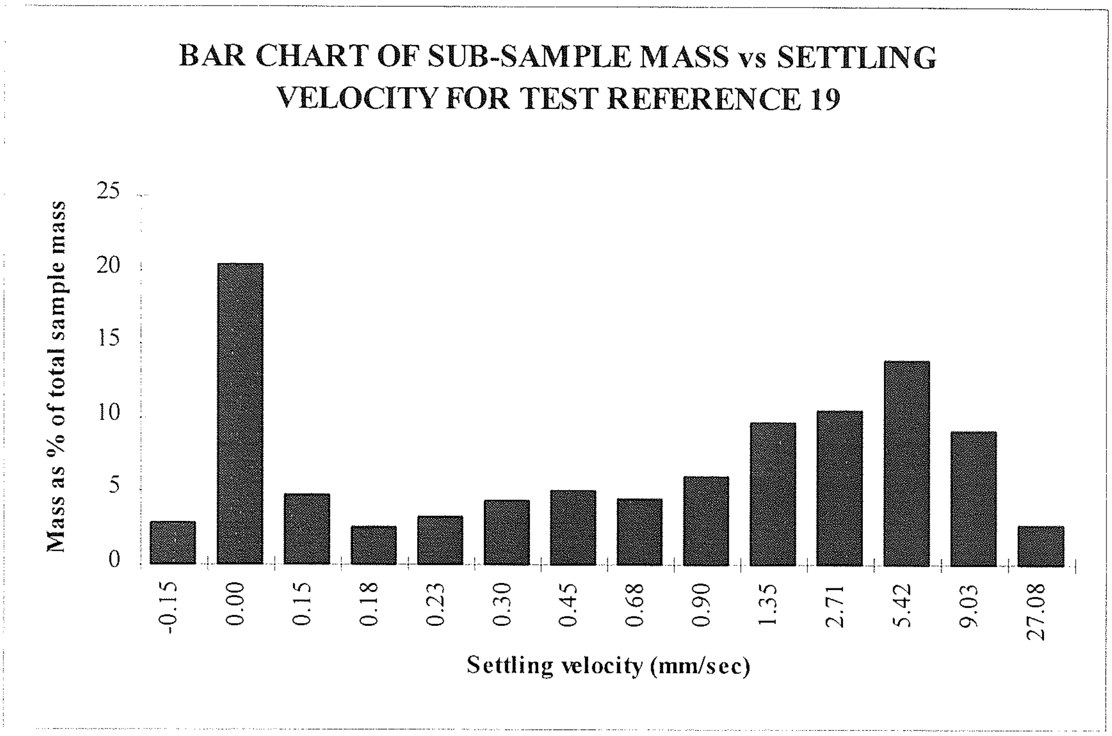


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 18
Mass as % of total sample mass
14
12
10
8
6
4
2
0
-27.08
-5.42
-1.35
-0.68
-0.23
0
0.18
0.3
0.68
1.35
5.42
27.08
Settling velocity (mm/sec)

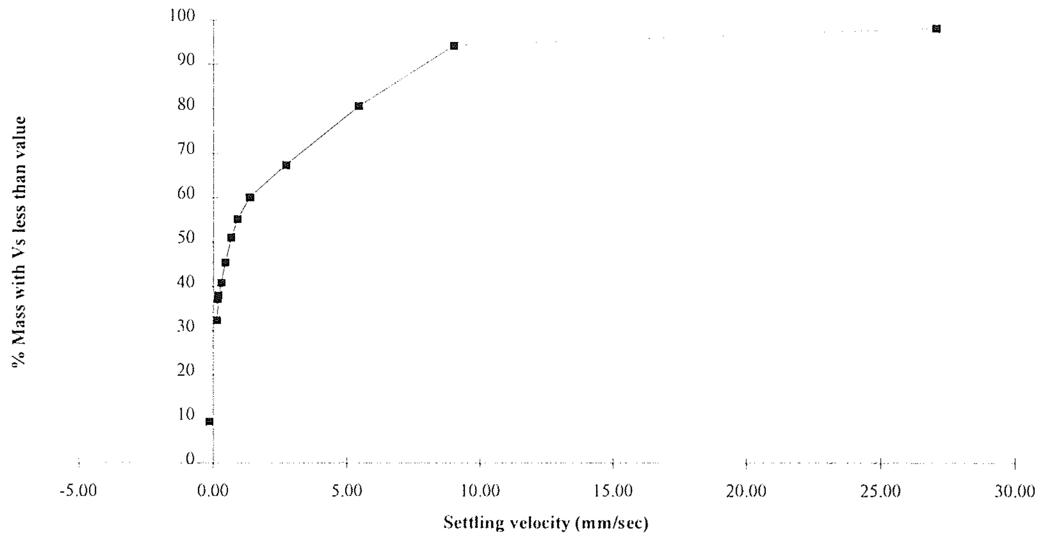
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	2.93	0.086	2.93	0.058	67.4	0.028
0.00		0.236	20.36	0.163	69.1	0.073
0.15	23.29	0.055	4.75	0.036	65.5	0.019
0.18	28.04	0.030	2.59	0.018	60.0	0.012
0.23	30.63	0.038	3.28	0.022	57.9	0.016
0.30	33.91	0.051	4.40	0.028	54.9	0.023
0.45	38.31	0.058	5.00	0.032	55.2	0.026
0.68	43.31	0.053	4.57	0.030	56.6	0.023
0.90	47.88	0.070	6.04	0.040	57.1	0.030
1.35	53.92	0.112	9.66	0.069	61.6	0.043
2.71	63.58	0.122	10.53	0.082	67.2	0.040
5.42	74.11	0.162	13.98	0.118	72.8	0.044
9.03	88.09	0.106	9.15	0.083	78.3	0.023
27.08	97.24	0.032	2.76	0.021	65.6	0.011



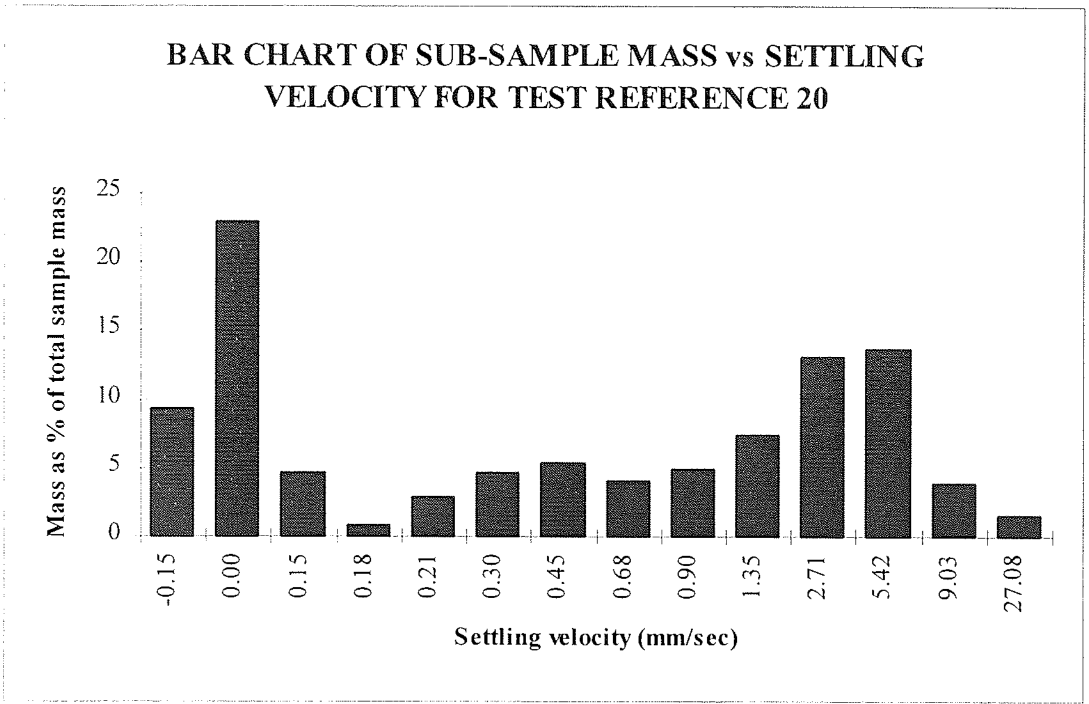
Results of the settling velocity measurement test and grading curve for site reference 19, test 19.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 19
Mass as % of total sample mass
25
20
15
10
5
0
-0.15
0.00
0.15
0.18
0.23
0.30
0.45
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

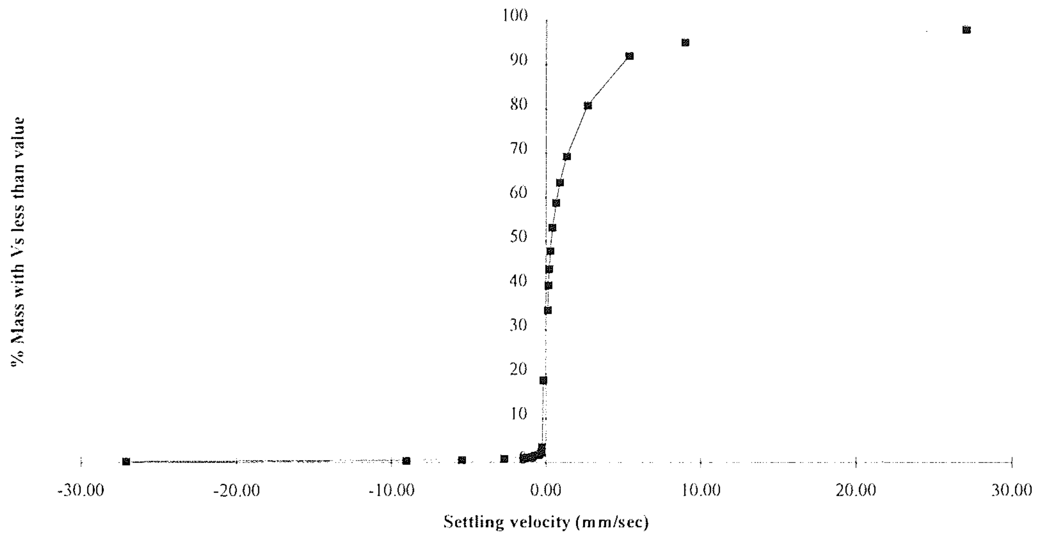
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	9.4	0.103	9.4	0.081	78.6	0.022
0.00		0.252	22.99	0.209	82.9	0.043
0.15	32.39	0.051	4.65	0.04	78.4	0.011
0.18	37.04	0.01	0.91	0.008	80.0	0.002
0.21	37.95	0.032	2.92	0.024	75.0	0.008
0.30	40.87	0.051	4.65	0.038	74.5	0.013
0.45	45.52	0.06	5.47	0.047	78.3	0.013
0.68	50.99	0.045	4.11	0.032	71.1	0.013
0.90	55.1	0.054	4.93	0.041	75.9	0.013
1.35	60.03	0.081	7.39	0.065	80.2	0.016
2.71	67.42	0.144	13.14	0.121	84.0	0.023
5.42	80.56	0.151	13.78	0.135	89.4	0.016
9.03	94.34	0.044	4.01	0.037	84.1	0.007
27.08	98.35	0.018	1.64	0.014	77.8	0.004



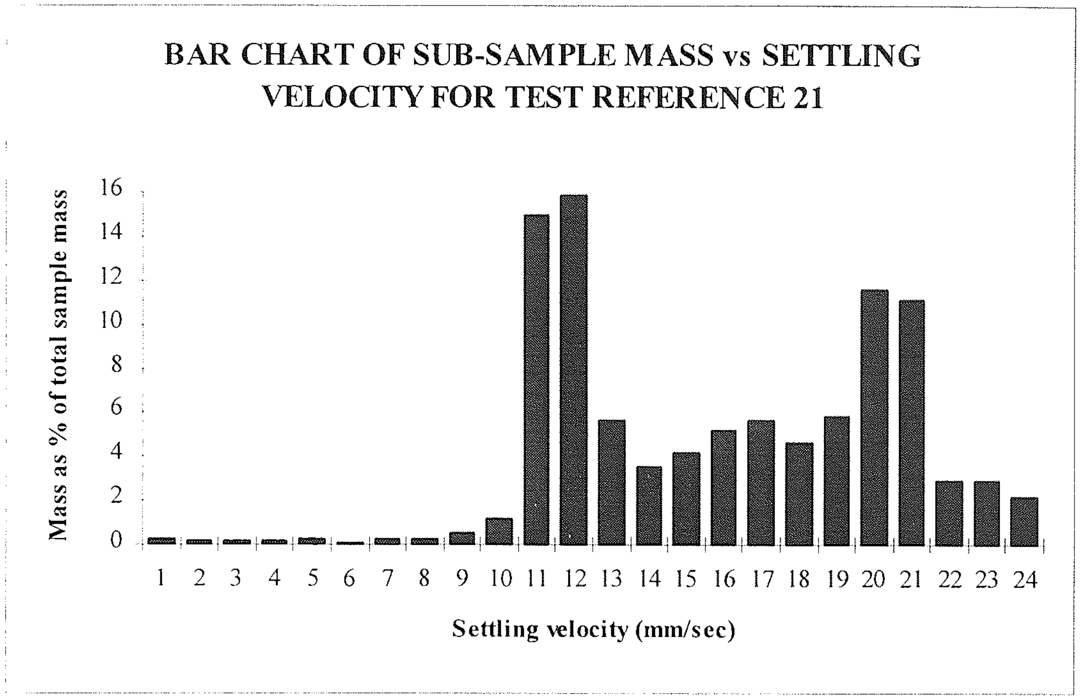
Results of the settling velocity measurement test and grading curve for site reference 20, test 20.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 20
Mass as % of total sample mass
25
20
15
10
5
0
-0.15
0.00
0.15
0.18
0.21
0.30
0.45
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

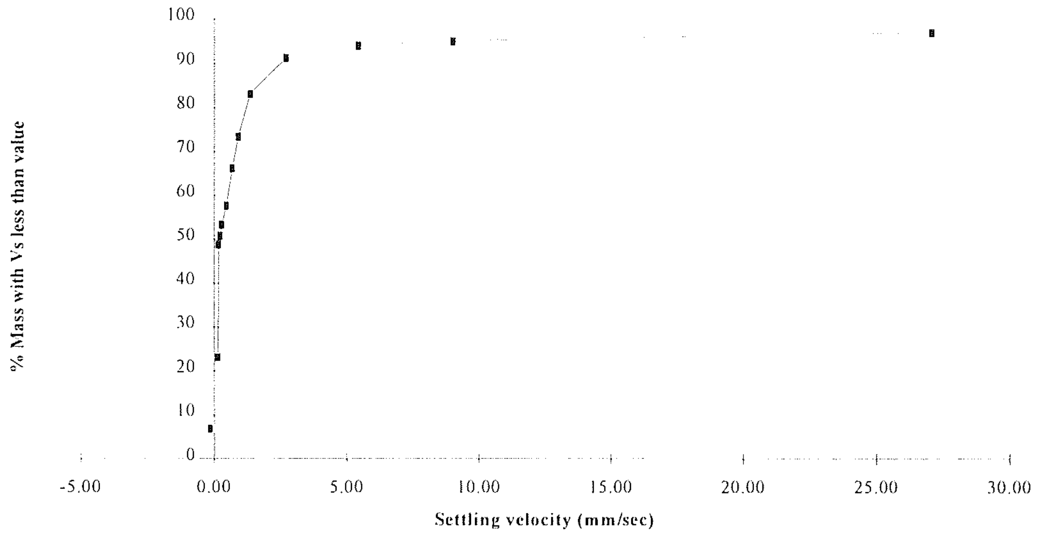
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.32	0.005	0.32	0.004	80.0	0.001
-9.03	0.51	0.003	0.19	0.003	100.0	0.000
-5.42	0.70	0.003	0.19	0.003	100.0	0.000
-2.71	0.89	0.003	0.19	0.003	100.0	0.000
-1.35	1.14	0.004	0.25	0.004	100.0	0.000
-0.90	1.27	0.002	0.13	0.002	100.0	0.000
-0.68	1.59	0.005	0.32	0.005	100.0	0.000
-0.45	1.84	0.004	0.25	0.003	75.0	0.001
-0.30	2.35	0.008	0.51	0.007	87.5	0.001
-0.23	3.55	0.019	1.20	0.017	89.5	0.002
-0.15	18.54	0.237	14.99	0.200	84.4	0.037
0.00		0.251	15.88	0.225	89.6	0.026
0.15	34.42	0.089	5.63	0.075	84.3	0.014
0.18	40.05	0.057	3.61	0.050	87.7	0.007
0.23	43.66	0.066	4.17	0.056	84.8	0.010
0.30	47.83	0.082	5.19	0.066	80.5	0.016
0.45	53.02	0.089	5.63	0.069	77.5	0.020
0.68	58.65	0.073	4.62	0.059	80.8	0.014
0.90	63.27	0.093	5.88	0.073	78.5	0.020
1.35	69.15	0.184	11.64	0.146	79.3	0.038
2.71	80.79	0.177	11.20	0.146	82.5	0.031
5.42	91.99	0.047	2.97	0.039	83.0	0.008
9.03	94.96	0.046	2.91	0.037	80.4	0.009
27.08	97.87	0.034	2.15	0.027	79.4	0.007



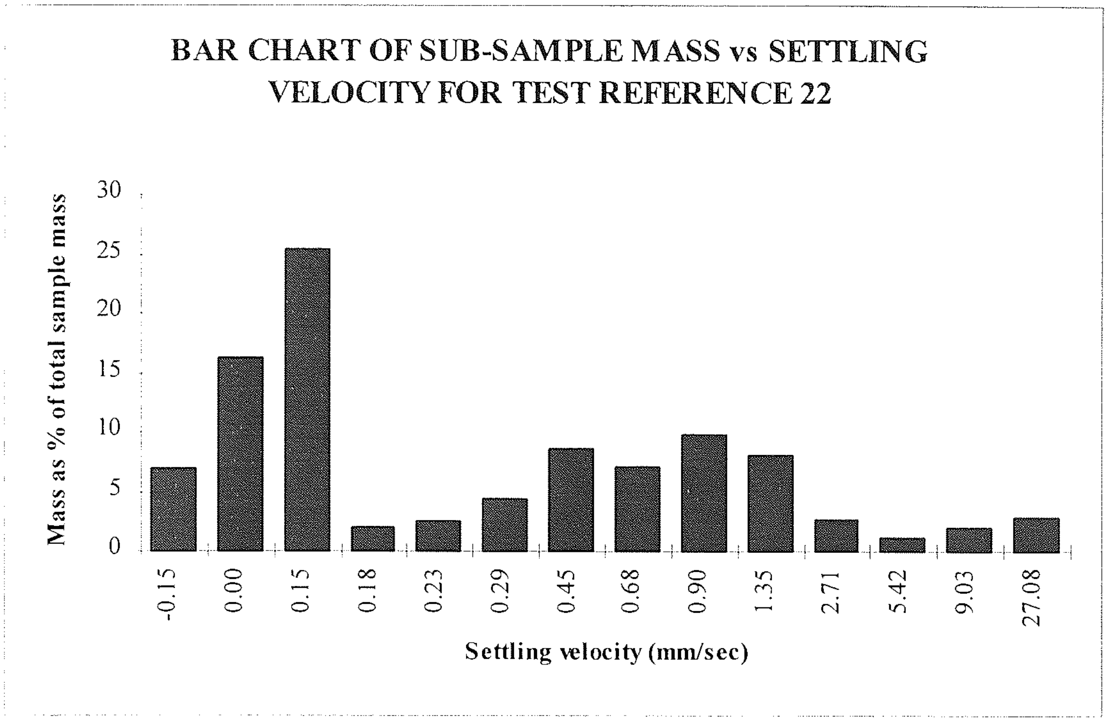
Results of the settling velocity measurement test and grading curve for site reference 21, test 21.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 21
Mass as % of total sample mass
0
2
4
6
8
10
12
14
16
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Settling velocity (mm/sec)

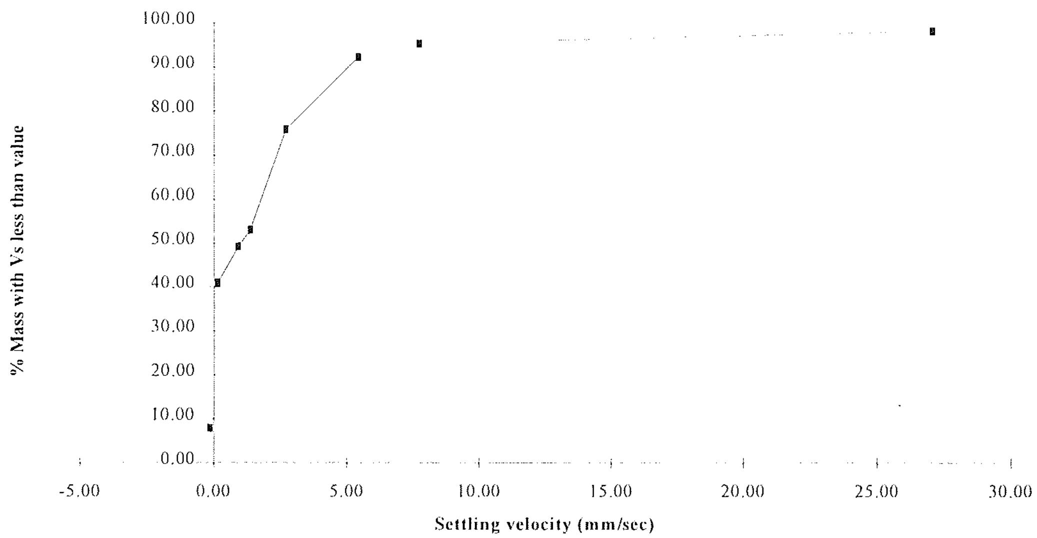
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	6.87	0.052	6.87	0.038	73.1	0.014
0.00		0.123	16.25	0.097	78.9	0.026
0.15	23.12	0.193	25.50	0.151	78.2	0.042
0.18	48.62	0.016	2.11	0.012	75.0	0.004
0.23	50.73	0.019	2.51	0.014	73.7	0.005
0.29	53.24	0.033	4.36	0.024	72.7	0.009
0.45	57.60	0.065	8.59	0.047	72.3	0.018
0.68	66.19	0.054	7.13	0.038	70.4	0.016
0.90	73.32	0.074	9.78	0.051	68.9	0.023
1.35	83.19	0.061	8.06	0.041	67.2	0.020
2.71	91.25	0.021	2.77	0.013	61.9	0.008
5.42	94.02	0.009	1.19	0.006	66.7	0.003
9.03	95.21	0.015	1.98	0.010	66.7	0.005
27.08	97.19	0.022	2.91	0.014	63.6	0.008



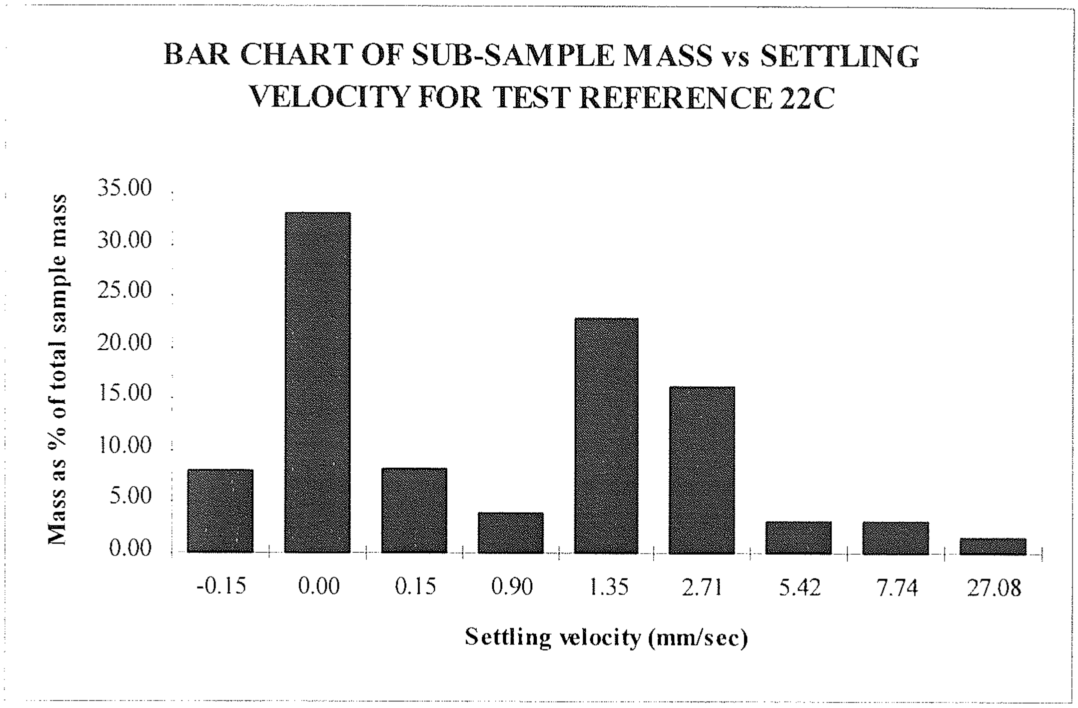
Results of the settling velocity measurement test and grading curve for site reference 22, test 22.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 22
Mass as % of total sample mass
30
25
20
15
10
5
0
-0.15
0.00
0.15
0.18
0.23
0.29
0.45
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

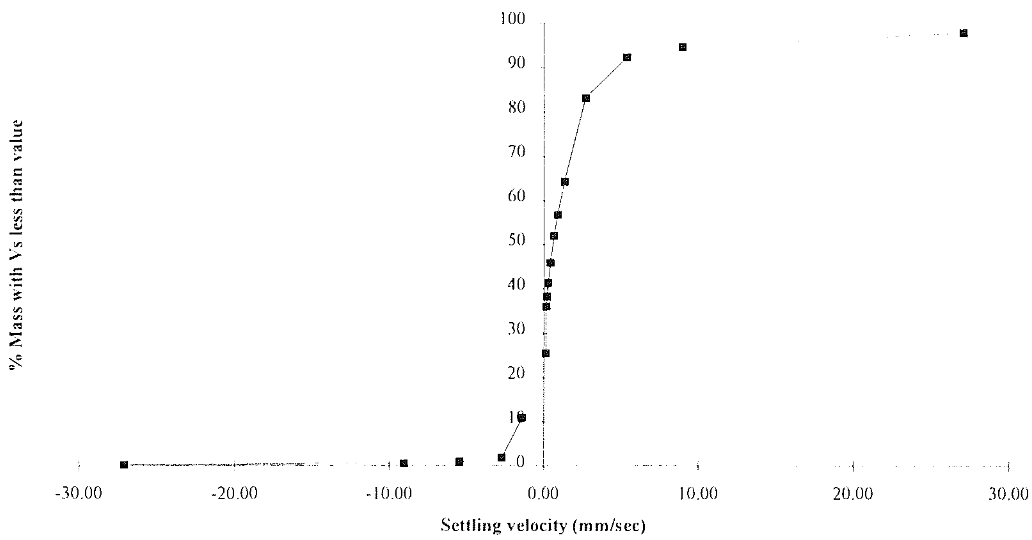
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	8.00	0.120	8.00	0.097	80.8	0.023
0.00		0.495	33.00	0.395	79.8	0.100
0.15	41.00	0.122	8.13	0.096	78.7	0.026
0.90	49.13	0.058	3.87	0.047	81.0	0.011
1.35	53.00	0.344	22.93	0.285	82.8	0.059
2.71	75.93	0.244	16.27	0.208	85.2	0.036
5.42	92.20	0.046	3.07	0.038	82.6	0.008
7.74	95.27	0.047	3.13	0.039	83.0	0.008
27.08	98.40	0.024	1.60	0.019	79.2	0.005



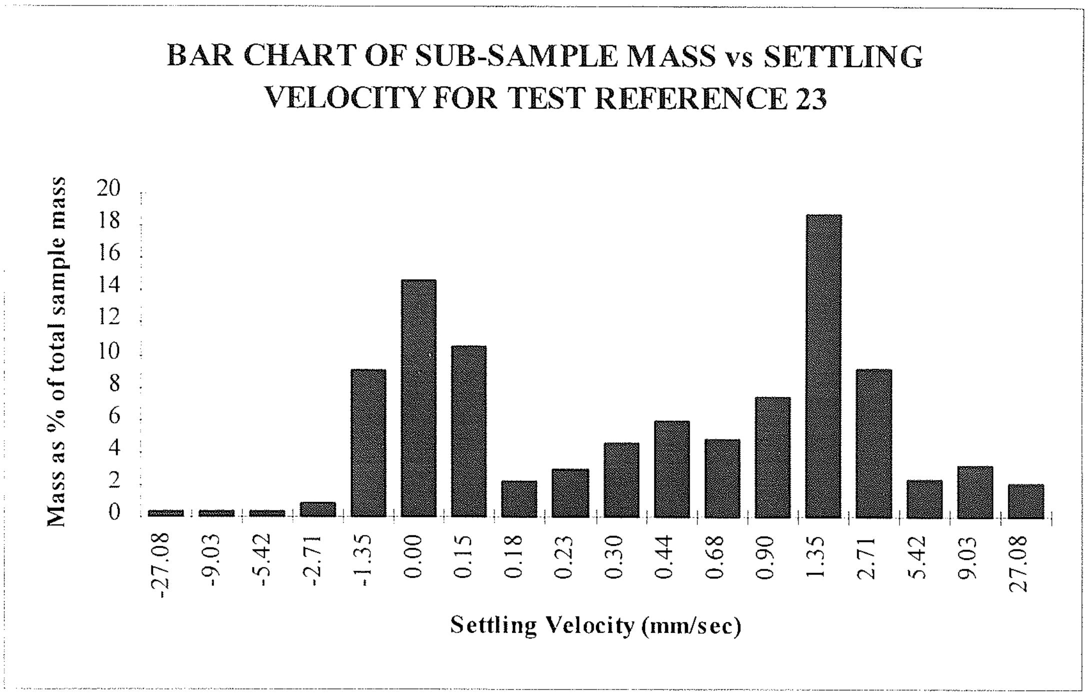
Results of the settling velocity measurement test and grading curve for site reference 22, test 22c.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 22C
Mass as % of total sample mass
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-0.15
0.00
0.15
0.90
1.35
2.71
5.42
7.74
27.08
Settling velocity (mm/sec)

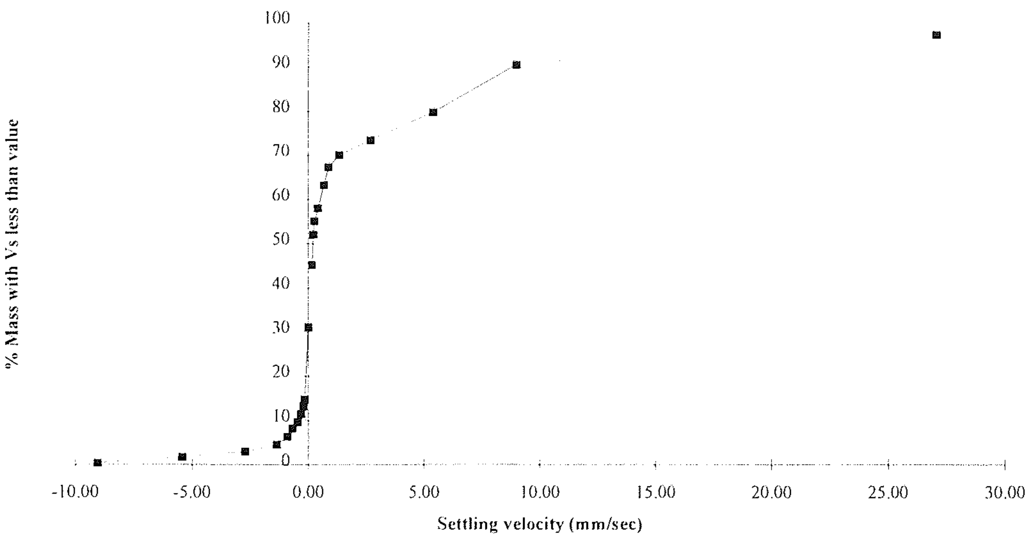
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.32	0.007	0.32	0.005	71.4	0.002
-9.03	0.69	0.008	0.37	0.006	75.0	0.002
-5.42	1.10	0.009	0.41	0.007	77.8	0.002
-2.71	1.97	0.019	0.87	0.013	68.4	0.006
-1.35	10.99	0.196	9.02	0.154	78.6	0.042
0.00		0.318	14.64	0.265	83.3	0.053
0.15	25.63	0.228	10.50	0.177	77.6	0.051
0.18	36.13	0.048	2.21	0.040	83.3	0.008
0.23	38.34	0.066	3.04	0.049	74.2	0.017
0.30	41.38	0.101	4.65	0.070	69.3	0.031
0.44	46.03	0.130	5.99	0.097	74.6	0.033
0.68	52.02	0.105	4.83	0.080	76.2	0.025
0.90	56.85	0.163	7.50	0.120	73.6	0.043
1.35	64.35	0.408	18.78	0.302	74.0	0.106
2.71	83.13	0.199	9.16	0.154	77.4	0.045
5.42	92.29	0.051	2.35	0.043	84.3	0.008
9.03	94.64	0.070	3.22	0.061	87.1	0.009
27.08	97.86	0.046	2.12	0.038	82.6	0.008



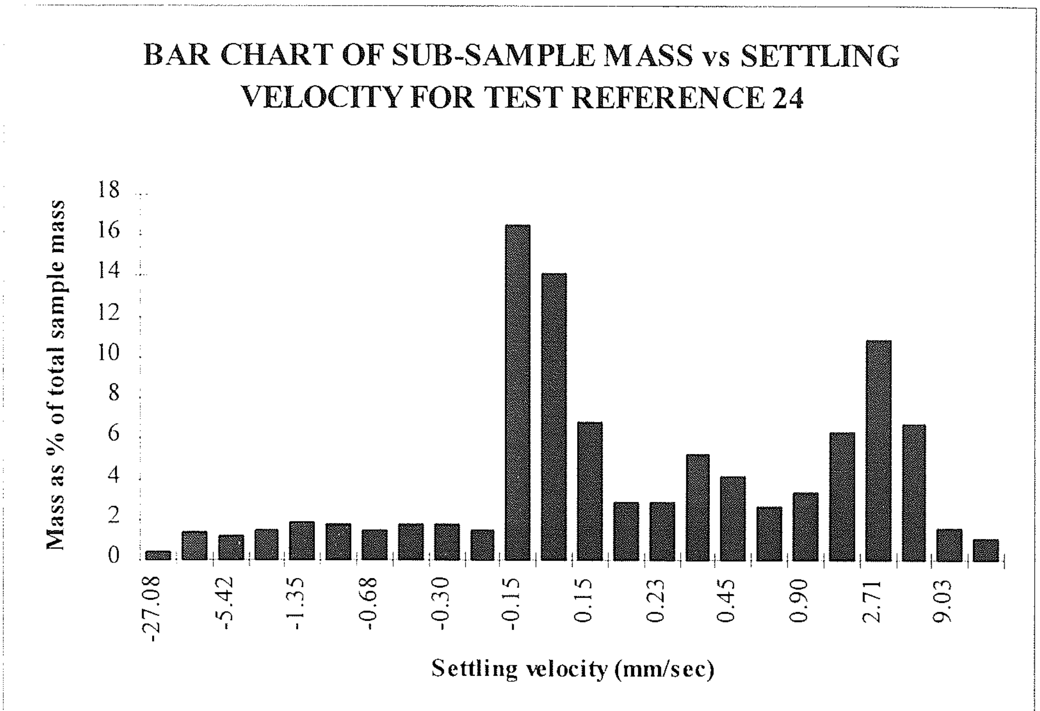
Results of the settling velocity measurement test and grading curve for site reference 23, test 23.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 23
Mass as % of total sample mass
0
2
4
6
8
10
12
14
16
18
20
-27.08
-9.03
-5.42
-2.71
-1.35
0.00
0.15
0.18
0.23
0.30
0.44
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling Velocity (mm/sec)

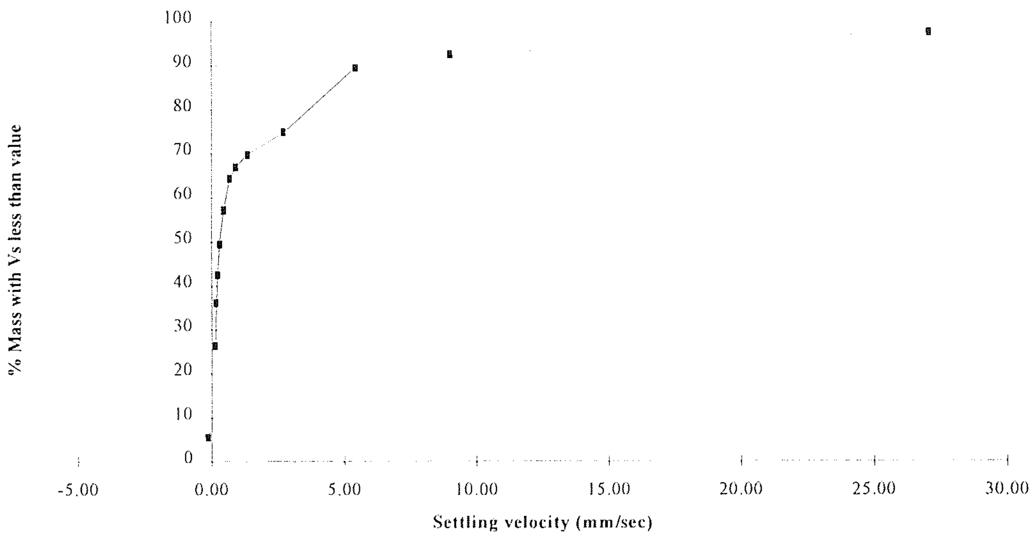
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.43	0.006	0.43	0.006	100.0	0
-9.03	1.81	0.019	1.38	0.015	78.9	0.004
-5.42	2.97	0.016	1.16	0.013	81.3	0.003
-2.71	4.49	0.021	1.52	0.016	76.2	0.005
-1.35	6.37	0.026	1.88	0.019	73.1	0.007
-0.90	8.18	0.025	1.81	0.019	76.0	0.006
-0.68	9.63	0.020	1.45	0.015	75.0	0.005
-0.43	11.44	0.025	1.81	0.019	76.0	0.006
-0.30	13.18	0.024	1.74	0.017	70.8	0.007
-0.23	14.63	0.020	1.45	0.015	75.0	0.005
-0.15	31.14	0.228	16.51	0.164	71.9	0.064
0.00		0.196	14.19	0.152	77.6	0.044
0.15	45.33	0.094	6.81	0.072	76.6	0.022
0.18	52.14	0.040	2.90	0.027	67.5	0.013
0.23	55.04	0.040	2.90	0.028	70.0	0.012
0.28	57.94	0.073	5.29	0.051	69.9	0.022
0.45	63.23	0.057	4.13	0.038	66.7	0.019
0.68	67.36	0.037	2.68	0.026	70.3	0.011
0.90	70.04	0.047	3.40	0.033	70.2	0.014
1.35	73.44	0.087	6.30	0.064	73.6	0.023
2.71	79.74	0.150	10.86	0.12	80.0	0.03
5.42	90.60	0.093	6.73	0.075	80.6	0.018
9.03	97.33	0.022	1.59	0.017	77.3	0.005
27.08	98.92	0.015	1.09	0.009	60.0	0.006



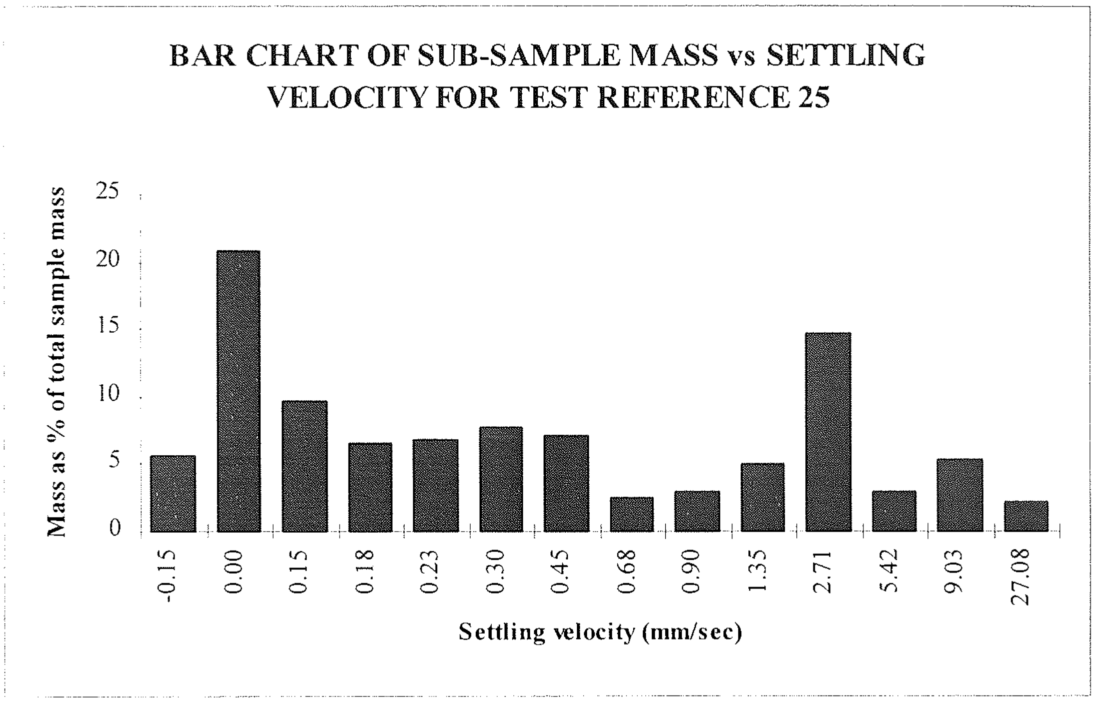
Results of the settling velocity measurement test and grading curve for site reference 24, test 24.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 24
Mass as % of total sample mass
0
2
4
6
8
10
12
14
16
18
-27.08
-5.42
-1.35
-0.68
-0.30
-0.15
0.15
0.23
0.45
0.90
2.71
9.03
Settling velocity (mm/sec)

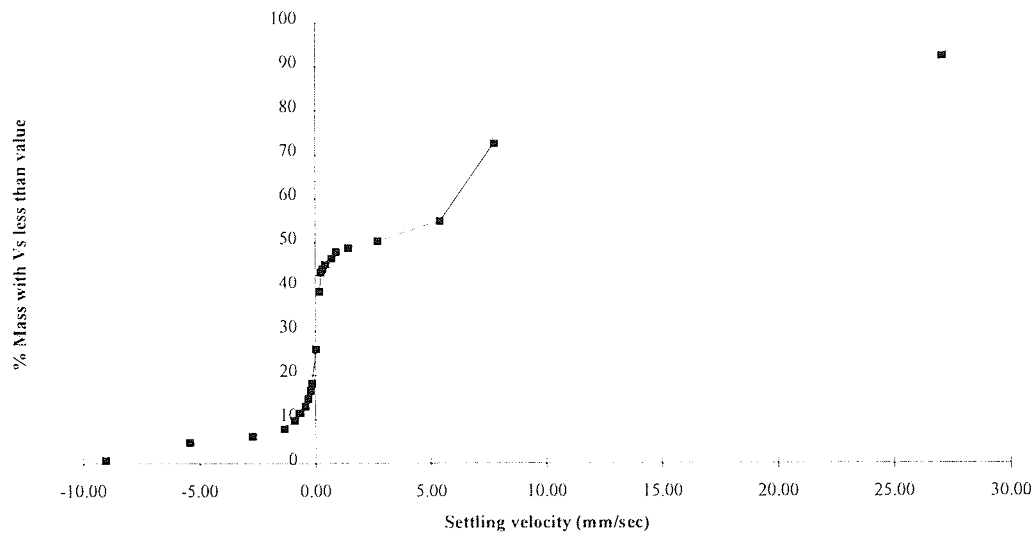
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	5.63	0.044	5.63	0.038	86.4	0.006
0.00		0.163	20.87	0.144	88.3	0.019
0.15	26.50	0.075	9.60	0.064	85.3	0.011
0.18	36.10	0.051	6.53	0.043	84.3	0.008
0.23	42.63	0.053	6.79	0.044	83.0	0.009
0.30	49.42	0.060	7.68	0.050	83.3	0.010
0.45	57.10	0.056	7.17	0.047	83.9	0.009
0.68	64.27	0.020	2.56	0.016	80.0	0.004
0.90	66.83	0.023	2.94	0.020	87.0	0.003
1.35	69.77	0.039	4.99	0.033	84.6	0.006
2.71	74.76	0.115	14.72	0.101	87.8	0.014
5.42	89.48	0.023	2.94	0.020	87.0	0.003
9.03	92.42	0.042	5.38	0.037	88.1	0.005
27.08	97.80	0.017	2.18	0.014	82.4	0.003



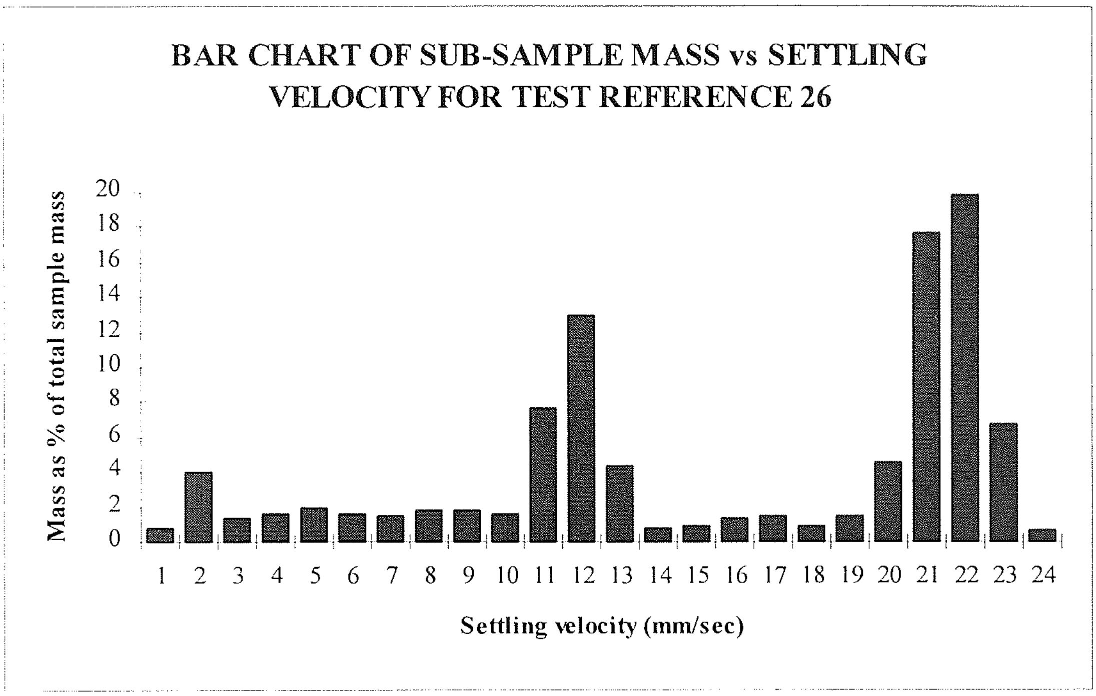
Results of the settling velocity measurement test and grading curve for site reference 25, test 25.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 25
Mass as % of total sample mass
25
20
15
10
5
0
-0.15
0.00
0.15
0.18
0.23
0.30
0.45
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

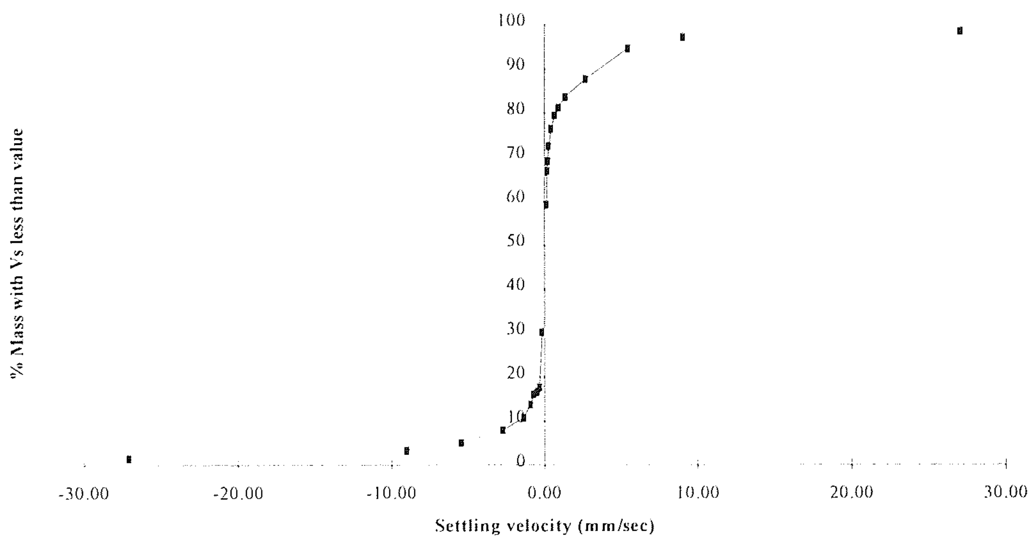
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	0.76	0.011	0.76	0.009	81.8	0.002
-9.03	4.83	0.059	4.07	0.054	91.5	0.005
-5.42	6.21	0.020	1.38	0.015	75.0	0.005
-2.71	7.87	0.024	1.66	0.019	79.2	0.005
-1.35	9.80	0.028	1.93	0.023	82.1	0.005
-0.90	11.46	0.024	1.66	0.018	75.0	0.006
-0.66	12.98	0.022	1.52	0.018	81.8	0.004
-0.45	14.77	0.026	1.79	0.022	84.6	0.004
-0.30	16.56	0.026	1.79	0.021	80.8	0.005
-0.23	18.22	0.024	1.66	0.018	75.0	0.006
-0.15	25.88	0.111	7.66	0.095	85.6	0.016
0.00		0.189	13.03	0.174	92.1	0.015
0.15	38.94	0.064	4.41	0.054	84.4	0.010
0.18	43.35	0.011	0.76	0.007	63.6	0.004
0.23	44.11	0.014	0.97	0.01	71.4	0.004
0.30	45.08	0.020	1.38	0.015	75.0	0.005
0.45	46.46	0.022	1.52	0.017	77.3	0.005
0.68	47.98	0.013	0.9	0.010	76.9	0.003
0.90	48.88	0.022	1.52	0.018	81.8	0.004
1.43	50.40	0.066	4.55	0.055	83.3	0.011
2.71	54.95	0.257	17.72	0.223	86.8	0.034
5.42	72.67	0.288	19.86	0.257	89.2	0.031
7.74	92.53	0.099	6.83	0.086	86.9	0.013
27.08	99.36	0.010	0.69	0.007	70.0	0.003



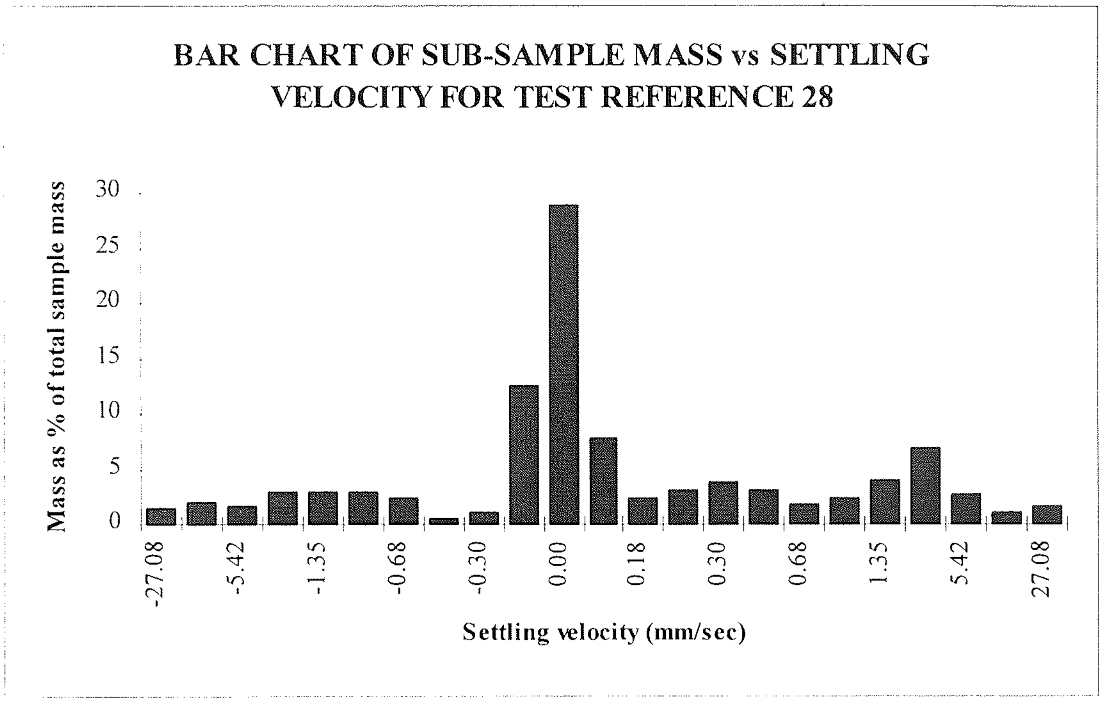
Results of the settling velocity measurement test and grading curve for site reference 26, test 26.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 26
Mass as % of total sample mass
0
2
4
6
8
10
12
14
16
18
20
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Settling velocity (mm/sec)

Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-27.08	1.46	0.030	1.46	0.007	23.3	0.023
-9.03	3.46	0.041	2.00	0.009	22.0	0.032
-5.42	5.02	0.032	1.56	0.008	25.0	0.024
-2.71	7.90	0.059	2.88	0.013	22.0	0.046
-1.35	10.87	0.061	2.97	0.014	23.0	0.047
-0.90	13.75	0.059	2.88	0.014	23.7	0.045
-0.68	16.09	0.048	2.34	0.010	20.8	0.038
-0.45	16.58	0.010	0.49	0.003	30.0	0.007
-0.30	17.65	0.022	1.07	0.007	31.8	0.015
-0.15	30.17	0.257	12.52	0.064	24.9	0.193
0.00		0.595	29.00	0.150	25.2	0.445
0.15	59.17	0.161	7.85	0.037	23.0	0.124
0.18	67.02	0.047	2.29	0.010	21.3	0.037
0.22	69.31	0.065	3.17	0.015	23.1	0.050
0.30	72.48	0.079	3.85	0.020	25.3	0.059
0.45	76.33	0.062	3.02	0.017	27.4	0.045
0.68	79.35	0.037	1.80	0.011	29.7	0.026
0.90	81.15	0.050	2.44	0.018	36.0	0.032
1.35	83.59	0.084	4.09	0.037	44.0	0.047
2.71	87.68	0.140	6.82	0.079	56.4	0.061
5.42	94.50	0.056	2.73	0.031	55.4	0.025
9.03	97.23	0.024	1.17	0.010	41.7	0.014
27.08	98.40	0.033	1.61	0.006	18.2	0.027

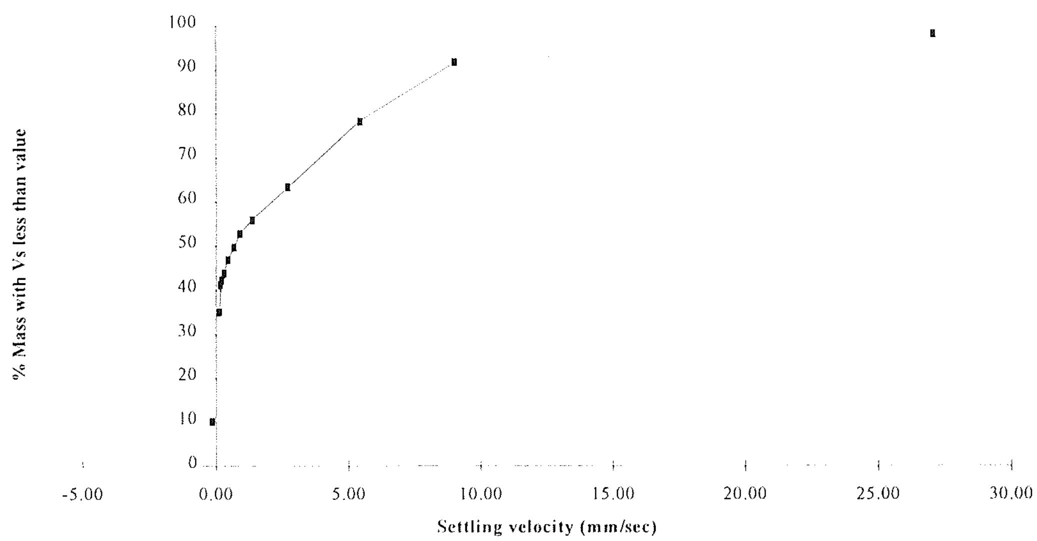


Results of the settling velocity measurement test and grading curve for site reference 28, test 28.

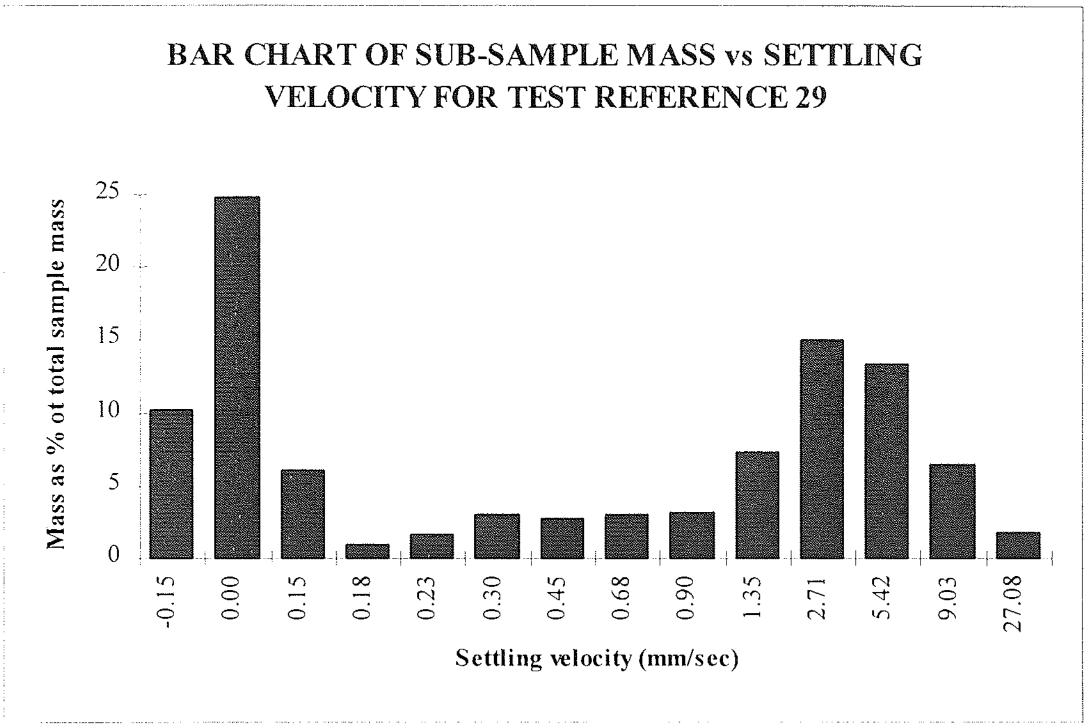


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 28
Mass as % of total sample mass
30
25
20
15
10
5
0
-27.08
-5.42
-1.35
-0.68
-0.30
0.00
0.18
0.30
0.68
1.35
5.42
27.08
Settling velocity (mm/sec)

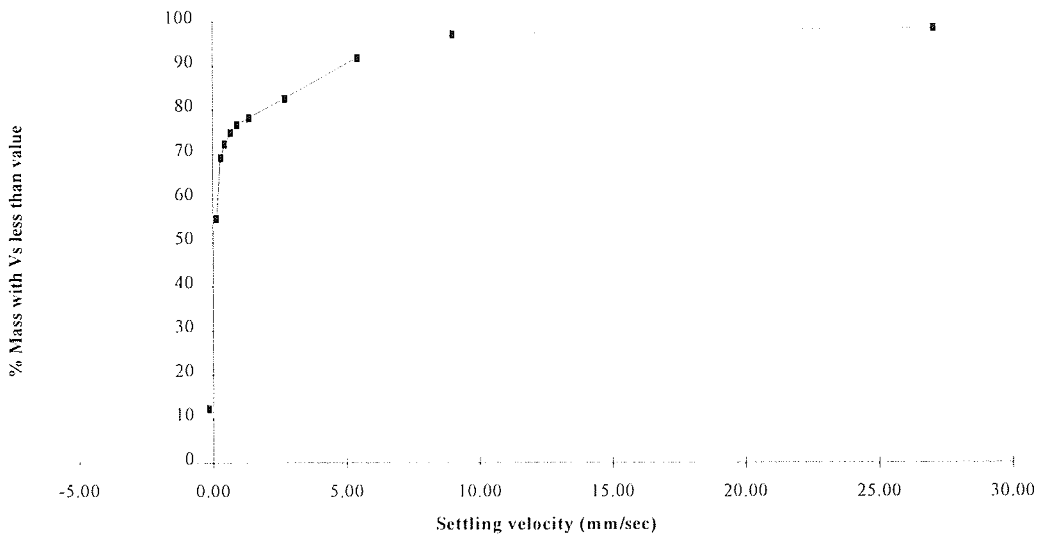
Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	10.26	0.113	10.26	0.099	87.6	0.014
0.00		0.274	24.89	0.253	92.3	0.021
0.15	35.15	0.067	6.09	0.058	86.6	0.009
0.18	41.24	0.011	1.00	0.008	72.7	0.003
0.23	42.24	0.018	1.63	0.015	83.3	0.003
0.30	43.87	0.034	3.09	0.028	82.4	0.006
0.45	46.96	0.031	2.82	0.026	83.9	0.005
0.68	49.78	0.033	3.00	0.028	84.8	0.005
0.90	52.78	0.035	3.18	0.030	85.7	0.005
1.35	55.96	0.081	7.36	0.071	87.7	0.010
2.71	63.32	0.165	14.99	0.149	90.3	0.016
5.42	78.31	0.147	13.35	0.134	91.2	0.013
9.03	91.66	0.072	6.54	0.066	91.7	0.006
27.08	98.20	0.020	1.82	0.017	85.0	0.003



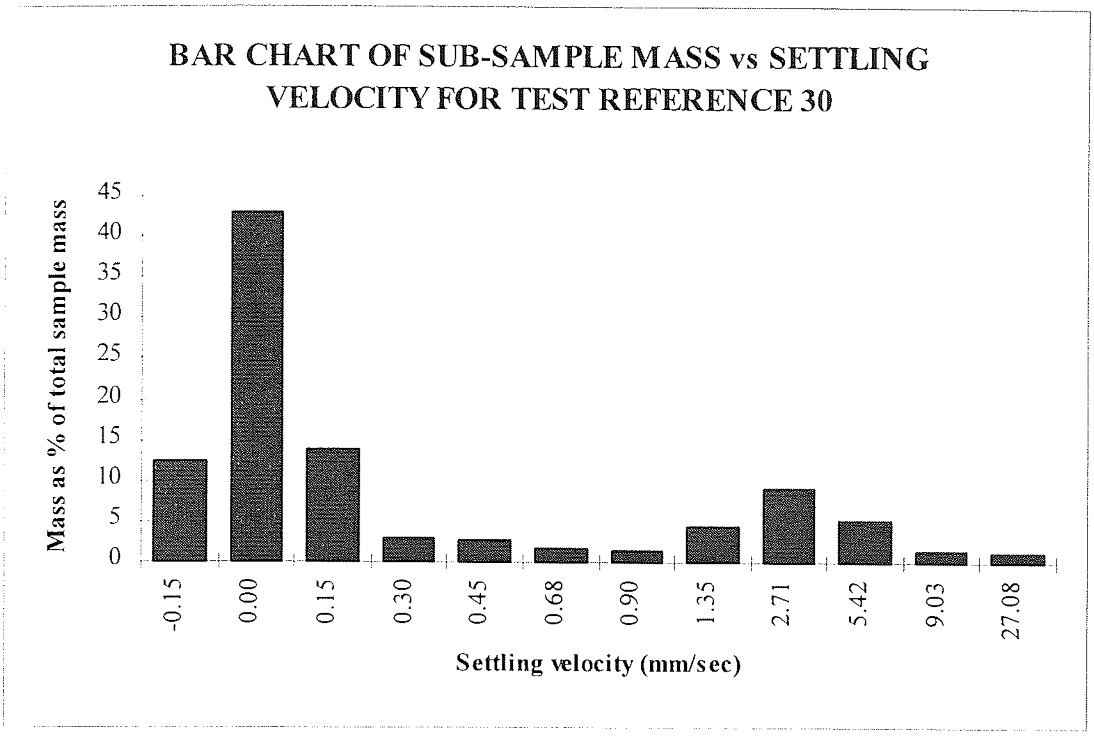
Results of the settling velocity measurement test and grading curve for site reference 29, test 29.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 29
Mass as % ot total sample mass
25
20
15
10
5
0
-0.15
0.00
0.15
0.18
0.23
0.30
0.45
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

Settling velocity (mm/sec)	Cumulative % of total mass	Mass (g)	Mass (% of total)	Organic material (g)	Organic material (% of mass)	Inorganic material (g)
-0.15	12.34	0.047	12.34	0.042	89.4	0.005
0.00		0.164	43.04	0.155	94.5	0.009
0.15	55.38	0.053	13.91	0.047	88.7	0.006
0.30	69.29	0.011	2.89	0.009	81.8	0.002
0.45	72.18	0.010	2.62	0.007	70.0	0.003
0.68	74.80	0.007	1.84	0.005	71.4	0.002
0.90	76.64	0.006	1.57	0.004	66.7	0.002
1.35	78.21	0.017	4.46	0.014	82.4	0.003
2.71	82.67	0.035	9.19	0.032	91.4	0.003
5.42	91.86	0.020	5.25	0.019	95.0	0.001
9.03	97.11	0.006	1.57	0.006	100.0	0.000
27.08	98.68	0.005	1.31	0.003	60.0	0.002



Results of the settling velocity measurement test and grading curve for site reference 30, test 30.


BAR CHART OF SUB-SAMPLE MASS vs SETTLING VELOCITY FOR TEST REFERENCE 30
Mass as % of total sample mass
45
40
35
30
25
20
15
10
5
0
-0.15
0.00
0.15
0.30
0.45
0.68
0.90
1.35
2.71
5.42
9.03
27.08
Settling velocity (mm/sec)

APPENDIX E

RESULTS OF STATISTICAL ANALYSIS OF DATA

	Total area	Area commerce	DWF	Area farmland	Area imperm.	Area industry	Area parkland
Area commerce	0.9777						
t value	2.15						
no. of pairs	28						
DWF	0.9913	0.9803					
t value	2.16	-1.77					
no. of pairs	28	28					
Area farmland	0.0979	-0.0068	-0.0137				
t value	1.92	-0.16	0.36				
no. of pairs	28	28	28				
Area impermeable	0.6941	0.6993	0.7080	-0.1290			
t value	2.11	1.64	1.76	1.68			
no. of pairs	28	28	28	28			
Area industry	0.9923	0.9795	0.9935	0.0326	0.7072		
t value	2.17	-0.71	1.99	0.04	-1.63		
no. of pairs	28	28	28	28	28		
Area parkland	0.8990	0.8273	0.8860	0.0451	0.5521	0.8794	
t value	2.10	1.35	1.61	1.23	-2.32	1.39	
no. of pairs	28	28	28	28	28	28	
Equiv. population	0.9953	0.9815	0.9967	0.0059	0.6940	0.9929	0.9060
t value	-1.93	-1.93	-1.94	-1.93	-1.93	-1.93	-1.93
no. of pairs	27	27	28	27	27	27	27
No. pumping stns	0.9311	0.9494	0.9385	-0.1134	0.6638	0.9285	0.8101
t value	2.08	1.69	1.75	1.62	1.63	1.64	2.56
no. of pairs	24	24	24	24	24	24	24
Pump/Gravity fed	0.1926	0.2155	0.2047	-0.1888	0.1745	0.1772	0.2249
t value	2.11	1.69	1.79	1.79	2.14	1.68	2.56
no. of pairs	28	28	29	28	28	28	28
Area residential	0.9924	0.9797	0.9973	-0.0225	0.7040	0.9911	0.9035
t value	2.45	-1.96	-1.96	-1.65	-1.92	-1.97	-1.90
no. of pairs	28	28	28	28	28	28	28
Sewer length.	0.8219	0.8615	0.7988	0.1358	0.4941	0.8183	0.6696
t value	-2.26	-2.26	-2.26	-2.26	-2.26	-2.26	-2.26
no. of pairs	28	28	28	28	28	28	28
System type	0.0584	0.0439	0.0589	0.0633	-0.0854	0.0959	0.1333
t value	2.08	1.70	1.78	1.62	2.13	1.68	2.49
no. of pairs	26	26	27	26	26	26	26

E.1 Correlation coefficients and t values for the catchment characteristics of sites used in the test programme.
Part 1 of 2.

	Equivalent population	No. of pumping stations	Pumped/ Gravity fed sewers	Area residential	Sewer length
No. pumping stns	0.9403 1.92 24				
Pump/Gravity fed	0.2062 1.94 28	0.3855 2.87 24			
Area residential	0.9986 1.93 27	0.9492 -1.91 24	0.2197 -1.93 28		
Sewer length	0.8172 -1.00 27	0.8005 -2.23 24	0.2706 -2.26 28	0.8018 -2.26 28	
System type	0.0676 1.93 27	-0.1789 2.68 23	-0.2500 -1.80 27	0.0436 1.92 26	0.1151 2.27 26

E.1 Correlation coefficients and t values for the catchment characteristics of sites used in the test programme.
Part 2 of 2.

	Total area	Area commerce	DWF	Area farm.	Area imperm.	Area ind.
Area commerce	0.9561					
cases	47					
significance (p)	0.000					
DWF	0.9236	0.9386				
cases	60	45				
significance (p)	0.000	0				
Area farmland	0.1795	0.0116	0.0092			
cases	50	47	48			
significance (p)	0.212	0.938	0.95			
Area impermeable	0.5199	0.6003	0.1945	0.1728		
cases	48	47	46	48		
significance	0	0	0.195	0.24		
Area industry	0.9866	0.9462	0.9433	0.1231	0.4836	
cases	48	47	46	48	48	
significance (p)	0	0	0	0.404	0	
Area parkland	0.7099	0.7596	0.4172	0.2278	0.9259	0.6681
cases	50	47	48	50	48	48
significance (p)	0	0	0.003	0.112	0	0
Equiv. population	0.9608	0.9606	0.9819	0.0483	0.2973	0.969
cases	61	46	74	49	47	47
significance (p)	0	0	0	0.742	0.042	0
No. pumping stns	0.8885	0.9134	0.8127	-0.0242	0.4684	0.8809
cases	40	33	40	36	34	34
significance (p)	0	0	0	0.889	0.005	0
Pump/Gravity fed	0.239	0.2201	0.2468	-0.1156	0.1412	0.2402
cases	62	47	75	50	48	48
significance (p)	0.061	0.137	0.033	0.424	0.339	0.1
Area residential	0.9917	0.9562	0.9412	0.0576	0.4898	0.985
cases	50	47	48	50	48	48
significance (p)	0	0	0	0.691	0	0
Sewer length.	0.8426	0.8337	0.7422	0.1885	0.4847	0.8288
cases	62	47	75	50	48	48
significance (p)	0	0	0	0.19	0	0
System type	0.0957	0.0495	0.0779	0.0958	0.0725	0.1296
cases	45	36	51	38	37	37
significance (p)	0.532	0.774	0.587	0.567	0.67	0.445

E.2 Correlation coefficients, number of cases used in the calculations and the 2-tailed significance for all the 77No. sites on which data was collected.
Part 1 of 2.

	Area park.	Equiv. pop.	No. p. stns	Pump/Grav	Area resid.	Sewer lth.
Equiv. population	0.5241					
cases	49					
significance (p)	0					
No. pumping stns	0.6451	0.8705				
cases	36	42				
significance (p)	0	0				
Pump/Gravity fed	0.183	0.2523	0.4367			
cases	50	76	42			
significance (p)	0.203	0.028	0.004			
Area residential	0.6807	0.9726	0.9126	0.2864		
cases	50	49	36	50		
significance (p)	0	0	0	0.044		
Sewer length.	0.6172	0.7819	0.7879	0.3387	0.829	
cases	50	76	42	77	50	
significance (p)	0	0	0	0.003	0	
System type	0.1313	0.0679	-0.0888	-0.2543	0.0609	0.1089
cases	38	53	37	53	38	53
significance (p)	0.432	0.629	0.601	0.066	0.717	0.438

E.2 Correlation coefficients, number of cases used in the calculations and the 2-tailed significance for all the 77No. sites on which data was collected.
Part 2 of 2

	% Floaters	% Residue	% Light	% Heavy	Mult. DWF	Equiv. pop.
% Residue	0.6862					
significance (p)	0					
% Light	0.7933	0.6293				
significance (p)	0	0				
% Heavy	0.5551	0.1677	0.3858			
significance (p)	0.003	0.403	0.047			
Mult. DWF	-0.1632	0.0500	-0.1693	-0.1709		
significance (p)	0.416	0.804	0.399	0.394		
Equiv. population	-0.0308	-0.0415	-0.1065	0.0695	0.1537	
significance (p)	0.879	0.837	0.597	0.731	0.444	
DWF	-0.0408	-0.0345	-0.1058	0.0500	0.1718	0.9978
significance (p)	0.840	0.864	0.599	0.804	0.391	0.000
Sewer length	-0.1109	-0.0968	-0.2326	0.0899	-0.0210	0.7473
significance (p)	0.582	0.631	0.243	0.656	0.917	0.000
System type	0.2140	0.3890	-0.0022	0.1182	0.1170	-0.2207
significance (p)	0.284	0.045	0.991	0.557	0.561	0.269
Pump/Gravity fed	0.2363	0.4588	0.2914	-0.0095	-0.0564	-0.2596
significance (p)	0.235	0.016	0.140	0.962	0.780	0.191
No. pumping stns	-0.1205	-0.1638	-0.1504	0.0301	0.1575	0.9646
significance (p)	0.549	0.414	0.454	0.882	0.433	0
Total area	0.0271	0.0087	-0.0549	0.1132	0.1506	0.9971
significance (p)	0.893	0.966	0.786	0.574	0.453	0
Area impermeable	-0.1394	-0.0087	-0.5079	-0.0155	0.2092	-0.1317
significance (p)	0.488	0.966	0.774	0.939	0.295	0.512
Area industry	-0.1140	-0.2001	-0.0300	0.1952	-0.0920	0.1417
significance (p)	0.571	0.317	0.882	0.329	0.648	0.481
Area commerce	-0.1567	-0.2651	-0.1268	0.0230	-0.1975	0.3771
significance (p)	0.435	0.181	0.529	0.909	0.324	0.052
Area farmland	0.5537	0.6776	0.2931	0.0254	0.0507	-0.2171
significance (p)	0.003	0	0.138	0.900	0.802	0.277
Area residential	-0.2993	-0.4829	-0.1668	-0.0117	-0.1214	0.2231
significance (p)	0.129	0.011	0.406	0.954	0.546	0.263
Area parkland	0.0358	0.1309	-0.0921	-0.2787	0.2584	-0.1403
significance (p)	0.859	0.515	0.648	0.159	0.193	0.458

E.3 Correlation coefficients and 2-tailed significance for all the data variables used in the data analysis for the four groups of sub-sample mass at all flows. Part 1 of 2.

	DWF	Sewer lth.	System type	Pump/Grav	No. p. stns	Total area
Sewer length significance (p)	0.7232 0					
System type significance (p)	-0.2116 0.289	-0.2934 0.137				
Pump/Gravity fed significance (p)	-0.2444 0.219	-0.3701 0.057	0.4443 0.020			
No. pumping stns significance (p)	0.9603 0	0.7707 0	-0.4021 0.038	-0.4219 0.020		
Total area significance (p)	0.9939 0	0.7621 0	-0.2197 0.271	-0.2511 0.207	0.9611 0	
Area impermeable significance (p)	-0.1218 0.545	-0.1959 0.328	0.2861 0.148	0.1104 0.584	-0.1595 0.427	-0.1363 0.498
Area industry significance (p)	0.1452 0.470	0.1596 0.427	-0.2001 0.317	-0.2358 0.236	0.1856 0.354	0.1434 0.475
Area commerce significance (p)	0.3397 0.083	0.7106 0	-0.3881 0.045	-0.4723 0.013	0.4841 0.011	0.3845 0.048
Area farmland significance (p)	-0.2219 0.266	-0.0303 0.881	0.4134 0.032	0.4474 0.019	-0.3045 0.123	-0.1756 0.381
Area residential significance (p)	0.2261 0.257	0.0581 0.773	-0.5457 0.003	-0.4405 0.021	0.3197 0.104	0.1937 0.333
Area parkland significance (p)	-0.1404 0.485	-0.2572 0.195	0.2842 0.151	0.3484 0.075	-0.2198 0.271	-0.1540 0.443

	Area impermeable	Area industry	Area commerce	Area farmland	Area residential
Area industry significance (p)	-0.3060 0.121				
Area commerce significance (p)	-0.2422 0.224	-0.0397 0.844			
Area farmland significance (p)	-0.1761 0.380	-0.2293 0.250	-0.2084 0.297		
Area residential significance (p)	-0.5047 0.007	0.1845 0.357	0.2763 0.163	-0.6959 0	
Area parkland significance (p)	-0.0920 0.648	-0.3942 0.042	-0.3231 0.100	0.4681 0.014	-0.3353 0.087

E.3 Correlation coefficients and 2-tailed significance for all the data variables used in the data analysis for the four groups of sub-sample mass at all flows.
Part 2 of 2.

	% Floaters	% Residue	% Light	% Heavy	Multiple of DWF	Equivalent population
% Residue	0.8789					
significance (p)	0					
t value	-9.79					
no. of pairs	21					
% Light	0.8148	0.8043				
significance (p)	0	0				
t value	-3.36	5.34				
no. of pairs	21	21				
% Heavy	0.7390	0.5725	0.4054			
significance (p)	0.001	0.020	0.119			
t value	-11.18					
no. of pairs	21					
Mult. DWF						
significance (p)						
Equiv. population	0.0009	-0.0850	-0.1432	0.0157		
significance	0.997	0.754	0.597	0.954		
DWF	-0.0069	-0.0848	-0.1382	-0.0073		0.9965
significance (p)	0.980	0.755	0.610	0.978		0
t value						2.06
no. of pairs						20
Sewer length	-0.1488	-0.1185	-0.3379	-0.0183		0.6350
significance (p)	0.582	0.662	0.201	0.946		0.008
System type	0.3850	0.3337	0.0698	0.7313		-0.1391
significance (p)	0.141	0.207	0.797	0.001		0.607
t value				12.36		
no. of pairs				19		
Pump/Gravity fed	0.3883	0.3654	0.4447	0.3811		-0.2423
significance (p)	0.137	0.164	0.084	0.145		0.366
No. pumping stns	-0.1361	-0.2063	-0.2104	-0.1484		0.9576
significance (p)	0.615	0.443	0.434	0.583		0
t value						2.06
no. of pairs						19
Total area	0.0854	0.0014	-0.0714	0.0811		0.9947
significance (p)	0.753	0.996	0.793	0.765		0
t value						2.05
no. of pairs						19
Area impermeable	-0.0301	-0.1276	-0.1743	0.0217		0.9597
significance (p)	0.912	0.638	0.519	0.936		19.000
t value						2.05
no. of pairs						19
Area industry	-0.1742	-0.1624	-0.1335	0.0297		-0.0016
significance (p)	0.519	0.548	0.622	0.913		0.995

E.4 Correlation coefficients, 2-tailed significance and t values for all the data variables used in the data analysis for the four groups of sub-sample mass at (1-2)DWF. Part 1 of 3.

	% Floaters	% Residue	% Light	% Heavy	Multiple of DWF	Equivalent population
Area commerce	-0.2691	-0.1679	-0.2302	-0.2489		0.2729
significance (p)	0.314	0.534	0.391	0.353		0.306
Area farmland	0.7672	0.6931	0.5026	0.6641		-0.1619
significance (p)	0.001	0.003	0.047	0.005		0.549
t value	-1.9800					
no. of pairs	20					
Area residential	-0.6008	-0.5257	-0.3696	-0.5743		0.1156
significance (p)	0.014	0.036	0.159	0.020		0.670
Area parkland	0.0789	-0.1130	-0.0341	-0.0733		-0.0694
significance (p)	0.771	0.667	0.900	0.787		0.798

	DWF	Sewer length.	System type (combined, separate, etc.)	Pump/Gravity fed sewer system	No. of pumping stations
Sewer length	0.5976				
significance (p)	0.014				
System type	-0.1457	-0.2094			
significance (p)	0.590	0.436			
Pump/Gravity fed	-0.2243	-0.4046	0.3426		
significance (p)	0.404	0.120	0.194		
No. pumping stns	0.9541	0.6859	-0.2931	-0.4400	
significance (p)	0	0.003	0.271	0.088	
t value	1.88				
no. of pairs	20				
Total area	0.9894	0.6567	-0.1145	-0.2165	0.9466
significance (p)	0	0.006	0.673	0.421	0
t value	1.07				-2.24
no. of pairs	20				19
Area impermeable	0.9576	0.5017	-0.1268	-0.2056	0.8820
significance (p)	0	0.048	0.640	0.445	0
t value	1.88				3.23
no. of pairs	20				19
Area industry	0.0109	0.0003	-0.0988	-0.0308	0.0617
significance (p)	0.968	0.999	0.716	0.910	0.820
Area commerce	0.2291	0.7070	-0.1332	-0.4035	0.3855
significance (p)	0.393	0.002	0.623	0.121	0.140
Area farmland	-0.1827	0.1663	0.2913	0.2100	-0.2223
significance (p)	0.498	0.538	0.274	0.435	0.408
Area residential	0.1455	-0.2926	-0.1720	-0.1511	0.1375
significance (p)	0.591	0.272	0.524	0.577	0.612
Area parkland	-0.0852	-0.3140	-0.0999	0.0435	-0.1401
significance (p)	0.754	0.236	0.713	0.873	0.605

E.4 Correlation coefficients, 2-tailed significance and t values for all the data variables used in the data analysis for the four groups of sub-sample mass at (1-2)DWF. Part 2 of 3.

	Total area	Impermeable area	Area of industry	Area of commerce	Area of farmland	Residential area
Area impermeable	0.9428					
significance (p)	0					
t value	2.25					
no. of pairs	20					
Area industry	-0.0049	0.0515				
significance (p)	0.986	0.850				
Area commerce	0.2781	0.1072	-0.3017			
significance (p)	0.297	0.693	0.256			
Area farmland	-0.0700	-0.2399	-0.0510	0.0039		
significance (p)	0.797	0.371	0.851	0.989		
Area residential	0.0313	0.1979	-0.2587	-0.0826	-0.9171	
significance (p)	0.908	0.463	0.333	0.761	0	
t value					-3.75	
no. of pairs					19	
Area parkland	-0.1018	0.0171	-0.4674	-0.2674	-0.1299	0.2532
significance (p)	0.707	0.950	0.068	0.317	0.631	0.344

E.4 Correlation coefficients, 2-tailed significance and t values for all the data variables used in the data analysis for the four groups of sub-sample mass at (1-2)DWF. Part 3 of 3.

	% Floaters	% Residue	% Light	% Heavy	Multiple of DWF	Equivalent population
% Residue significance (p)	-0.1719 0.635					
% Light significance (p)	0.1398 0.700	-0.5472 0.102				
% Heavy significance (p) t value no. of pairs	-0.4205 0.226	-0.8063 0.005 0.63 11	0.2759 0.440			
Mult. DWF significance (p)						
Equiv. population significance (p)	0.3680 0.295	-0.6095 0.061	0.1162 0.749	0.3846 0.272		
DWF significance (p) t value no. of pairs	0.2651 0.459	-0.6879 0.028	0.2457 0.494	0.4972 0.144		0.9377 0 2.27 11
Sewer length significance (p)	0.3090 0.385	-0.5227 0.121	0.1031 0.777	0.3349 0.344		0.1454 0.689
System type significance (p)	-0.0230 0.950	0.5434 0.105	0.1280 0.725	-0.5629 0.090		-0.4981 0.143
Pump/Gravity fed significance (p)	-0.1783 0.622	0.6822 0.030	-0.0650 0.858	-0.5782 0.080		-0.5148 0.128
No. pumping stns significance (p)	0.0768 0.833	-0.6306 0.051	-0.1006 0.782	0.6152 0.058		0.6467 0.043
Total area significance (p) t value no. of pairs	0.2707 0.449	-0.6486 0.042	0.0161 0.965	0.4994 0.142		0.9417 0 2.27 11
Area impermeable significance (p)	-0.4177 0.230	-0.0730 0.841	0.3887 0.267	0.2332 0.517		-0.2029 0.574
Area industry significance (p)	-0.1306 0.719	-0.2887 0.418	0.2377 0.508	0.3199 0.368		0.2863 0.423
Area commerce significance (p) t value no. of pairs	0.3736 0.288	-0.7332 0.016	0.0513 0.888	0.5204 0.123		0.8718 0.001 2.29 11
Area farmland significance (p) t value no. of pairs	0.3103 0.383	0.7556 0.011	-0.4400 0.203	-0.8543 0.002 2.31 11		-0.4810 0.159

E.5 Correlation coefficients, 2-tailed significance and t values for all the data variables used in the data analysis for the four groups of sub-sample mass at (2-5.9)DWF. Part 1 of 3.

	% Floaters	% Residue	% Light	% Heavy	Multiple of DWF	Equivalent population
Area residential significance (p)	0.1197 0.742	-0.5428 0.105	-0.0629 0.863	0.4957 0.145		0.5160 0.127
Area parkland significance (p)	0.1653 0.648	0.3537 0.316	-0.3194 0.368	-0.3907 0.264		-0.2333 0.517

	DWF	Sewer length.	System type (combined, separate, etc.)	Pump/Gravity fed sewer system	No. of pumping stations
Sewer length significance (p)	0.1433 0.693				
System type significance (p)	-0.4194 0.228	-0.3873 0.269			
Pump/Gravity fed significance (p)	-0.6664 0.035	-0.3724 0.289	0.4924 0.148		
No. pumping stns significance (p) t value no. of pairs	0.5860 0.075	0.3583 0.309	-0.9731 0 -0.40 11	-0.6264 0.053	
Total area significance (p) t value no. of pairs	0.8714 0.001	0.1415 0.697	-0.7138 0.020 -2.86 11	-0.6154 0.058	0.8331 0.003 -2.87 11
Area impermeable significance (p)	-0.1864 0.606	-0.2436 0.498	0.2246 0.533	0.0572 0.875	-0.1878 0.603
Area industry significance (p)	0.5586 0.093	-0.2034 0.573	-0.0726 0.842	-0.4609 0.180	0.1491 0.681
Area commerce significance (p) t value no. of pairs	0.7836 0.007	0.5350 0.111	-0.7436 0.014 -2.60 11	-0.6273 0.052	0.8384 0.002 -2.87 11
Area farmland significance (p)	-0.6326 0.050	-0.2667 0.456	0.4788 0.162	0.6619 0.037	-0.5689 0.086
Area residential significance (p) t value no. of pairs	0.6040 0.064	0.5549 0.096	-0.7506 0.012 -5.15 11	-0.6544 0.040	0.7617 0.010 -5.21 10
Area parkland significance (p)	-0.3806 0.278	-0.2169 0.547	0.3599 0.307	0.4980 0.143	-0.4071 0.243

E.5 Correlation coefficients, 2-tailed significance and t values for all the data variables used in the data analysis for the four groups of sub-sample mass at (2-5.9)DWF. Part 2 of 3.

	Total area	Impermeable area	Area of industry	Area of commerce	Area of farmland	Residential area
Area impermeable	-0.1823					
significance (p)	0.614					
Area industry	0.2742	-0.3114				
significance (p)	0.443	0.381				
Area commerce	0.8974	-0.1923	0.0501			
significance (p)	0	0.595	0.891			
t value	2.84					
no. of pairs	11					
Area farmland	-0.5335	-0.3873	-0.4052	-0.5533		
significance (p)	0.112	0.269	0.245	0.097		
Area residential	0.6007	-0.5487	0.4973	0.6825	-0.5104	
significance (p)	0.066	0.100	0.144	0.030	0.132	
Area parkland	-0.2530	-0.3149	-0.2993	-0.3427	0.7553	-0.4697
significance (p)	0.481	0.376	0.401	0.332	0.012	0.171
t value					0.74	
no. of pairs					11	

E.5 Correlation coefficients, 2-tailed significance and t values for all the data variables used in the data analysis for the four groups of sub-sample mass at (2-5.9)DWF. Part 3 of 3.

	% Floaters	% Residue	% Light	% Heavy	Multiple of DWF	Equivalent population
% Residue significance (p)	0.6951 0					
% Light significance (p)	0.7921 0	0.6360 0				
% Heavy significance (p)	0.5568 0.003	0.1683 0.411	0.3864 0.051			
Mult. DWF significance (p)						
Equiv. population significance (p)	0.0394 0.848	-0.1080 0.599	-0.0793 0.700	0.0995 0.629		
DWF significance (p)	0.0268 0.897	-998.0000 0.628	-0.0784 0.703	0.0737 0.720		0.9960 0
Sewer length significance (p)	-0.0793 0.700	-0.1383 0.500	-0.2255 0.268	0.1042 0.613		0.6679 0
System type significance (p)	0.2064 0.312	0.3980 0.044	-0.0099 0.962	0.1183 0.565		-0.2019 0.323
Pump/Gravity fed significance (p)	0.2278 0.263	0.4706 0.015	0.2854 0.158	-0.0104 0.960		-0.2372 0.243
No. pumping stns significance (p)	-0.0831 0.687	-0.2633 0.194	-0.1372 0.504	0.0445 0.829		0.9384 0
Total area significance (p)	0.1171 0.569	-0.0395 0.848	-0.0096 0.963	0.1580 0.441		0.9948 0
Area impermeable significance (p)	-0.1453 0.479	-0.0055 0.979	-0.0622 0.763	-0.0159 0.939		-0.1265 0.538
Area industry significance (p)	-0.1066 0.604	-0.2066 0.311	-0.0235 0.909	0.1966 0.336		0.1072 0.602
Area commerce significance (p)	-0.1435 0.484	-0.2806 0.165	-0.1160 0.573	0.0245 0.905		0.3501 0.080
Area farmland significance (p)	0.5488 0.004	0.6938 0	0.2866 0.156	0.0248 0.904		-0.1661 0.417
Area residential significance (p)	-0.2913 0.149	-0.4954 0.010	-0.1592 0.437	-0.0110 0.957		0.1839 0.368
Area parkland significance (p)	0.0298 0.885	0.1354 0.510	-0.0975 0.636	-0.2798 0.166		-0.1267 0.537

E.6 Correlation coefficients and 2-tailed significance for all the data variables used in the data analysis for the four groups of sub-sample mass at (1-5.9)DWF. Part 1 of 2.

	DWF	Sewer length.	System type (combined, separate, etc.)	Pump/Gravity fed sewer system	No. of pumping stations
Sewer length significance (p)	0.6318 0				
System type significance (p)	-0.1901 0.352	-0.2763 0.172			
Pump/Gravity fed significance (p)	-0.2171 0.287	-0.3537 0.076	0.4366 0.026		
No. pumping stns significance (p)	0.9308 0	0.6999 0	-0.4387 0.025	-0.4489 0.021	
Total area significance (p)	0.9890 0	0.6899 0	-0.2002 0.327	-0.2252 0.269	0.9321 0
Area impermeable significance (p)	-0.1133 0.581	-0.1912 0.349	0.2820 0.163	0.1041 0.613	-0.1610 0.432
Area industry significance (p)	0.1121 0.586	0.1320 0.520	-0.1920 0.347	-0.2268 0.265	0.1649 0.421
Area commerce significance (p)	0.2994 0.137	0.7174 0	-0.3770 0.058	-0.4605 0.018	0.4883 0.011
Area farmland significance (p)	-0.1728 0.399	0.0394 0.848	0.4045 0.040	0.4373 0.025	-0.2817 0.163
Area residential significance (p)	0.1883 0.357	-0.0022 0.991	-0.5394 0.004	-0.4310 0.028	0.3106 0.122
Area parkland significance (p)	0.1272 0.536	-0.2541 0.210	0.2790 0.168	0.3431 0.086	-0.2297 0.259

	Total area	Impermeable area	Area of industry	Area of commerce	Area of farmland	Residential area
Area impermeable significance (p)	-0.1323 0.519					
Area industry significance (p)	0.1095 0.594	-0.3025 0.133				
Area commerce significance (p)	0.3596 0.071	-0.2361 0.246	-0.0579 0.779			
Area farmland significance (p)	-0.1096 0.594	-0.1864 0.362	-0.2193 0.282	-0.1876 0.359		
Area residential significance (p)	0.1438 0.483	-0.5024 0.009	0.1745 0.394	0.2589 0.201	-0.6902 0	
Area parkland significance (p)	-0.1450 0.480	-0.0964 0.640	-0.3903 0.049	-0.3165 0.115	0.4641 0.017	-0.3299 0.100

E.6 Correlation coefficients and 2-tailed significance for all the data variables used in the data analysis for the four groups of sub-sample mass at (1-5.9)DWF.
Part 2 of 2.

APPENDIX F

RESULTS OF STATISTICAL ANALYSIS OF PEAK AND TROUGH MASS VALUES

Test reference	Peak mass (g)	Trough mass (g)	Velocity at which peak mass occurred (peakvel)	Velocity at which trough mass occurred (trouvel)
1	23.49	1.17	2.71	0.68
1s	19.64	2.33	1.35	0.68
2	20.76	1.65	2.71	0.68
3	14.95	0	0.45	0
4	21.71	1.32	2.71	0.45
4i	21.19	1.21	2.71	0.68
4iii	21.89	2.45	2.71	0.68
5	12	3.7	2.71	0.68
7	26.33	2.04	2.71	0.9
8	19.31	2.79	2.71	0.68
9	30.22	1.65	2.71	0.68
10s	17.34	3.2	2.71	0.68
11	20.4	3.47	9.03	0.68
12	19.23	2.64	2.71	0.68
13	22.35	2.26	2.71	0.68
14	20.35	1.46	2.71	0.68
15	17.02	3.22	2.71	0.68
16	18.77	3.32	5.42	0.68
17	12.66	1.81	2.58	0.68
18	13.98	5.33	2.71	0.68
19	13.98	4.57	5.42	0.68
20	13.78	4.11	5.42	0.68
21	11.64	4.62	1.35	0.68
22	9.78	7.13	0.9	0.68
22s	22.93	3.87	1.35	0.9
23	18.78	4.83	1.35	0.68
24	10.86	2.68	2.71	0.68
25	14.72	2.56	2.71	0.68
26	19.83	0.87	5.42	0.68
28	6.82	1.8	2.71	0.68
29	14.99	2.82	2.71	0.45
30	9.19	1.57	2.71	0.9

F.1 Peak and trough mass values and the velocities at which they occurred for all tests.

	Peak mass (g)	Vel. at peak mass (mm/sec)	Trough mass (g)	Vel. at trough mass (mm/sec)
Equiv. population	0.2567	-0.2662	-0.2888	-0.0055
significance (p)	0.205	0.189	0.152	0.979
DWF	0.2348	-0.2580	-0.2715	-0.0089
significance (p)	0.248	0.203	0.180	0.966
Sewer length	0.3531	-0.2451	-0.4167	-0.1920
significance (p)	0.077	0.227	0.034	0.347
System type	-0.0464	-0.0093	-0.1418	0.1694
significance (p)	0.822	0.964	0.490	0.408
Pump/Gravity fed	-0.2873	-0.1607	0.2167	-0.0036
significance (p)	0.155	0.433	0.288	0.986
No. pumping stns	0.2691	-0.1985	-0.2668	-0.0140
significance (p)	0.184	0.331	0.188	0.946
Total area	0.2836	-0.2732	-0.3056	-0.0229
significance (p)	0.160	0.177	0.129	0.911
Area impermeable	-0.1489	0.3587	0.2710	-0.0479
significance (p)	0.468	0.072	0.180	0.816
Area industry	0.0439	-0.0155	0.2717	-0.0909
significance (p)	0.831	0.940	0.179	0.659
Area commerce	0.4049	-0.2138	-0.2782	-0.0398
significance (p)	0.040	0.294	0.169	0.847
Area farmland	-0.1390	-0.1442	-0.4907	-0.1382
significance (p)	0.498	0.482	0.011	0.501
Area residential	0.2329	-0.0933	0.1551	0.2459
significance (p)	0.252	0.650	0.449	0.226
Area parkland	-0.3285	-0.2060	-0.1626	-0.2671
significance (p)	0.101	0.313	0.427	0.187
Peak mass		0.0131	-0.4165	-0.0208
significance (p)		0.949	0.034	0.920
Vel. at peak mass			0.2050	0.0030
significance (p)			0.315	0.988
Trough mass				-0.0399
significance (p)				0.846

F.2 Correlation coefficients and 2-tailed significance for all the data variables used in the data analysis with the peak and trough mass values and the velocities at which they occurred, at all flows.

	Peak mass (g)	Vel. at peak mass (mm/sec)	Trough mass (g)	Vel. at trough mass (mm/sec)
Equiv. population	0.3374	-0.1563	-0.4179	-0.0520
DWF	0.2979	-0.1405	-0.3912	-0.0863
Sewer length	0.3568	-0.1879	-0.5349	-0.0418
System type	0.5507	-0.1738	-0.1772	0.5222
Pump/Gravity fed	-0.2073	-0.4066	0.5223	-0.1174
No. pumping stns	0.3005	-0.0243	-0.4184	-0.0082
Total area	0.3831	-0.1590	-0.4411	-0.0740
Area impermeable	0.2721	-0.1264	-0.3887	-0.1267
Area industry	-0.4032	0.6367	0.4263	-0.2775
Area commerce	0.2867	-0.4555	-0.3546	0.4246
Area farmland	0.4550	0.2087	-0.4098	-0.1795
Area residential	-0.3293	-0.3623	0.2630	0.1966
Area parkland	0.1160	-0.0832	-0.1975	0.1085
Peak mass		-0.0376	-0.7825	0.4186
significance (p)			0.003	
Vel. at peak mass			-0.1221	-0.0907
Trough mass				-0.1314

F.3 Correlation coefficients, 2-tailed significance and t values for all the data variables used in the data analysis for the four groups of sub-sample mass, at DWF (12 cases).

APPENDIX G

RESULTS OF CURVE FITTING ANALYSIS

Variable	a	b
b significance (p)	0.8878 0	
Total area	-0.0117	-0.0663
Area commerce	0.0086	-0.0462
DWF	-0.0009	-0.0556
Area farmland	-0.0743	-0.1209
Area impermeable	-0.0882	-0.1537
Area industry	-0.0546	-0.1004
No. pumping stns	0.0824	0.0422
Area parkland	-0.0295	-0.0376
Equiv. population	-0.0093	-0.0684
Pump/Gravity fed	0.1313	0.0505
Area residential	0.0008	-0.0462
Sewer length	-0.0487	-0.1359
System type	-0.3920	-0.4004

G.1 Correlation coefficients and 2-tailed signifcance value (where appropriate) of empirical constants a and b from the curve fitting calculations with all the catchment characteristics in the test programme.

Variable	a	b
b significance (p)	0.5298 0.0040	
Total area	-0.1080	-0.1131
Area commerce	-0.0993	-0.1176
DWF	-0.0729	-0.1105
Area farmland	-0.0724	-0.1092
Area impermeable	-0.1114	-0.1742
Area industry	-0.1062	-0.1036
No. pumping stns	-0.1351	-0.1021
Area parkland	-0.1018	-0.0967
Equiv. population	-0.0750	-0.1234
Pump/Gravity fed	-0.2619	-0.4397
Area residential	-0.1002	-0.0980
Sewer length	-0.1267	-0.2615
System type	-0.1825	-0.0342

G.2 Correlation coefficients and 2-tailed signifcance value (where appropriate) of empirical constants a and b from the curve fitting calculations with all the catchment characteristics in the test programme less the two wild readings.

APPENDIX H

RESULTS OF ANALYSIS OF THE UNIFORMITY COEFFICIENT C_V

Test ref.	% less than at velocity (mm/sec)		Uniformity coefficient
	40	90	
1	0.18	7.18	40
1s	0.17	5.13	30
2	0.58	10.22	18
3	0.26	2.63	10
4	0.16	8.45	53
4i	0.15	7.33	49
4iii	0.72	12.79	18
5	0.17	5.75	34
6	0.96	7.39	8
7	2.23	15.3	7
8	0.29	6.04	21
9	1.54	5.33	3
10s	0.37	8.02	22
11	0.66	20.91	32
12	0.23	6.9	30
13	0.17	6	35
14	0.16	6.89	43
15	0.76	17.51	23
16	0.4	8.48	21
17	0.15	5.18	35
18	0.47	7.93	17
19	0.53	12.8	24
20	0.27	7.89	29
21	0.18	4.94	27
22	0.17	2.5	15
22c	0.15	5.05	34
23	0.27	4.74	18
24	0.15	5.27	35
25	0.21	6.06	29
26	0.16	8.57	54
28	0.15	3.63	24
29	0.17	8.58	50
30	0.15	4.87	32

H.1 Uniformity coefficients calculated as $C_v = \frac{u_{90}}{u_{40}}$

Variable	Velocity coefficient, C_V	u_{40}	u_{90}
u_{40}	-0.6196		
u_{90}	-0.0215	0.5022	
Total area	0.0919	-0.0703	-0.0563
Area commerce	0.1474	-0.0897	-0.0542
DWF	0.1054	-0.0928	-0.0759
Area farmland	-0.0416	0.1444	0.0433
Area impermeable	0.0703	-0.1082	0.0241
Area industry	0.1243	-0.1122	-0.0701
No. pumping stns	0.0579	-0.0396	-0.0057
Area parkland	-0.0060	-0.0338	-0.1024
Equiv. population	0.1101	-0.0813	-0.0619
Pump/Gravity fed	0.1840	-0.0402	0.2815
Area residential	0.0873	-0.0812	-0.0628
Sewer length	0.2666	-0.0581	0.0901
System type	0.1652	0.0075	-0.0215

H.2 Correlation coefficients for u_{40}, u_{90} and the uniformity coefficient C_V with the catchment characteristics for all tests.