Erosion resistance and behaviour of highly organic in-sewer sediment

I. Seco, M. Gómez Valentín, A. Schellart and S. Tait

ABSTRACT

Reliable prediction of time-varying pollutant loads in combined sewer systems during storm periods can aid better management of the release of pollution into natural environments as well as enhancing storage tank design. Better understanding of the behaviour of sewer sediments is crucial for the development of models that adequately describe the transport of in-sewer solids and accurately predict the changes in pollutant concentration within combined sewers during storm events. This paper reports on the results of a test programme to examine the erosion of highly organic sewer sediment under the application of time-varying shear stress. The tests were carried out with and without supplying oxygen, and varying simulated dry-weather periods. The aim was to investigate the behaviour of real in-sewer sediment with a high organic content (around 80%) in an attempt to improve prediction of the transport rates under the particular Mediterranean conditions of long dry-period/build-up and intense rainfall/wash-off, and understand how this environment affects the erosional resistance and subsequent sediment release. Results have been compared with previous work on lower organic content sewer sediments and artificial organic sediment.

Key words | erosion rate, laboratory experiments, organic sediments, sediment transport, shear stress, sewer sediment

I. Seco (corresponding author)
M. Gómez Valentín
Department of Hydraulic,
Maritime and Environmental,
Flumen Institute,
Technical University of Catalonia,
c/Jordi Girona 1-3,
08034, Barcelona,
Spain
E-mail: *irene.seco@upc.edu*

A. Schellart
S. Tait
School of Engineering,
Pennine Water Group,
University of Bradford,
BD7 1DP, Bradford,
UK (since moved to the University of Sheffield, UK)

INTRODUCTION

Pollution from combined sewer systems can significantly affect the quality of receiving waters, and the release of sediments from previously formed in-sewer deposits plays a significant role in wet weather pollution (Gasperi *et al.* 2010). The Mediterranean climate results in long dry-weather periods, during which the relatively low dry-weather foul flow allows in-pipe sedimentation and accumulation of deposits with high organic content to form. For example, in Catalonia, Spain, 23% of storm events recorded in the last two years showed an antecedent dry period longer than a week and a maximum of 70 days without rainfall was registered. These long dry periods are typically followed by intense precipitation events that erode the in-sewer deposits and as a consequence high concentrations and amounts of pollutants are released into natural receiving waters through combined sewer overflows (CSO). With the additional circumstance of low flows in many rivers of the Mediterranean region during these prolonged dry periods, and the consequent low dilution capacity of these rivers significant ecological impact can occur. Due to an increasing interest in the preservation of the quality in natural water bodies in Spain it has become necessary to achieve better quantification of solids and attached pollutants that reach natural watercourses from combined sewers.

Sewer sediment shows an agglomerate structure, as it has a variety of sources and contains a mixture of organic and inorganic materials. Organic cohesion together with microbiological activity in sewer sediments can develop strong bonding forces between particles, influencing the structure of the surface of the bed (Mehta *et al.* 1997; Banasiak *et al.* 2005). This can have a significant influence on the behaviour of a sewer sediment deposit regarding its resistance to erosion. This 'bonding' behaviour adds additional difficulties to the prediction of the rate of erosion and the modelling of sediment transport in sewers, which already involves considerable uncertainty even when this behaviour is not taken into account (Schellart *et al.* 2010).

In an attempt to improve predictions of the sewer sediment transport loads that can be applied to the particular Mediterranean conditions of long dry-period/build-up and

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intense rainfall/wash-off, a study on how this affects the initiation of sediment motion is needed.

This work reports on a series of laboratory erosion tests using real sewer sediment with a high percentage of organic matter (around 80%). The erosion tests were carried out using an erosionmeter device based on a design by Liem *et al.* (1997). In these tests a prepared sample of sewer sediment has been exposed to a consolidation period and subsequently subjected to increased shear stress, to simulate increased flows through sewer pipes at the start of a storm event. The erosion tests were performed at room temperature under aerobic and anaerobic conditions.

The aim of this work is to analyse changes in transport potential for different lengths of antecedent dry-weather period and in-sewer environmental conditions. Suspended solid concentrations were measured and used to calculate the erosion rate linked to the applied shear stress. Previous laboratory work (Tait *et al.* 2003b; Schellart *et al.* 2005) using a similar device was considered in order to compare the behaviour of real sewer sediment with low organic content and artificial sediment with a very high organic content.

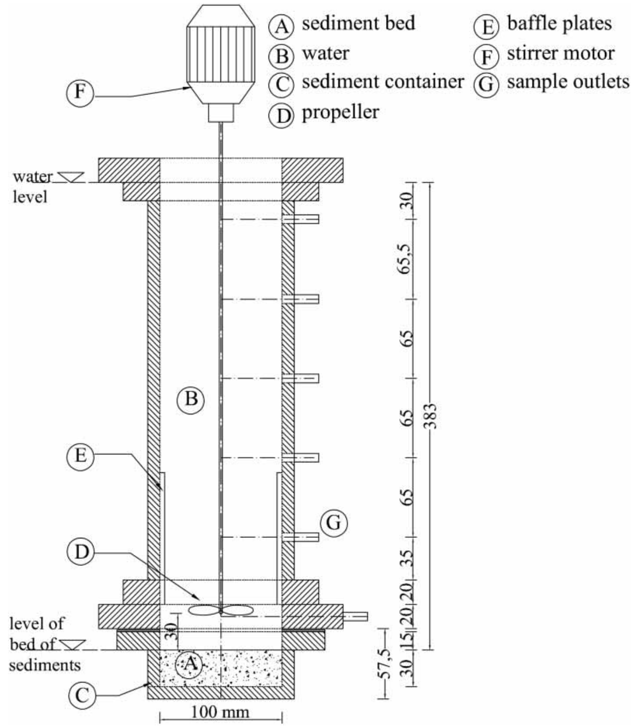

Figure 1 | Erosion meter device.

METHODS

Equipment and calibration procedures

The erosion measurement device used was developed by Liem *et al.* (1997), based on the design proposed by Schünemann & Kühl (1993) named EROMES, with a slight modification introduced by Liem *et al.* (1997) to allow for the use of prepared samples instead of in-situ collected samples.

The main purpose of the device is the assessment of the critical threshold of motion at the solid–fluid interface by applying an angular velocity to the water column resulting in a radial velocity pattern over the sediment deposit, and collecting the resulting eroded material.

The erosion meter utilised in this work consists of a cylindrical Perspex tube (100 mm inner diameter) with a container inserted into the bottom of the tube (Figure 1). The sample has an exposed surface area of 8,170 mm^2. A 50 mm diameter propeller is placed 30 mm above the sediment surface and is used to apply a reasonably uniform shear stress. Five baffle plates fixed perpendicular to the inner wall of the tube prevent circulating flow when the propeller is running. A stirrer motor (RW-16 Ika Laboratechnik, speed range: 40–1,200 rpm) is used to operate the propeller. There are six vertically spaced sample outlets to remove suspended sediment samples during the tests.

Calibration of the instrument is essential to find the relationship between revolutions per minute (rpm) of the propeller and the shear stress on the surface of the sediment sample. Several uniformly sized sand samples were used to create single size beds. During the calibration procedure, the angular velocity of the propeller is increased gradually until the instant when the start of a continuous movement of the sand particles is observed. Critical shear stress is described by Wilcock (1988) as the shear stress that produces a small transport rate; however, different methods to define the amount of particles in movement at critical shear stress exist which can lead to different values. For the current research therefore, critical shear stress was defined as the point when 5% of the superficial bed is moving continuously, to be consistent with the calibration used by Camuffo (2001). To account for the influence of the observer in judging the threshold of movement, the calibration was repeated by five different observers. The value of shear stress at the threshold of motion for each sand fraction is calculated using the modified Shield's criterion (van Rijn 1984) and this can be related to the rpm value at that instant. Following the calibration tests, a curve is obtained that relates the angular velocity of the propeller in rpm with the applied bed shear stress

(Figure 2). For each particle size, the observer errors are assumed to be normally distributed and a mean and standard deviation in critical shear stress have been calculated. The average value of this standard deviation was SD = 0.07 N/m^2.

Real sewer sediment

The sediments used in the erosion tests were collected from a sewer system in Granollers (Catalonia, Spain). The material corresponds to the sediment accumulated in a pipe and manhole situated in a residential and commercial (restaurants, bars) area. The sediment particles from Granollers (see Table 1), were found to exhibit quite a uniform distribution. Nevertheless, it is necessary to deal with these values carefully as the sediment particles were formed by agglomerates of fine sediments and greases that were difficult to disaggregate. Due to the high presence of greases in the composition of the sample, the sieve analysis was performed independently for the gross part (>1 mm), following the British Standards (BS 1796-1:1989.Test sieving), while the fine part (<1 mm) was performed by laser diffraction method (ISO 13320:2009 Particle size analysis. Laser diffraction methods). An average particle density of 1,310 kg/m^3 and a mean organic content of 74% were found.

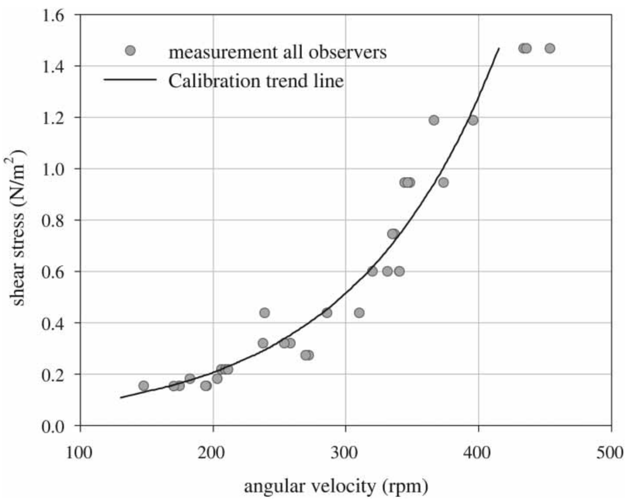

Figure 2 | Erosionmeter calibration curve. Shear stress against angular velocity and second-order trend curve.

Laboratory tests

A range of erosion laboratory tests have been performed under aerobic and anaerobic conditions at ambient room temperature in order to study the erodibility and transport of sediments deposited in the base of sewer pipes, as well as the influence of the microorganism activity on the resistance to erosion of the sediment.

Based on previous research (Skipworth *et al.* 1996; Tait *et al.* 2003a; Banasiak *et al.* 2005) it is assumed that the degree of consolidation in a cohesive sediment bed is strongly influenced by the length of the consolidation period and biological activity. It is also considered that the consolidation process will result in an increasing bed density and furthermore will cause an increase of erosional strength with depth (Ristenpart 1995; De Sutter *et al.* 2003).

Consolidation period

Three different consolidation periods of 16, 64 and 140 h were used to simulate dry-weather periods (Table 2). During these consolidation periods the sediment bed was subjected to a constant and relatively low shear stress of 0.15 ± 0.07 N/m^2, comparable with the dry-weather flow levels inside conduits, obtained from data collected in the real network in Granollers.

The sewer sediment samples were also exposed to different oxygen levels during consolidation, and subsequently exposed to incremental levels of bed shear strength.

Performed tests

Increasing shear stress is applied in a stepwise way through the rotation of the propeller. Each step is maintained

Table 1 | Characteristics of sewer sediment samples from Granollers and other locations

Sample location	Sieve analysis d_{50} (mm)	Standar deviation (σ)	Sediment density (kg/m^3)	Organic content (%)
Granollers (Spain)	0.31	0.16	1,310	74(VS/TSS = 69–79%)
London (UK)[a]	0.8–1.0	1.7	1,802	3.6
Loenen (The Netherlands)[a]	0.3–0.4	3.4	1,800	10.5
Crushed olivestone[b]	0.047		1,445	100

[a]Schellart *et al.* (2005).
[b]Skipworth *et al.* (1996); Tait *et al.* (2003b).

Table 2 | Test condition used in the consolidation periods in the erosion experiments

Identification	T1	T2	T3	T4	T5
Dry-weather period (hours)	16	64	140	16	64
Aerobic/anaerobic conditions	anaerobic			aerobic	

approximately constant during an interval of 45 min. This period for the application of the shear stress steps was assumed to be suitable to achieve a steady suspended solids concentration in the water column, based on the findings by Tait *et al.* (2003b) and verified by Schellart *et al.* (2005).

The water temperature during all experiments was 23.5 °C ± 1.5 °C, a value similar to the maximum dry-weather wastewater temperature during spring and summer seasons measured in the sewer system where the sediments were collected. The lighting conditions could not be controlled during the experiments.

To create an aerobic environment a small air pump was used. In tests T4 and T5 it was attempted to maintain the dissolved oxygen saturation level (8.51 mg O_2/l at 24 °C) during the entire test, so as to promote aerobic microorganism activity. The air stone of the pump was placed in a way to not disturb the sediment surface with the air supply. Full mixed conditions and uniform dissolved oxygen concentration in the entire water volume was assumed due to the flow generated by the propeller.

Based on pre-existent laboratory experience, six standard shear stress steps were applied, aside from the value used during consolidation.

During each interval of applied shear stress, samples were withdrawn from the six vertically distributed orifices after 3, 10, 30 and 40 min, counting from the setting of each new rpm of the propeller. The volume of water removed during the sampling was always restored at the end of the removal step, to maintain a constant volume of water in the erosion meter.

An integrated sample was then prepared, assumed to be representative of the whole water column sediment concentration in the erosion meter at the sampling time. Each integrated sample was analysed for total suspended sediments (TSS), fixed solids and volatile solids (VS) following the *Standard Methods for the Examination of Water and Wastewater* (2005) test procedures. The level of dissolved oxygen and temperature, as well as the angular velocity of the propeller is recorded in each interval of applied shear stress. After each erosion test was performed, the remaining sediment deposit was collected and analysed for organic content and particle size distribution.

Relationship between the erosion rate and the bed shear strength

The erosion of sediments from the bed during the experiments was monitored in terms of the suspended sediment concentration and related to the erosion rate q as follows:

$$q_i = \left(C_{SS,i} - C_{SS,i-1}\right)\frac{V}{(A_s.(t_i - t_{i-1}))} \tag{1}$$

$$q = \sum_{i=0}^{n} q_i \tag{2}$$

where q is the average erosion rate in a shear stress step, q_i is the erosion rate in the instant i expressed in (g/m^2/s), ($C_{SS,i}$–$C_{SS,i-1}$) the difference in suspended sediment concentration (in g/m^3) between the sampling instant i and the previous i–1, V is the water volume of the column over the sediment sample, and A_S (in m^2) is the surface area of the bed subjected to erosion.

Knowing the value of the erosion rate (q) linked to the applied shear stress (τ_b) it is possible to obtain a function for erosion rate by fitting a curve through the obtained points. The value of the critical shear stress (τ_c) for sediment threshold of motion can be found with this curve.

RESULTS AND DISCUSSION

The sediment started to be eroded as soon as any of the beds were exposed to the low shear stress representing dry-weather flow conditions. The absolute threshold of motion was therefore difficult to observe for all experiments carried out.

The value of erosion rate can be determined using Equation (2) for each of the steps of applied shear stress. The average erosion rate can then be plotted against shear stress (Figure 3) to analyse the sediment deposit behaviour during the tests carried out under anaerobic and aerobic conditions and for different dry-weather simulated periods.

In Figure 3 it can be seen generally that as the shear stress increased in all tests the erosion rate curve shows a slight rise. Due to the overall incremental values of erosion rates obtained, it was assumed that no significant sedimentation of particles occurred during the erosion phase of the experiment. Only in test T4 the erosion rate increased at first and then decreased later in the test. The slight decrease on the erosion rate towards the end of the tests may be due

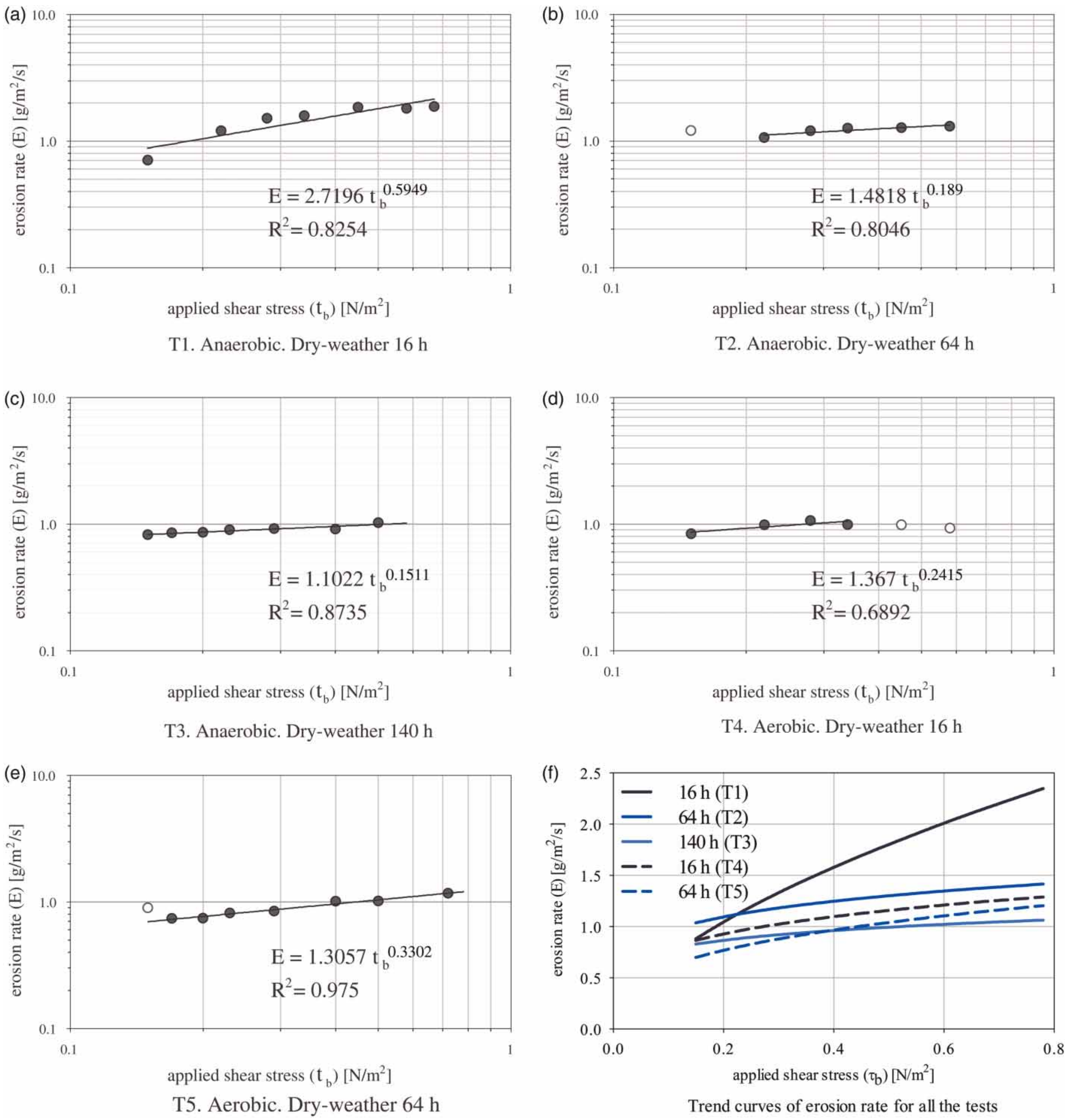

Figure 3 | (a) to (e) Erosion rate against applied shear stress during tests under anaerobic (T1–T3) and aerobic (T4–T5) conditions. Double log plot and best fitting-trend curves (power trend). (f) Power trend lines obtained for T1 to T5 are shown comparatively.

to the existence of a locally stronger consolidated layer within the original deposit. Differences in the R^2 values can be explained due to the inherent variability in the sample being tested.

When comparing between tests with increasing periods of consolidation without added oxygen, there is a clear drop in the overall values of erosion rate, related to the values of the applied shear stress. This suggests that as the consolidation period lengthens the deposit strengthens.

Comparing cases T1 with T4 and T2 with T5, a decrease in the overall values of the erosion rate was noticed. This is thought to be associated with aerobic biological activity, which appears to have generated a stronger deposit regarding the resistance to erosion.

First, samples in tests identified as T2 and T5 in Figure 3 have a relatively high erosion rate, which may be related with a weak layer formed in the upper bed, this may be composed mainly by the settling of lower density particles consisting of flocs of sludge and a high percentage of fats that have not then had the time to be able to transform and generate sufficient cohesive bonding to strengthen, as is the case in T3.

It is difficult to find a general trend in erosion rate against shear stress. It is clear however that the presence or absence of oxygen and the length of the consolidation period significantly influence the behaviour and resistance of the deposit against erosion.

An empirical relationship between the rate of erosion and the applied bed shear stress is adopted by establishing a power trend. Figure 3 shows the empirical erosion equation and the trend line obtained in each test. The trend curves then are plotted in Figure 3(f), which present a comparison between the trends lines obtained in all the tests. A clear trend of increasing erosion strength in bed can be seen, as the duration of the dry period is increased.

The slopes of the erosion rate versus shear stress curves are much lower than that expected for a purely granular bed (1.2 to 1.5). The slopes values range from 0.59 to 0.15 indicating a deposit that is increasing in strength with depth. The increase of strength with depth of erosion can be suggested to be related to changes in the internal structure of the deposit (Skipworth *et al*. 1996).

The effect that the oxygen has on the erosion strength could also be seen by analysing the curves in Figure 4 which shows the differences between the tests carried out with and without added oxygen, for the same duration of consolidation period. The dotted lines in Figure 4 indicate the possible variation that can be considered according to the errors in the assessment of the shear stress during the calibration procedure (shear stress ± 0.07 N/m^2).

In tests performed with oxygen supply, the shear stress required for the erosion of the sediments was significantly higher compared with experiments run without supplying oxygen (around 40% between erosion rate values in tests T1 and T4 at 0.6 N/m^2). The difference in behaviour is still significant despite the errors that may have been incurred during the test (compound error calculated following estimation of the measurement errors and given accuracy of the equipment: accuracy in the assessment of the shear stress related with the angular velocity, accuracy of balance for weighing supernatant sample 0.1 g, accuracy of balance for weighing filter papers 0.0001 g).

Another relevant fact was obtained from the analysis of the remaining sediments after the erosion tests. The remaining sediment shows an increasing trend in organic content and a decline in the median size of the particles that form the leftover deposit with the duration of dry weather (Figure 5). This behaviour might be explained by the added time available for biological reactions between organic particles during the dry-weather period, resulting in the generation of more bonding internal forces and a stronger sediment deposit. This trend implies that the longer the dry-weather period, the finer and more organic particles were retained in the whole mass of the bed linked with bonding forces, and developing a stronger deposit. Oxygen supply during this period leads to more

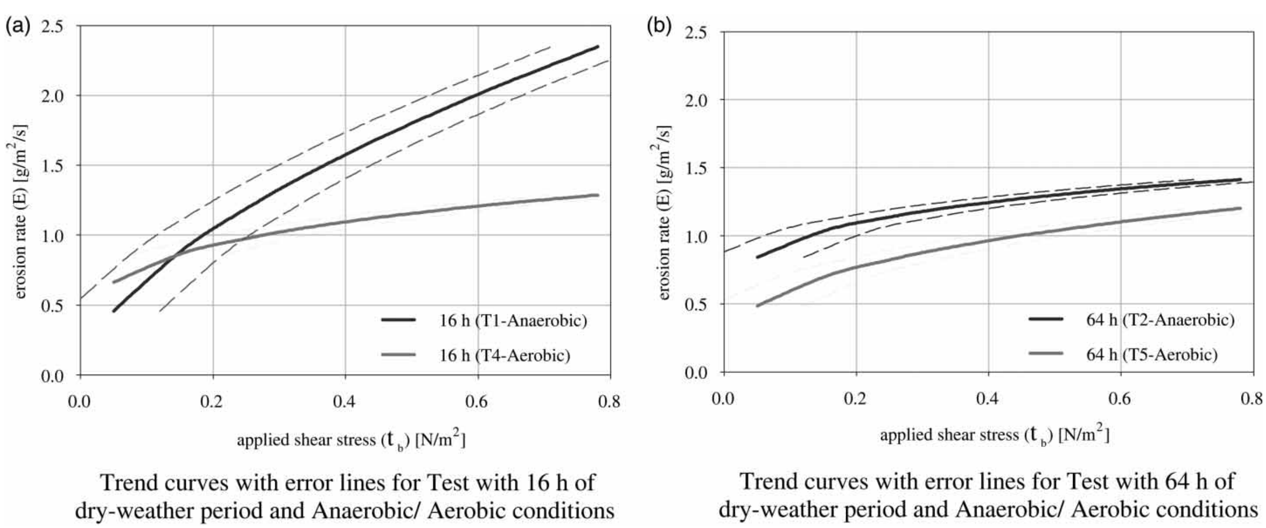

Figure 4 | Trend curves of erosion rate (see equations in Figure 3) showed comparatively for different length and oxygen supply during the consolidation period.

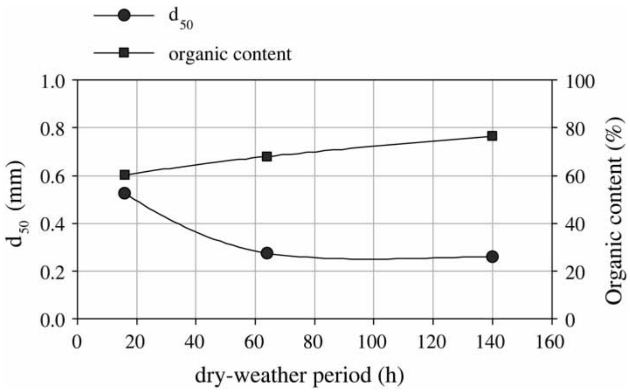

Figure 5 | Analysis leftover after erosion tests under anaerobic conditions. Variation in particle size and organic content with length of dry-weather period.

biological activity and to an increase in the resistance to erosion of the whole bed of sediments.

CONCLUSION

A series of laboratory tests were carried out to help estimate the erosional resistance and hence erosion rate from highly organic sewer sediment beds under storm runoff conditions in a sewer network subject to Mediterranean climatic conditions. All tests contained a consolidation followed by an erosion phase.

Environmental conditions in the consolidation phase may generate changes in the nature (because of the biological growth) and in the structure (because of the formation of bonds between particles) of the highly organic sediment bed. These changes are translated in the development of the resistance against erosion of the sediment deposits.

Similar erosion patterns have been observed between the results obtained in this work and those found by Tait *et al.* (2003b) using synthetic sediment, both with a clear increase in the resistance of the deposited bed with time of consolidation (around 95% between erosion rate values in tests T1-16 h and T3-140 h at 0.6 N/m^2), especially when there was oxygen available (around 40% between erosion rate values in tests T1-anaerobic and T4-aerobic at 0.6 N/m^2). Conclusions about the significant influence of the organic content, oxygen availability and length of the consolidation period (dry-weather) on the subsequent erosion of the deposit are similar also to that observed by Schellart *et al.* (2005).

Although there were similarities with previous findings related to the general behaviour of the sediment, the immediate suspension of sediments at the beginning of the erosion test suggest marked differences in the shear stresses at the threshold of motion. Lesser magnitudes of critical shear stresses can be predicted from the tests conducted in this work with the high organic sediment found in Granollers (Spain) with regards to those collected from London and Loenen with low-organic content, and the synthetic sediment. This behaviour is assumed to be due to the differences in the sediment properties with regards to both the relatively low density and the high organic composition and high bacterial potential activity.

Future laboratory investigation is needed considering the influence of temperature and also the application of lower stresses in the starting steps of the erosion. A change in the motor of the testing device may be required allowing the operation at more stable low-speeds. As well, a larger number of tests are needed in order to confirm the range of values of critical shear stresses to be used in the determination of transport rates for high organic sediments; nevertheless general conclusions about the behaviour of this kind of sediments remain valid.

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