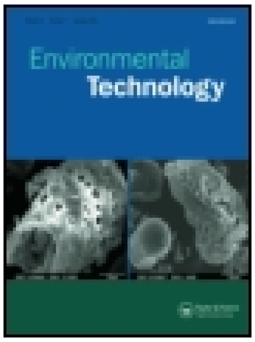

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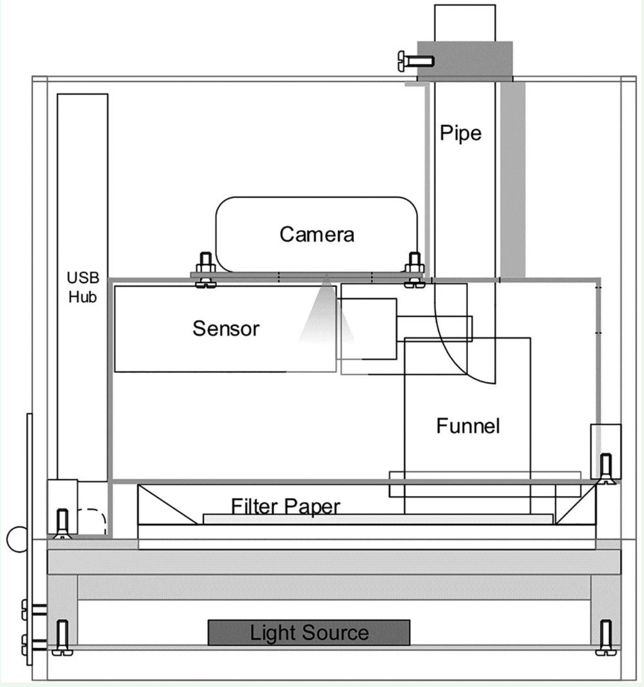
Highlights of the novel dewaterability estimation test (DET) device

Miklas Scholz [a,b,c], Suhad Almuktar[a,d], Christian Clausner[a] and Apostolos Antonacopoulos[a]

[a]Division of Water Resources Engineering, Lund University, Lund, Sweden; [b]School of Computing, Science and Engineering, The University of Salford, Salford, UK; [c]Department of Civil Engineering Science, University of Johannesburg, Johannesburg, South Africa; [d]Department of Architectural Engineering, The University of Basrah, Al Basrah, Iraq

ABSTRACT

Many industries, which are producing sludge in large quantities, depend on sludge dewatering technology to reduce the corresponding water content. A key design parameter for dewatering equipment is the capillary suction time (CST) test, which has, however, several scientific flaws, despite that the test is practical and easy-to-perform. The standard CST test has a few considerable drawbacks: its lack of reliability and difficulties in obtaining results for heavy sludge types. Furthermore, it is not designed for long experiments (e.g. >30 min), and has only two measurement points (its two electrodes). In comparison, the novel dewaterability estimation test (DET) test is almost as simple as the CST, but considerably more reliable, faster, flexible and informative in terms of the wealth of visual measurement data collected with modern image analysis software. The standard deviations associated with repeated measurements for the same sludge is lower for the DET than for the CST test. In contrast to the CST device, capillary suction in the DET test is linear and not radial, allowing for a straightforward interpretation of findings. The new DET device may replace the CST test in the sludge-producing industries in the future.



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CONTACT Miklas Scholz miklas.scholz@tvrl.lth.se Division of Water Resources Engineering, Faculty of Engineering, Lund University, P.O. Box 118, Lund 22100, Sweden; School of Computing, Science and Engineering, The University of Salford, Salford, UK; Department of Civil Engineering Science, University of Johannesburg, Johannesburg, South Africa

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Introduction

Background

Sludge contains solids of varying inorganic and organic nature and sizes, but predominantly liquid, which is commonly water. Industries such as water and wastewater utilities, breweries, and pulp and paper manufacturers produce large volumes of sludge every day [1]. Sludge dewatering and disposal accounts for approximately 40% of the treatment costs [2].

The CST test, which essentially measures the advancement of liquid drawn from sludge within a chromatographic paper, is often applied to optimise coagulation processes in industry [3]. Coagulation is an essential process in water and wastewater treatment plants [3,4]. The influence of different shapes and types of mixers on floc formation and stability has been neglected in the scientific literature due to the complexity of the coagulation process [3,5,6]. Empirical findings show that the use of different types of mixers produces different floc types and sizes [7], which have different dewaterability characteristics. Furthermore, rapid mixing units also impact on the dewaterability characteristics of sludge. The effect of hydraulic turbulence on turbidity removal has been assessed for rapid mixing units [8]. Furthermore, Fitra et al. [9] assessed the impact of sludge floc size and water composition on dewaterability. The reader may wish to refer to Scholz [10] for a full review of the subject matter.

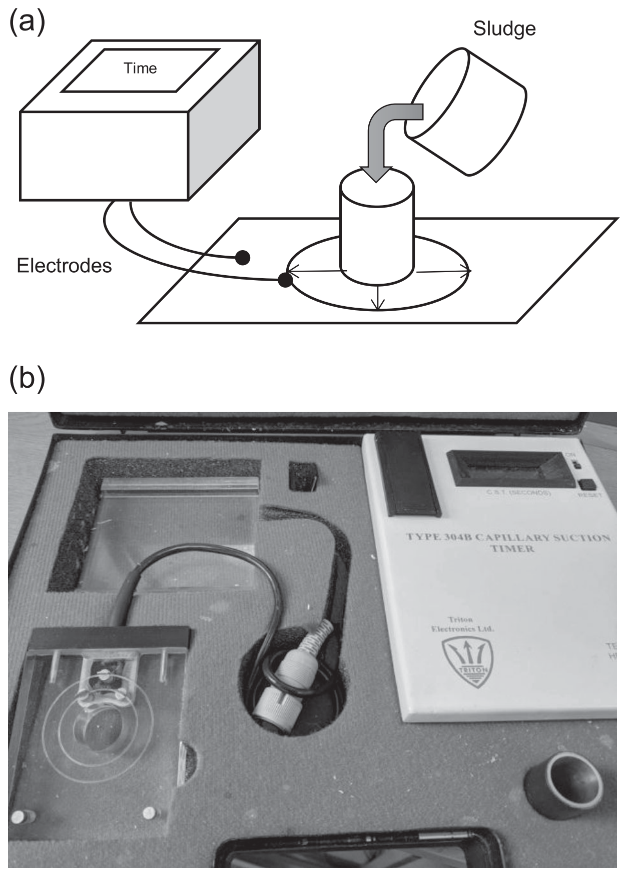

Figure 1. Standard apparatus (model 304B CST) to measure the capillary suction time (CST).

Dewatering tests

Dewatering tests are indispensable to quantify the ease of removing liquids from slurry and sludge with a moisture content of above 90% [10]. An indication of dewaterability can be used to help to characterise the viscosity of slurry, which is needed in the design of industrial dewatering facilities and equipment [11]. Volume reduction of sludge is important to reduce the environmental and financial burden of disposal, and to alleviate land capacity constraints, which are mainly a function of weight and volume. Therefore, dewatering is also an essential step before incineration can be undertaken efficiently [1].

Different methods to estimate how easy it is to dewater sludge are available: CST, specific resistance to filtration [12], conditioned filtrate, filtrate total solids and streaming current [13]. The most commonly used method is currently the CST test, which has been proven to be cost-effective, rapid and simple-to-execute [10,11,14,15]. The standard test provides only one value per experiment. However, the multi-radii CST device provides up to five measurements, but is based on the same principles as the standard CST device.

The CST apparatus was developed in 1967, and since then, it has been used worldwide in various applications and disciplines [16]. However, the standard CST test has major drawbacks of inconsistency of results and relatively high consumable costs associated with the use of the Whatman No. 17 chromatographic paper, which is the standard CST paper. The capillary suction pressure generated by this non-homogenous paper is used to suck water and fine solids radially (difficult to treat mathematically) from the sludge, and the time taken for the water front to pass between two electrodes constitutes the CST. Fine solids can partly clog the pores within the paper leading to elevated CST values [10,14,15].

Rationale, aim and objectives

The novel DET apparatus has been developed to address the scientific shortfalls of the traditional CST test [14] and the complexity of laboratory tests such as resistance to filtration [12]. The aim of this article is to outline the design, operation and performance of the new DET

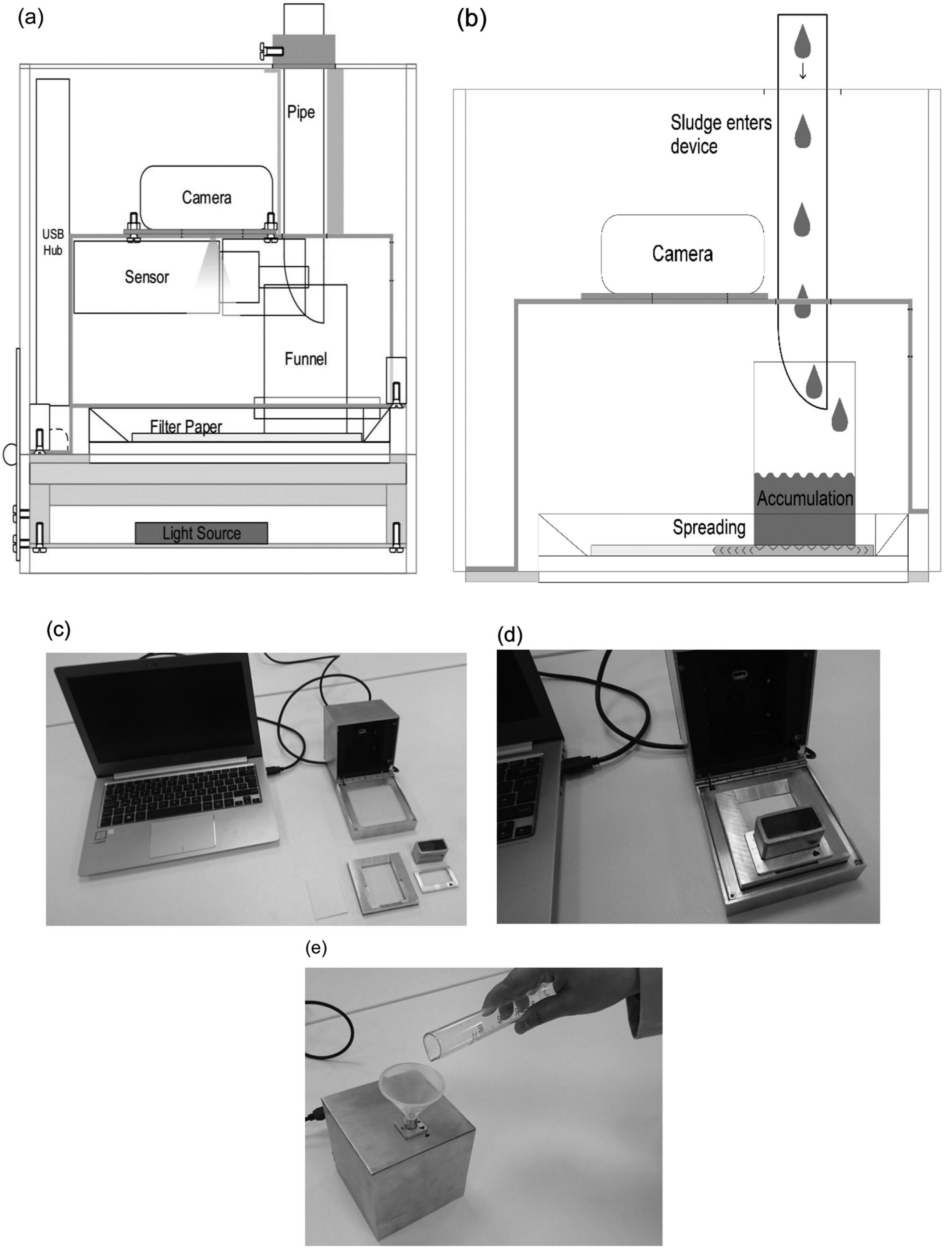

Figure 2. Components of the dewaterability estimation test (DET) prototype (stainless steel casing): (a) outline sketch; (b) sketch showing the travel stages of sludge; (c) picture of key components; (d) picture of key assembled components; and (e) picture of adding sludge process.

invention. The corresponding objectives are to (a) make a case for the need of the DET apparatus, (b) compare the CST and DET tests with each other, and (c) outline the operation of the DET device by using test examples.

Method developments

Capillarity suction time device

Figure 1 shows the standard CST device (Model 304B CST) provided by Triton Electronics Ltd., which was used to conduct the experiments. The equipment consists of a cylindrical steel funnel resting on the filter paper fitted between two Perspex plates with electrode sensors across the top plate [17]. The electrodes are placed at a standard interval of 3.7 mm, and at distances of 18.6 and 22.3 mm from the centre of the funnel. The electrodes are connected to a timer. The recorded CST value is a measure of the time required for the water front to move through a stretch of paper positioned between the two electrodes.

An adequate and representative amount of suspension is poured into the funnel of the CST device until the liquid is level with the top rim of the funnel. The pressure difference between the funnel and the paper is typically 5–10 kpa, and it originates from the capillary pressure difference across the liquid-air interface of the wetting front in the paper [18]. The capillary suction pressure forces the filtrate to be sucked from the suspension into the porous media, and a cake on top of the paper is subsequently leftover.

The capillary suction pressure of the porous paper is about twice as large as the hydrostatic pressure head within the funnel. Therefore, it can be assumed that the CST value is independent of the quantity of the liquid in the funnel as long as there is sufficient liquid to generate the suction pressure [10,17,18]. The rate at which the filtrate permeates through the paper varies depending on the condition of the sludge and the filterability of the cake formed on the paper. A large CST value indicates a high specific resistance to filtration.

Dewaterability estimation test device

The DET test relies on both the DET equipment and the DET software. The equipment is currently available as a prototype (Figure 2), which has not entered the market, yet. The prototype is made of stainless steel to allow for high durability and precision. Key components of the device (in no particular order) are the slot funnel, camera, light-emitting diode, light diffuser, sensors to measure temperature and humidity, laptop (hosting the DET software), fan and thermal paste for cooling.

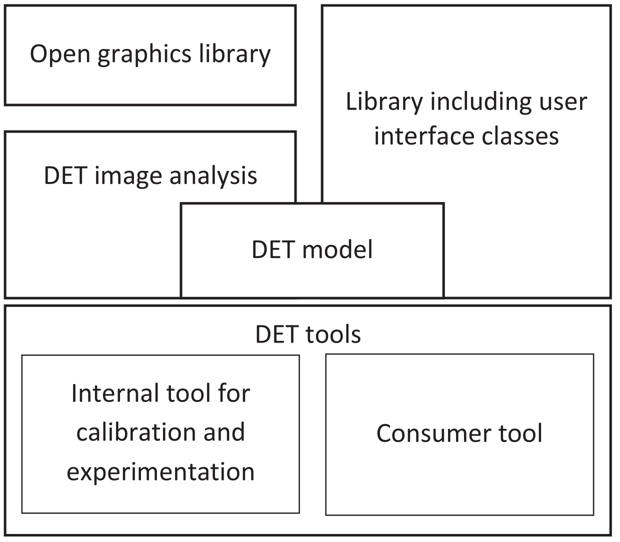

Figure 3. Dewaterability estimation test (DET) software architecture.

The water distribution during the start of the experiment has been studied carefully to allow for a uniform initial distribution of the sludge onto one side of the paper. This allows for a straight waterfront development; parallel to the side of the filter where the sludge touches the paper for the first time. In order to achieve a uniform distribution, a slot funnel outlet type (located parallel to the paper) was chosen. Furthermore, to avoid edge effects impacting on the waterfront, the funnel length had to be sufficient, and the funnel had to be located some distance away from the end of the paper to avoid water escaping through gaps between the funnel and the filter paper at the edges (Figure 2).

Finding the appropriate weight of the funnel was also an important design consideration. Therefore, experiments with different funnel heights (including 2.5 and 4.55 cm) were performed. The waterfronts of higher (and heavier) funnels performed consistently better in comparison to the shorter funnels. A tall and heavier funnel flattens the paper, subsequently reducing seepage. However, the act of flattening might influence the water spread speed, because the filter paper is more compacted. Experiments seem to support this theory at least for the standard CST filter paper. Therefore, it was necessary to find empirically the best paper and most suitable funnel using trial and error.

The negative impact of warped paper, particularly if the paper is very thick, is influenced by the dimensions of the funnel (the wider, the greater the risk) and the funnel weight (the lighter, the less the paper will be flattened). A solution was therefore the selection of a small, but heavy funnel. In order not to increase the local pressure on the filter paper, this was achieved by increasing the wall thickness of the funnel to an optimum.

Figure 4. Binary (black and white) image analysis with the dewaterability estimation test software: (a) start of the test and waterfront development; (b) the waterfront has passed the first line of interest; (c) the waterfront has passed the second line of interest.

Sawalha & Scholz [19] have shown that temperature fluctuations lead to high sludge dewatering variability characteristics. Therefore, the fan component in the DET device was seen as essential for the experiment to keep the measurement temperature constant and close to the temperature of the environment in which the sludge will be dewatered. The light source emits heat to raise the temperature by up to 2°C for experiments lasting more than three minutes, which alters the viscosity of the sludge, and therefore the time required for the liquid to travel through the paper.

Software description

The DET software architecture is shown in Figure 3. The software uses an area range for checking how the sludge moves, and then analyses liquid characteristics. The software detects the spread across the area of interest. Measurement parameters include average time, maximum time, minimum time, centre location time, standard deviation (expressed in percentage) and the magnitude between the top trace and the side trace.

When auto-stop has been enabled by the user, the software regularly performs the image analysis in the background, while a measurement is being taken. If it is detected that the liquid has spread across the area of interest, the measurement will be stopped automatically.

The dynamic frame rate is also an important feature of the DET device. The user no longer has to select a recording frame rate depending on the expected duration of a measurement. Using the automatic setting for the frame rate, the software starts recording with a high frame rate and lowers it thereafter logarithmically, the longer the measurements takes.

The specific requirements of the DET software (Figure 3) are to access the hardware, record data (images, temperature and humidity), detect and follow the spread of the sludge, store results as well as visualise and present relevant data to the user. The software is based on two open source software libraries (OpenCV and Qt) commonly used for image processing and graphical user interface functionality.

The software was developed with the C++ programming language and follows a modular design. Figure 4 shows a binary image analysis example applying the dewaterability estimation test software. There are two software tools with graphical user interface: one for end-users (essential functions only) and a second one that provides extended features for calibration and settings (Online Resource 1). The area between the dotted lines is the area of interest for the DET measurements. Note that the black patches on top of Figure 4(b) is data noise, which is not being considered by the software, because it is outside the area of interest.

The method developed for the DET project uses motion tracking to follow the water front throughout the recording. The analysis is restricted to an area of interest, a rectangular region within the full-size recording canvas. The processing pipeline for each frame (i.e. picture taken from the webcam) is as follows:

(1) Subtract the previous frame: the result reflects the movement of the waterfront between the previous and the current frame.
(2) Median filter to reduce noise.
(3) Binarisation via adaptive threshold; this creates a bitonal black-and-white image.
(4) Validation: If the area of the change is smaller than 15% of the area of interest (or if the maximum threshold is reached, continue with step 5. Otherwise, increase the threshold and go back to step 3
(5) Add the result from step 3 to an accumulative image.
(6) Measure the water spread for each measurement strip: (a) follow the water flow pixel row by pixel row and count the pixels that were classified as 'wet filter paper'. If a certain number of pixels is found, classify the while row as 'wet filter paper'; (b) the spread is defined as the maximum number of continuous 'wet filter paper' pixel rows, starting from the beginning of the area of interest; and (c) translate measurements from pixel units into relative

Table 1. Characteristics of tested sludges.

Abbre-viation	Sludge name	Location of orign	Composition/characteristics
A	Synthetic sludge	Not applicable	Dextrin (150 mg/l); ammonium (130 mg/l). Ammonium (130 mg/l); yeast extract (120 mg/l); glucose 100 (mg/l); soluble starch (100 mg/l); sodium carbone (150 mg/l); detergent –commercial (10 mg/l); sodium dihydrogen orthophosphate (100 mg/l); potassium sulfate (8.3 mg/l); kaolin (10000 mg/l).
B	Mixed wastewater sludge	Coventry	Real sludge (primary settlement tank) obtained from a sewage treatment plant serving an estate with highly variable domestic but mainly industrial wastewater.
C	Ochre sludge	Bacup	Aluminum (177.8 mg/kg); boron (37.0 mg/kg); calcium (25677.4 mg/kg); cadmium (8.7 mg/kg); chromium (22.5 mg/kg); copper (95.7 mg/kg); iron (470458.5 mg/kg); magnesium (286.6 mg/kg); manganese (4276.3 mg/kg); nickel (15.8 mg/kg); zinc (70.4 mg/kg); sulphur (15033.8 mg/kg).
D	Domestic wastewater sludge	Stoke-on-Trent	Highly variable but thick domestic sludge obtained from septic tanks after conditioning.

spread (percentage of coverage of the area of interest).

(7) Clean-up the accumulative image: clear all pixels after the current water front position to remove noise (e.g. Figure 4(b)).

(8) Failsafe: Check if there are two or more measurement strips where no spread time could be established. If this is not the case, the process is finished. If there are two or more problematic strips, reanalyse with a different algorithm: (a) always subtract the first frame; (b) apply a fixed threshold; and (c) measure water spread.

The software records in a dynamic frame rate, starting with many frames per minute at first, and then slowing down to reduce the amount of recorded data for long measurement. Data will still be produced for each frame using interpolation for frames where no image analysis was applied.

Experiments conducted

About 450 experiments in total were conducted to test different (filter) papers, types of sludge and funnels. Due to instability in real sludge properties [20], synthetic sludge was used to simulate consistent properties, which is required for research purposes [9]. The synthetic sludge A recipe was chosen following published guidelines [21]. The solution was prepared by adding the items displayed in Table 1 to 1 L of hot tap water followed by adding 10 g of kaolin. Kaolin was used to simulate the total suspended solids concentrations of 1%, which are similar to those available in synthetic raw water [9]. Moreover, all chemicals shown in Table 1 were supplied by Sigma Aldrich Co. Ltd. (Gillingham, UK). After that the solution was mixed well using

Table 2. Overview of the dewaterability estimation test device results for different funnel types and synthetic domestic wastewater sludge (10 samples were tested per each variable).

		Funnel types	
Parameter	Unit	High thick funnel	Medium thick funnel
CST-filter paper (equivalent to Whatman No. 17)			
Average time	S	1328	1447
Minimum time	S	1211	1310
Maximum time	S	1550	1661
Centre time	S	1215	1327
Standard deviation	%	7.8	7.3
Magnitude	Mm	2	2
BF3-filter paper			
Average time	S	1437	1243
Minimum time	S	1246	1086
Maximum time	S	1858	1513
Centre time	S	1377	1195
Standard deviation	%	11.7	10.8
Magnitude	Mm	3	3
EE.2OH- filter paper			
Average time	S	2636	1400
Minimum time	S	1529	564
Maximum time	S	3705	2802
Centre time	S	2576	935
Standard deviation	%	32.5	45.0
Magnitude	Mm	8	11

Note: Highly thick, and medium thick with dimensions of 40 mm × 20 mm × 45.5 × 2 mm and 40 mm × 20 mm × 35 mm × 2 mm, respectively.

Table 3. Overview of dewaterability estimation testing device results when using different filter paper types (10 samples were tested per each variable).

		Filter paper type		
Parameter	Unit	CST	BF3	EE.2OH
Synthetic sludge (A)				
Average time	s	1328	1437	2636
Minimum time	s	1211	1246	1529
Maximum time	s	1550	1858	3705
Centre time	s	1215	1377	2576
Standard deviation	%	7.8	11.7	32.5
Magnitude	mm	2	3	8
Coventry sludge (B)				
Average time	s	191	109	158
Minimum time	s	166	98	129
Maximum time	s	266	126	193
Centre time	s	194	99	154
Standard deviation	%	15.2	8.4	20.1
Magnitude	mm	3	3	3
Ochre sludge (C)				
Average time	S	27	21	16
Minimum time	S	24	19	9
Maximum time	S	30	23	28
Centre time	S	25	20	15
Standard deviation	%	6.3	5.3	50.8
Magnitude	mm	2	2	3

Table 4. Overview of capillary suction time (CST) device results when using different filter paper types (10 samples were tested per each variable).

Parameter	Unit	Filter paper type CST	BF3	EE.2OH
Coventry sludge (B)				
Average time	s	734	577	1128
Minimum time	s	113	378	108
Maximum time	s	575	748	1781
Centre time	s	–	–	–
Standard deviation	–	951.1	139.8	566.9
Magnitude	Mm	–	–	–
Ochre sludge (C)				
Average time	s	31	49	180
Minimum time	s	11	42	56
Maximum time	s	38	70	416
Centre time	s	–	–	–
Standard deviation	–	9.2	8.5	93.6
Magnitude	mm	–	–	–

1200 rpm mixing intensity and a magnetic stirrer for 5 min. This synthetic domestic wastewater was prepared fresh and was always stored in the fridge to avoid uncontrolled growth of microorganisms [9].

The following test papers have been explored: CST (equivalent to Whatman No. 17), BF3 and EE 2.0H. The Whatman No. 17 paper (Whatman Plc, Brentford, England, UK) is a chromatographic paper made of cellulose with a high flow rate of 6.33 mm/min and with a mean pore diameter of 8 µm, basic weight of 413 g/m^2 and thickness of 920 µm. However, the paper has some disadvantages in the context of the CST test including its anisotropic properties and oversized pores besides its high cost. Therefore, alternative cheaper filter and chromatographic papers from different sources were used: BF3 filter paper (Santa Cruz Biotechnology, Inc., Heidelberg, Germany), and EE2.0H filter paper (Carlson Filtration ltd, Barnoldswick, UK) were also tested and subsequently compared with the Whatman No. 17 chromatographic paper. The blotting non- Isotropic filter paper (BF3) has a flow rate of 13 mm per min, while the Isotropic EE 2.0H paper has a flow rate of 2245 mm/min with basic weight of 700 g/m^2 and thickness of 3000 µm.

These funnels have been tested: Highly thick, and medium thick with dimensions of 40 mm × 20 mm × 45.5 × 2 mm, and 40 mm × 20 mm × 35 mm × 2 mm, respectively. Ten measurements for each paper, sludge (20 ml) and funnel were taken per experimental run.

Statistical analysis

IBM SPSS Statistics Version 20 was applied. Comparisons between two independent variables were performed using the T-Test, when data are normally distributed, while the Mann Whitney U- test was used instead for not normally distributed data Moreover, the one-way analysis of variance (ANOVA) was used to determine whether there are any significant differences between the means of three or more groups, which are normally distributed, while the Kruskal-Wallis test was used instead for non-normally distributed data [22].

Results and discussion

Dewaterability estimation test device results

Due to variability and instability in real sludge properties [1,20], synthetic sludge was used to simulate consistent properties [9]. Tables 2 and 3 show the DET device results for different funnel types when using synthetic domestic wastewater sludge and corresponding statistical analysis. Findings indicated that the required time for synthetic sludge dewatering in term of average time, minimum time, maximum time and centre time where lower for the high thick funnel than those for the medium thick funnel (Table 2) when using CST filter paper type. Concerning Table 3, note that no readings were obtained when using Stoke-on-Trent sludge (D), which is very thick, and can therefore not be sucked-up.

Statistical analysis results (Online Resource 2) indicated that there are no significant differences ($p > 0.05$) in sludge dewaterability time for the two funnel types when the samples were test using Whatman No. 17 filter paper. On the other hand, average time, minimum time, maximum time and centre time were recorded to be greater for high thick funnel than those for medium thick funnel when using BF3 and EE-2OH filter papers (Table 2) to dewater the sludge type A showing some

Table 5. Comparison of the dewaterability estimation test (DET) with the capillary suction time (CST) test.

Test	CST A	BF3 A	EE 2.0H A	CST B	BF3 B	EE 2.0H B	CST C	BF3 C	EE 2.0H C
Number of measurements									
DET	10	10	10	10	10	10	10	10	10
CST	n.a.	n.a.	n.a.	10	10	10	10	10	10
Average measurement times (s)									
DET	1328	1437	2636	191	109	159	27	21	16
CST	n.a.	n.a.	n.a.	734	577	1128	31	49	180
Relative standard deviations (%)									
DET	7.8	12	33	15	8	20	6	5	51
CST	n.a.	n.a.	n.a.	15	24	50	30	17	52

Note: A, synthetic sludge; B, Coventry sludge, and C, ochre sludge; n.a., not applicable; DET, dewaterability estimation test; CST, capillary suction time test.

significant ($p < 0.05$) statistical differences (Online Resource 2) mainly for BF3 type indicating the impact of filter paper properties on sludge dewaterability as discussed by [23,24,14]. However, the waterfronts of higher (and heavier) funnels performed consistently better in comparison to the shorter funnels. This can be explained by avoiding warping of the filter paper when the funnel is too light. A tall and heavier funnel flattens the paper, subsequently reducing seepage. Nevertheless, the act of flattening might influence the water spread speed, because the filter paper is more compacted [10]. The negative impact of warped paper, particularly if the paper is very thick, is influenced by the dimensions of the funnel (the wider, the greater the risk) and the funnel weight (the lighter, the less the paper will be flattened). Based on that, the authors decided to continue the experimental work with the high thick funnel.

Table 3 show the DET device results when using different filter paper types per each sludge type and corresponding statistical analysis for the impacts of different filter papers (Online Resource 3) and sludge types (Online Resource 4). Results highlight that the CST and BF3 filter papers resulted in lower and more stable results than the EE.2OH paper (Table 3). However, different sludge types might require specific filter papers to obtain optimal results. In theory, an almost endless amount of filter papers and sludge types could have been tested, which is practically impossible but might be justified and feasible for very specific and stable industrial liquid wastes [1].

Capillary suction time device results

Table 4 shows an overview of CST device results when using different filter paper types. A corresponding statistical assessment of different filter paper and sludge impacts on the CST results can be found in Online Resources 5 and 6, respectively. Findings indicate that the CST test only produces results for half of the tested sludge samples. No readings were obtained when using synthetic sludge (A) and Stoke-on-Trent sludge (D), which cannot be sucked-up by the papers, because they are too thick. Centre time and magnitude could not be measured by the CST device. Moreover, the data are highly variable, which indicates low reproducibility. This can be explained by the flaws of the CST test outlined in the methodological development explained above.

Test comparisons

Table 5 shows a comparison between DET and CST tests. The filter paper EE 2.0 H is highly anisotropic and very thick. Therefore, sludge spreading appears to be random and takes a long time using the CST apparatus (even no measurements for sludge A could be recorded). Particles within the sludge are not retained fully by paper EE 2.0 H, and are taken along with the liquid during the test.

When comparing the performances of both competing devices, the following claims can be made for the tests outlined in Table 5: The DET apparatus is usually more reliable (lower standard deviations) than the CST device. The new device gives faster results than the CST apparatus (Table 5).

Software performance

The DET apparatus is fully supported by the DET software for testing in the lab and field. The software performs image analysis in the background while measurements are being taken. The new equipment produces considerably more data (multiple points of measurement, deceleration of dewatering throughout measurement and video recording) than the CST test. The DET device is also the only dewaterability test supported by image analysis.

The DET software worked without any complications. However, on occasions, the software did not recognise the waterfront within paper EE 2.0H, which was considered, however, inappropriate for the test as explained above.

Conclusions and recommendations

The DET apparatus is faster and more reliable than the CST apparatus with respect to the sludge types tested and filter papers used. It can obtain readings that the CST apparatus is not able to provide particularly for heavy sludge. In contrast to the CST, the DET apparatus is supported by image analysis software allowing for the recording and analysis of as many pictures as required.

The commercial potential of the DET apparatus is significantly high, since it is likely to replace the CST apparatus, which currently dominates the market due to lack of competition by other portable devices. A patent application is currently pending. The authors recommend further work on testing the new device in various sludge-producing industries, and produce tables allowing practitioners to easily transform their previous CST data into DET equivalent ones, wherever scientifically justifiable. Furthermore, quantitative comparisons and qualitative relations to measures of real dewaterability linked to industrial dewatering technologies should be provided.

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Disclosure statement

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ORCID

Miklas Scholz http://orcid.org/0000-0001-8919-3838

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