### Background to CST measurements

Various measurements of dewaterability such as the CST, specific resistance to filtration (SRF), the conditioned filtrate (liquid stream) streaming current and filtrate total solids were assessed. A significant correlation between the filtrate viscosity and CST was established, with both related to dewaterability. There was also a clear relationship between the CST, the filtrate streaming current and solids recovery. A minimum CST, filtrate streaming current values close to zero for both filtrate and conditioning sludge and minimum filtrate viscosity correlated well with maximum solids recovery.1,2

The CST equipment has long been established as a practical but empirical method for the determination of sludge dewaterability. The CST was shown as a good index for sludge filterability, if only the product of solid concentration and average SRF is of interest. On the other hand, the bound water content cannot be directly evaluated from the CST data.3 The CST values usually correlate well with SRF measurements. However, the CST values do not allow for the solids content and therefore it is necessary to specify the solids content of the sludge experimentally. It is possible for sludge with a low CST value and high solids content to be easily dewatered.1

### CST devices and measurements

The CST was measured with a patented standard CST device. The Model 304B CST (see Figure 1) was designed to comply with European and U.S. electromagnetic compatibility standards. Two 10- and 18-mm diameter funnels were applied for ‘fast’ and ‘slow’ filtering of ‘light’ and ‘heavy’ sludges, respectively. The 10-mm diameter funnel had a cone-shape inlet at the top. The funnel volumes were 5.62 and 6.36 cm² for the 10- and 18-mm funnel, respectively.

Concerning the CST apparatus application procedure, sludge is poured into a small open funnel (circular tube) resting on a piece of paper. Filtrate is extracted by capillary suction and a cake is formed at the bottom of the funnel. However, the cake formation is enhanced for ‘heavy’ sludges by sedimentation that leads to artificially high CST values.1,5 The CST is obtained from two electrodes placed at a standard interval from the funnel. The time taken for the waterfront to pass between these two electrodes constitutes the CST. The force generated by capillary suction is much greater than the hydrostatic head within the funnel, so the test is relatively independent of the amount of sludge, as long as there is sufficient to generate a CST measurement.

This is therefore usually the case except for very ‘heavy’ sludges.5

The rate at which filtrate is extracted depends on the resistance of the cake. By measuring the distance the filtrate requires to travel along the paper as a function of time, the cake resistance can be determined. The method relies upon the varying pressure applied by the movement of water through the paper, so that a theoretically complete mathematical treatment of the CST data is difficult.1

A further set of experiments was performed with a rectangular funnel of 18 x 18 x 20 mm (width, length and height, respectively) as a replacement of the circular funnel. The volume was therefore 6.48 cm³. The apparatus was modified by Triton Electronics Limited according to recommendations by the author (Scholz). It has to be noted that the rectangular funnel should be suitable for virtually all sludges.1

### Testing of different papers

Filter, chromatographic and other papers (all called papers for the purpose of this article) from Whatman (distributed by Camlab), Hollingsworth and Vose (HOVO), Carlson Filtration (Carlson), Schleicher and Schuell Microscience...
Whatman provides the standard CST paper that is by far the most expensive one in this comparison but sets the benchmark criteria. This smooth cellulose paper of grade 17 chr has a relatively high flow rate. However, the wet front moves faster along the grains than across, resulting in an elliptical shape of the wet front. Papers SS 1107 and SS 3205 are isotropic and papers Whatman No. 17 chr, SS 2668 chr, SS3324 chr and Fisher 200 chr are anisotropic.

**Testing of different sludges**

Experiments were undertaken with ‘heavy’ primary sludge and ‘light’ surplus activated sludge (sludge blanket of a CYCLAZUR sequencing batch reactor) delivered by Scottish Water (Bo’Ness wastewater treatment works, West Lothian). The sludges were constantly aerated and stored at 4°C in the fridge for not more than 35 days before analysis. CST experiments were conducted with various papers and three different funnels (see above).

Synthetic activated sludge can be prepared by flocculating negatively charged polystyrene latex particles (bacteria replacement) using sodium alginate (a polysaccharide produced from brown seaweed [*Phaeophyceae*] representing the extracellular polymeric substances) and calcium chloride (acts as general bridging cations). However, the polystyrene latex particles are expensive. At least £1,270 (for 100 ml) would need to be spent to enable one series of simple experiments requiring a few liters of synthetic sludge (e.g., *Interfacial Dynamics Corporation* catalog). These economic constraints severely limit the use of the proposed synthetic sludge for reference purposes. However, the polystyrene latex particles are not essential for alginate floc formation. Therefore, 180 mg/l alginate was mixed with 1,000 mg/l calcium chloride only to simulate a cheap and stable synthetic sludge for reference purposes. Quantities are based on optimization calculations published elsewhere.7

**Stirred CST test**

A revised Typhoon Europe Frother Product Code 35712 with an L-shaped shaft of 1.6-mm diameter was applied as a micro-mixer to stir the sludges during an additional experiment to assess the influence of hindered sedimentation. The length of the horizontal part of the shaft was 4 mm. The deviation from the center during rotation was ± 1 mm. The stirrer was inserted at a right-hand angle to a depth of approximately 2 mm above the bottom of the funnel. Moreover, the individual price of a modified frother is approximately $3 and therefore adds only an insignificant cost to any CST apparatus.
**CST and paper application**

Since the invention of the CST test in 1967, the same paper (Whatman No. 17 chr) has been used to allow for an easy comparison of test results worldwide. However, the paper type was virtually selected at random. For example, concerns that depth filtration of colloids might be likely due to the relatively large pore size of eight mm have not been addressed. Therefore, other (non-chromatographic) papers with a smaller pore diameter such as HOVO TO w/s, SS 1107 and SS 3205 were also chosen for detailed investigation.

Paper water flow can physically be described by the theory of water flow in porous media. This theory is based on the material balance for the water and Darcy’s law. The matric potential or suction (arising from the interaction of water with the solid surfaces and their geometry) and the hydraulic conductivity of both the paper and the suspension are functions of the water content.\(^1\)\(^5\)

The one-dimensional CST using a circular funnel was analyzed considering the material balance and continuity of the water potential on the paper and suspension interface. Experiments agreed with the theory and illustrated that flow in the paper is unsaturated. The advance of the wetting front in the paper is a function of the interaction of the sorptivity and matric potential functions of both the paper and the suspension. Extension of this approach to radial flow in the paper is complicated and does not permit a simple interpretation of the wetting front advance. The standard CST method is therefore a useful empirical tool for practicing engineers.

However, the use of a CST apparatus with a rectangular funnel is able to overcome the problem of anisotropic chromatographic paper by making use of only one direction of the paper. Both the diffusion-like (linear diffusion) and piston-like (constant capillary suction pressure) approaches could be used to support the interpretation of results.

**Rectangular CST device**

Fluid flow and cake formation in a rectangular CST apparatus were investigated experimentally and theoretically. The wet front shape is taken as an ellipse in a CST test using a cylindrical funnel, and as a straight line in using a rectangular funnel. Particle sedimentation affects the CST in a cylindrical capillary suction apparatus. In contrast, sedimentation effects should be insignificant if a rectangular funnel and Whatman No. 17 chr paper is used for the CST tests.\(^1\)

**Stirring of sludge to avoid sedimentation**

One problem with the conventional CST test using a circular funnel is the effect of sedimentation, which cannot be neglected for a majority of flocculated ‘heavy’ slurries and ‘heavy’ sludges.\(^1\)

Sediments such as suspended solids and heavy flocs accumulate on top of the paper during the standard CST test procedure. The CST theory does not take the effect of sedimentation into account. This may subsequently lead to an overestimation of the cake resistance. The application of a rectangular chamber and/or a stirrer might solve this problem. Recent results show that stirring had only a relatively low impact on CST measurements in comparison to unstirred (allowing for sedimentation) primary sludge.

**Primary sludge**

Capillary suction time measurements are consistently higher with the 10-mm in comparison to the 18-mm diameter funnel. However, the latter funnel is recommended for ‘heavy’ sludges. The application of this large funnel results in a quick test procedure (e.g., more than six times faster for Whatman No. 17 chr).

Stirring has a greater impact on Whatman No. 17 chr in comparison to both SS 3324 chr and Fisher 200 chr, for example. The reductions were 22, eight and two percent, respectively, if the 18-mm funnel was used. It follows that Fisher 200 chr is not negatively influenced by sedimentation and therefore superior to Whatman No. 17 chr. However, the mean CST of Whatman No. 17 chr and Fisher 200 chr are most similar for comparable unstirred (but not stirred) samples. Further experiments are required to find a solid explanation.

Moreover, the ratio of standard deviation over mean (when applying a circular funnel) is lower for Fisher 200 chr than for all other papers. This indicates very reliable and reproducible results due to the high filter paper quality.

Using a rectangular funnel, CST mean measurements for Fisher 200 chr are only nine percent lower in comparison to Whatman No. 17 chr. The data variability for Fisher 200 chr is also smaller than Whatman No. 17 chr indicating a greater reliability of the findings due to a reduced impact of sedimentation (see above). Both papers are therefore, for all intents and purposes, similar for primary sludge application. However, Fisher 200 chr would be an adequate and cheap replacement for the standard CST paper if ‘light’ sludges are to be investigated.

**Surplus activated sludge**

The SS 1107 and Fisher 200 chr papers were most similar to Whatman No. 17 chr in terms of their mean time using the 10-mm funnel. However, the ratio of standard deviation over mean was the lowest for Fisher 200 chr if compared to all other papers.

Using a rectangular funnel, Fisher 200 chr was the most similar paper to Whatman No. 17 chr. The ratio of standard deviation over mean for Fisher 200 chr was lower in comparison to Whatman No. 17 chr, but higher compared to HOVO TO w/s, SS 1107 and SS2668 chr and the same as for SS 3324 chr.

**Synthetic sludge**

Conducting physical and chemical tests with any natural sludge is difficult because of its constantly changing properties. To overcome this difficulty a synthetic sludge that physically and chemically resembles natural sludge and is stable over time was created. Even though there are some differences in properties due to the absence of living biomass, because the physical behavior of synthetic sludge is close to that of natural sludge, it can be used as a surrogate material when reproducibility in testing is required.

A simplified but affordable synthetic sludge (see above) was used as a reliable reference material to develop the CST test further. The synthetic sludge has a CST of 12.6 ± 0.24 (based on eight measurements).\(^7\) In comparison, the simplified synthetic sludge used for the purpose of this paper has a CST of only 5.2 ±0.25 s (based on ten measurements). The difference is due to the absence of polystyrene latex particles that tend to clog the relatively large pores of Whatman No. 17 chr.

Experiments with synthetic sludge frequently resulted in more consistent results, but synthetic sludge (large and ‘heavy’ flocs) had the tendency to settle faster than natural sludges (small and ‘light’ flocs) and therefore required vigorous stirring before the start of the experiment. Nevertheless, Fisher 200 chr was most similar to Whatman No. 17 chr if a 10-mm funnel was used. However, the ratio of standard deviation over mean was higher for the former if compared to the latter paper regardless of funnel type.

As expected for CST tests using a rectangular funnel, relative synthetic sludge variability (ratio of standard deviation over mean) was frequently lower than the variabilities for natural sludges (27 out of 32 comparisons). Synthetic sludge could therefore be used as a benchmark for ‘light’ sludges such as
surplus activated sludge but not for ‘heavy’ sludges (e.g., most primary sludges). Considering the greater need to test for dewaterability of ‘heavy’ sludges, the need for synthetic sludge in practice (except for predictive modeling purposes) is questionable.

Synthetic sludge was not a reliable reference sludge for CST tests using the rectangular funnel. Only five out of sixteen relative standard deviations improved. Further experiments should be considered to entirely exclude experimental error for the data interpretation. Consistent improvements for both natural sludges were noted only for Whatman No. 17 chr indicating the advantage of large filter paper pore sizes for synthetic sludge lacking fine particles (see above).

**Selection of an alternative CST apparatus, procedure and paper**

An alternative improved CST apparatus in comparison to the standard Model 304B CST using a circular funnel should have the following attributes:
- More accurate (i.e., less variable results);
- Results should relate more closely to the dewaterability problem (advantage of using a rectangular funnel); and
- Cheaper to construct (standard and modified CST apparatus have similar construction costs).

The application of an alternative improved CST measurement procedure should result in the following benefits:
- The negative effect of sedimentation (e.g., by using a stirrer) should be reduced;
- The procedure should be easy and time-efficient (e.g., use of a stirrer adds only approximately 30 s to the test); and
- The associated costs should be low (e.g., stirrer costs are approximately $3).

An alternative cheaper paper that has the potential to replace the expensive standard Whatman No. 17 chr paper should have the following attributes:
- Similar in terms of mean CST results for various sludges and procedures so that past and future CST values are comparable with each other;
- The standard deviation for a set of measurements of the same sludge should be smaller (or at least similar) indicating higher reliability; and
- The individual and bulk costs for the paper should be lower so that the consumable costs for the user can be reduced.

**Conclusions**

The CST test is easy to conduct, cost-effective and accurate, if the product of solid concentration and average SRF is of interest. On the other hand, the bound water content cannot be directly evaluated from the CST.

A study of different papers showed that Fisher 200 chr could replace Whatman No. 17 chr. If the sludge is stirred to avoid sedimentation, Fisher 200 chr, and possibly SS 2668 chr and SS3324 chr can replace the standard Whatman No. 17 chr paper. All alternative papers are cheaper than the currently used standard paper. However, historical CST records are entirely based on Whatman No. 17 chr paper.

The use of a rectangular funnel was the most promising innovation. Flow patterns using a rectangular instead of a circular funnel consistently led to more reliable CST measurements. Moreover, stirring of the sludges during the CST test resulted in a small (mostly insignificant) reduction of the sedimentation effect for most sludges.

The potential for modeling processes within the conventional CST apparatus that uses a circular funnel were assessed. However, the conventional test kit is
empirical and therefore requires modification to enable dynamic modeling of filter wetting processes, which is possible if a rectangular funnel is used. Moreover, the water content and pressure relationships can be clearly described for the modified apparatus (prototype).

**Further research needs**

Based on the experimental findings of this paper, the following program (in order of increased importance) of future laboratory work and analysis will be undertaken by the authors:

- The influence of sedimentation on filtration for cake-forming sludges (not allowing the assumption of a gravity-free solution throughout the experiment) will be studied. It will be assessed if a constant current (induced by a stirrer) within the sludge chamber to avoid sedimentation might be beneficial for sludges heavier than primary sludge (see above).
- Research on affordable and appropriate (more isotropic; reduced pore diameter) papers or even different porous filter media for specific applications (i.e., different types of sludge) will be undertaken.
- The use of a rectangular chamber and applying a constant pressure head (to allow filterability to be described by sorptivity) during filtration will be researched. This would be the basis for spreadsheet and subsequently dynamic modeling in the future.
- The development of a novel prototype is currently pursued. The authors would welcome the involvement of readers in the testing of the new apparatus or as members of either the academic or industrial advisory boards.

**References**


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